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16. ABSTRACT <p>This project was defined in terms of four main Tracks. Each Track addressed a specific research component of emergency operations. Track I involved the development of a prototype, mobile, virtual emergency operations center. Track II was concerned with testing and developing modeling approaches for emergency evacuation. Track III addressed a number of needs for interoperable communication facing intelligent transportation systems (ITS) and public safety (PS), and track IV was concerned with potential applications of wireless sensor networks (WSN). Here we emphasized the development of WSN that can be used to improve work zone safety. A demonstration of the Virtual Emergency Operations Center which was developed as a part of this project were highlighted by the Department of Homeland Security. It was demonstrated that for some large scale emergencies that contra-flow operations may be valuable in substantially reducing clearing times, however, manpower and equipment needed to support such an operation may not be available on a timely basis. A survey of evacuation participants subject to a mandatory evacuation indicated that nearly 10% of the population did not leave and that the choice of an exit location could alter clearing times. Both micro-scale traffic simulation and multi-commodity flow-optimization were tested in modeling evacuation. The feasibility of interoperable communications between ITS and PS has been investigated. We reported on best field practices for deploying wireless broadband, specifically for the Dedicated Short Range Communications (DSRC), and multihop ITS/PS networks. To reduce Caltrans' worker injuries and fatalities in work zones, we investigated the use WSN and cooperative algorithms for sub-meter localization. Our simulation shows promising results for using the emerging Internet of Things (IOT) for work zone safety in both urban and rural environments.</p>		
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First Responder Support Systems Testbed (FiRST)

Contract # 65A0257

Cross-Cutting Cooperative Systems Final Report

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The First Responders Systems Testbed (FiRST) is comprised of a number of interrelated tasks, all with a focus of addressing the needs of the State of California and Caltrans. This project was conceived as an attempt to address a number of critical issues that Caltrans and other public agencies will face in the event of disasters and disruptive events. California needs the capability of responding quickly and efficiently to any disaster, and its road, communication, and data systems networks will play key roles in any response. Caltrans will play a significant role in operating and managing the highway infrastructure during any crisis, whether it be flooding in the central valley, a large earthquake in an urban center such as Los Angeles or San Francisco, a Tsunami that will take out segments of Highway 101 on the North coast of California or the Ports of LA or Long Beach, or even a major industrial crisis like that of a failure at Diablo Canyon Power Plant.

A set cross-cutting cooperative systems is required to respond to any major emergency, the different tracks developed under the FiRST contract addressed the integration of such systems. It investigated the significant capability required to manage assets, communicate and share information across jurisdiction and geographical boundaries, and the ability to access up-to-date information and model possible



consequences of action. This is not a simple task and often complacency can set in when the return period for such events can be long. For example, the 1994 Northridge 6.7 earthquake caused considerable damage, even though it is considered to be a mild earthquake compared to a 7.5 or greater trembler. For Caltrans to promote safety, aid in emergency response, secure roadways, and enhance maintenance, there are a number of key elements



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that should be addressed. This includes the development of a virtual operations center. In major disasters, there are no guarantees that operations centers will remain intact or be capable of operating. In several recent past events, like that in Santa Barbara County, the county's emergency operation center was at risk to a major wildfire and had to be closed, making coordinated operations more difficult to control. In response the county built a new state of the art facility that contains on-line records for all county operations, is configured to serve as a fully functional command and control center, backup generators and fuel storage to support the center in times of power disruptions, as well as many other features. But, such brick and mortar facilities cannot be fully relied upon and it is important to develop the capabilities to operate a virtual emergency operations center from anywhere. It is also important to develop communications systems that can cross agencies, handle voice, video, and data, so that managers can easily communicate, coordinate, and operate their response effectively and efficiently. It is also important to be able to develop and test approaches for operating a transportation system in a crisis, supporting both supply and evacuation needs. The citizens of the State rely on Caltrans to ensure safe highway operations on a daily basis, but even more so in a time of crisis. The FiRST project was designed to address a number of these needs by developing state-of-the art prototypes and models for possible use in future Caltrans operations.

This project was defined in terms of four main tracks or Tasks. Each Track addressed a specific component of emergency operations. Track I involved the development of a prototype emergency operations center. Track II was concerned with testing and developing a modeling approach for emergency evacuation. Track III addressed a number of needs for interoperable communication and their integration to support those cooperative systems, and track IV was concerned with investigating the use of wireless sensor and communication network. Here we emphasized the development of wireless sensor networks that can be used to improve work zone safety.

This report covers developments of those cross-cutting cooperative systems investigated in all four tracks. Altogether, this project has accomplished several significant milestones. These include:

- The development of a prototype virtual emergency operations center (VEOC). The VEOC prototype implemented the Unified Incident Command and Decision Support (UICDS) architecture originally developed by the Department of Homeland Security (DHS). This effort was demonstrated during the Golden Guardian statewide exercise in 2012 and 2013, and was recognized by DHS as the first successful implementation of the UICDS architecture in California. In addition, this VEOC was designed to integrate and use the Caltrans PeMS data, as well access to the Caltrans Earth.
- Developed a simulation of a large are evacuation associated with San Luis Obispo. This simulation utilized PTV VISSIM micro-scale traffic simulation system. Two approaches were developed, one based upon dynamic trip assignment, and the other based upon fixed trip assignment. Both approaches were test on a mock contra-flow operations plan as well as a baseline operations scenario. The mock contra-flow plan was shown to providesubstantial



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promise in clearing a large region like San Luis Obispo. This result is important in that this may form the basis for better levels of service in an emergency for Caltrans assets.

- Surveyed participants in a wildfire evacuation and demonstrated that the number of people deciding to evacuate and their timing could be estimated by a Rayleigh Probability Model. Our survey indicated that approximately 10% of the homes had at least one occupant who stayed behind, even when the neighborhood was engulfed in flames. This fact alone suggests that emergency managers will have to address a relatively large population who stayed behind.
- Developed a new prototype multi-commodity flow optimization model that can be used as a potentially fast tool to estimate clearing times and bottlenecks at a meso-scale. This model could mimic actual routes chosen when tested against actual evacuation data.
- Developed an emergency equipment and personnel allocation model that can be used to allocate resources during a major contra-flow event with the objective of placing a contra-flow plan in action as quickly as possible. This model was not fully tested or developed as appropriate data was not supplied by Caltrans.
- Integrated the on-going national standards development activities to achieve interoperable communications between agencies using the intelligent transportation systems (ITS), and the public safety (PS) frequency bands. It developed and documented best field practices for the deployment of wireless broadband for Caltrans and other first responders.
- Investigated multihop networks as an alternative approach for integrating both ITS & PS networks to enhance wireless services required by first responders.
- Developed and demonstrated the use of broadband channel emulation technology as a robust tool for broadband wireless protocol testing and validation in various deployment environment
- Developed a prototype for Hastily Deployed intranet Network (HDiN) nodes. The HDiN prototype provides different communications technologies to connect to the Internet, and provides a local intranet to connect cooperating first responders. When connectivity to the Intranet is restored, it synchronizes itself; it is designed to work when other systems won't. The HDiN nodes could be engineered to support the VEOC functionality including the integration of PeMS, hosting a local copy of Caltrans' Earth, as well as broadcasting video streams from selected sources. It is envisioned that the current suitcase size prototype could provide critical support of Caltrans and other first responders without relying on the availability of the Internet or the cloud.
- Developed innovative solutions to reduce Caltrans' worker injuries and fatalities in work zones using networked wireless sensors. These sensors can be deployed along work sites to monitor the safety of work zones. It can be deployed on traffic cones and its cost would be relatively low to fully deploy. Potentially, this technology could also extended to the emerging connected vehicles environment.

Overall this project was a significant success, providing cutting edge modeling, technology enhancement and prototype development that can be used by future generations of Caltrans employees. Reports on each of the project tracks follows in order.

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**First Responder Support Systems Testbed (FiRST)
Contract # 65A0257
Cross-Cutting Cooperative Systems**

TRACK I – Virtual Emergency Operation Center (VEOC)

Final Report

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Virtual Emergency Operation Center (VEOC): This research was requested by Caltrans to support statewide multi-agency disaster response operations and management, as well as for day-to-day incident management at the Districts. The task was to investigate a robust architecture and to develop a standard-based prototype implementation for a VEOC. The selected VEOC architecture was to be scalable across functional, jurisdictional, and geographical boundaries.

This effort developed a set of requirements and demonstrated a prototype implementation that is based on the Unified Incident Command and Decision Support (UICDS) architecture originally developed by the Department of Homeland Security (DHS). Additionally, it developed for the first time a special software adapter to integrate the Caltrans' PeMS data into the VEOC implementation. This effort was demonstrated during the Golden Guardian statewide exercise in 2012 and 2013, and was recognized by DHS as the first successful implementation of the UICDS architecture in California.



Virtual Emergency Operations Center Architecture, Prototype, and Demonstration

February 3, 2014



1 VEOC Executive Summary

This report presents an operational scenario and a high level architecture developed for the Virtual Emergency Operation Center (VEOC). A subset of the VEOC architecture has been implemented using the Unified Incident Command and Decision Support (UICDS). A high-level comparison between VEOC and WebEOC is described.

The operational scenario developed is intended to demonstrate how the VEOC is able to support incident management across functional, jurisdictional, and geographical boundaries. The scenario shows how VEOC enables incident management organizations from various jurisdictions and performing different incident response functions to interwork transparently as single integrated virtual incident management organization.

The VEOC architecture is designed to support incident management applications from different vendors that perform different incident management functions to inter-work across different jurisdictions and geographical locations. The architecture of VEOC enables it to scale up to support large incidents and provides an efficient mechanism for communications and information distribution.

A prototype implementation of a scaled-down VEOC architecture is developed using the UICDS. The prototype receives information from PeMS and LCS, and analyzes the data in real time for traffic incidents. When a traffic incident is detected, a UICDS incident is created that triggers off other incident response actions. A Viewer application is also developed for viewing incident information and data from PeMS and LCS.

2 Project Description

2.1 Objectives and Scope

The main objectives of this project are threefold: to identify major high-level requirements for a virtual emergency operations center (VEOC), to implement a simplified prototype based on the Unified Incident Command and Decision Support (UICDS) framework to study the feasibility of essential requirements, and to investigate and compare selected essential enabling technologies.

2.2 Introduction

The project demonstrated the critical impact of the status of the transportation network during few state-wide exercises, namely the Golden Guardian in handling earthquake scenario.

- **Architecture and Prototype**
This section describes the high-level VEOC architecture, and a prototype based on UICDS.
- **VEOC High-Level Systems Requirements**
This section presents the high-level systems requirements and testing for future implementation efforts.

3 VEOC High-Level Architecture

The architecture of VEOC is designed to support incident management across jurisdictional, functional, and geographical boundaries, ranging from small local incidents to large-scale incidents. The VEOC architecture is organized as a network of systems. Each system connects a group of incident management applications within the same jurisdiction or geographical area. Different incident management applications connected to a system may provide different incident management functions. In addition, different sensors may also be connected to a system to provide data for monitoring and managing incidents. The systems are interconnected to form a federation to enable communications and information exchange throughout the entire federation.

Scalability

The network-of-systems architecture enables VEOC to scale up to support management of large incidents. As the scale of incident response increases to include more jurisdictions or geographical areas, the number of systems in the federation that are involved in the incident management also increases. Similarly, as more incident response functions are needed, the number of incident management applications that are involved in the incident response also increases.

Information and Communication Model

The VEOC architecture provides an efficient information dissemination and communication model. Each system in the federation supports information exchange between incident management applications using the publish-subscribe model. It enables information relevant to the incident response to be published and accessible by incident management applications connected to the system. Each incident management application subscribes and receives only information that is relevant or of interest.

The VEOC architecture also supports information exchange between systems in the federation. Information is forwarded from one system to the others based on pre-arranged mutual agreements. When forwarded information is received by a system, it delivers the information to the local management applications according to their subscription preferences. This approach not only supports information dissemination across the federation, but also minimizes the amount of information that is exchanged between systems, as it eliminates pair-wise information exchange between incident management applications connected to different systems.

UICDS Implementation

The VEOC architecture can be implemented using UICDS. The UICDS architecture (Figure 1) consists of a network of ‘cores’, with each core connecting multiple clients. Each VEOC system in a federation can be implemented by a UICDS core. VEOC inter-system communication is provided by UICDS inter-core communication.

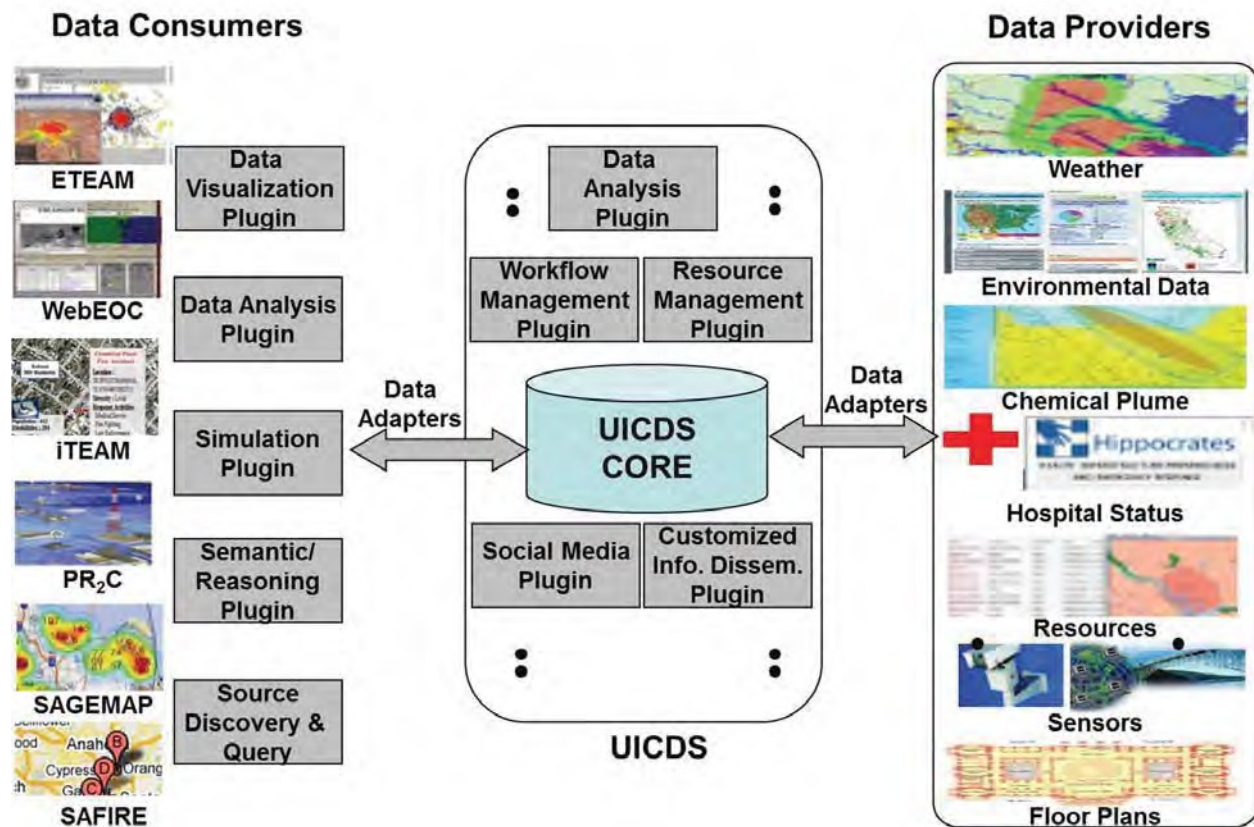


Figure 1: UICDS High Level Architecture

The high-level architecture of VEOC is as shown in Figure. It supports the operation scenario described in Section 4 that involves incident management across a number of jurisdictions, geographical areas, and functional organizations. There are four jurisdictions shown in Figure, namely Caltrans, county, state, and federal jurisdictions. Each jurisdiction is supported by a UICDS core. Each UICDS core has a number of incident management applications connected to it. For example, at the state level, the state police and state Office of Emergency Management (OEM) are connected to the State UICDS Core. Similarly, the County UICDS Core and Federal UICDS Core have, respectively, county level and federal level incident management applications connected to them.

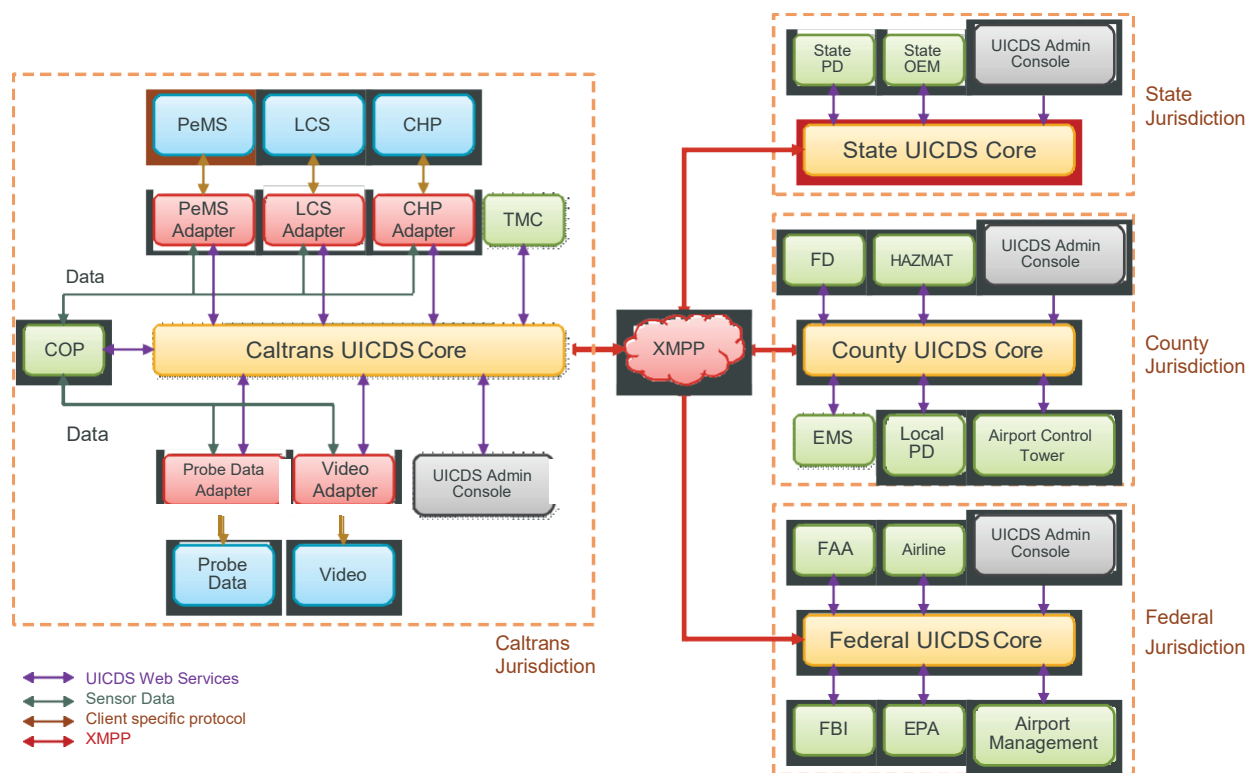


Figure 2: VEOC High Level Architecture

Adapters

In Figure, the Caltrans UICDS Core has a number of traffic applications connected to it via adapters, including PeMS, CHP, LCS, probe data, and roadside video. These applications collect various important traffic incident information and traffic data that are needed in monitoring and managing incident responses. In UICDS, these data sources are considered as data sensors. The functionalities of the adapters that connect these data sensors to the UICDS core include:

- Data and operations adaptation

The adapters connect to the UICDS core and data sensors using APIs and data formats specified by the UICDS and data sensors respectively. Inside the adapters, mapping of data and operations is performed between the two data formats and APIs.

- Sensor data retrieval

In the UICDS architecture, sensor data is delivered using an out-of-band approach whereby incident management applications are notified of sensor data availability by the UICDS core. The incident management applications then proceed to retrieve sensor data directly from the sensors. The adapters provide such an interface for the retrieval of sensor data.

- Incident detection and creation

In addition to receiving data continuously from the sensors, the adapters may also analyze the data in real time to detect various traffic incidents or events, such as accidents or congestions. Upon detecting such traffic incidents or events, the adapters register the incidents in UICDS by creating a UICDS incident in the UICDS core. Notifications are then sent by the UICDS core to incident management applications to inform them of the incidents.

Common Operating Picture

In the VEOC architecture, a Common Operating Picture (COP) application is connected to the Caltrans UICDS Core. The role of the COP application is to continuously collect information from various sources and create a common operating picture that provides important information needed for monitoring and managing incidents. Examples of such information include information about traffic incidents, such as the type, location, time and description of incidents, and traffic data related to incidents.

Administration Console

The UICDS Administration Console provides the capabilities for managing UICDS cores, such as managing information sharing agreements and resource profiles.

Standards

UICDS adopts a number of standards related to incident management. The Emergency Data Exchange Language – Distribution Element (EDXL-DE) is used to encapsulate messages to and from the UICDS core. EDXL-DE facilitates routing of properly formatted XML emergency messages to recipients. The Emergency Data Exchange Language – Resource Messaging (EDXL-RM) is used to provide a set of standard formats for emergency response messages. The Common Alerting Protocol (CAP) is used to provide the format for exchanging emergency alerts. Access to the UICDS core is via web services as defined in the UICDS Web Service Definition Language (WSDL). The Extensible Messaging and Presence Protocol (XMPP) is used for messaging between UICDS cores.

4 Operation Scenario

In this section, we describe an operational scenario to show how a UICDS-based VEOC can integrate emerging capabilities with traditional emergency management functions to achieve integrated cross-organizational emergency management.

Scenario – Concept of Operation

The following describes details of the scenario, and the operation flows:

Creation of an incident in a UICDS core causes notifications to be sent to incident management systems or applications that are connected to the core. This enables incident management systems to be informed of the incident and to initiate incident response procedures. Incident notifications are also sent to other UICDS cores that are involved in the incident management and that have pre-arranged agreements to share incident information.

- a) Incident notifications are sent by the County UICDS Core to local incident management organizations, namely the local Police Department (PD), Fire Department (FD), EMS, and HAZMAT.

A UICDS core often connects incident management organizations that are in the same jurisdiction. When an incident is created in the core, incident notifications are automatically sent to these organizations, enabling them to respond to the incident immediately.

- b) Inter-core incident notifications are also sent by the County UICDS Core to Caltrans, State, and Federal UICDS Cores.

In addition, incident notifications are also forwarded to other UICDS cores that have pre-arranged agreements for information sharing. These other UICDS cores then deliver the notifications to their local incident management systems. This approach allows the system to scale up and minimize traffic between cores.

- c) Upon receiving the incident notification, the Caltrans UICDS Core delivers the notification to local incident management systems, namely the Traffic Management Center (TMC) and the Common Operating Picture (COP) application, to inform them of the incident and enable them to initiate appropriate response actions. The Caltrans UICDS Core forwards the incident notification to the local TMC.
- d) The TMC detects a traffic incident on the interstate highway from real-time analysis of PeMS data. The TMC is continuously receiving data from PeMS, and CHP, as well as live roadside videos. It analyzes the data in real time to detect any traffic incident and anomaly.
- e) The TMC verifies the incident has occurred by cross-correlating the PeMS data with CHP data and other resources such as live videos. This significantly increases the

accuracy and timeliness of incident detection. It enables the TMC to verify that the incident has occurred, and to provide further information on the incident, such as location, time, and nature of the incident. After verifying the incident, the TMC creates (registers) an incident in the Caltrans UICDS Core. This enables other incident management organizations to initiate their response actions.

- f) The TMC creates Sensor Observation Information (SOI) Work Products (WP) in the Caltrans UICDS Core for CHP data, PeMS data, video, and LCS data.

To ensure the involved incident management organizations stay informed and have access to latest sensor data from Caltrans, the TMC creates SOI WPs in the UICDS core for sensor data that is related to the incident. This enables incident management applications to obtain sensor data needed to support their response action plans.

- g) The TMC associates SOI WPs with the specific incident in the Caltrans UICDS Core.

This creates in the UICDS system an association between the incident and sensor data that is related to the incident. In this way, incident management applications will stay informed as they will be notified when sensor data related to the incident is available.

- h) The Caltrans UICDS Core sends incident and WP notifications to the field incident response team to inform it of the incident and available sensor data.
- i) The Caltrans UICDS Core also forwards incident and WP notifications to the County, State, and Federal UICDS Core.

Through interconnection and information sharing agreements, the County, State, and Federal UICDS Cores receive notifications of the incident and available sensor data. These notifications are then delivered to incident management organizations in the county, state, and federal jurisdictions, thereby enabling these organizations to immediately initiate their incident response actions.

- j) Upon receiving incident and WP notifications, the field incident response team through the COP application requests and retrieves CHP data, PeMS data, and LCD data.

The COP application, using information in the notifications, retrieve data from sensors to create a common operating picture that contains important information needed for monitoring and managing the response to the incident, including the type, location, time, and description of the incident, and traffic data related to the incident.

- k) When the County UICDS Core receives incident and WP notifications from the Caltrans UICDS Core, it delivers the notifications to incident management organizations in its jurisdiction, including the local PD, FD, EMS, and HAZMAT.

The notifications inform county-level incident management organizations of the specific incident and provide them with access to sensor data related to the incident. This enables county-level incident management organizations to immediately respond to the incident.

- l) In case of a wide area emergency that goes beyond a single county, the State UICDS Core may then receive the emergency notification from the County UICDS Core, it delivers the notification to the state law enforcement (CHP) and the state Office of Emergency Management (e.g. CalEMA) to enable them to initiate state-level response.
- m) Upon receiving incident and WP notifications from the Caltrans UICDS Core about the wide area emergency, the State UICDS Core sends the notifications to the CHP and CalEMA. These notifications from the Caltrans UICDS Core contain more precise and detailed information on the incident.

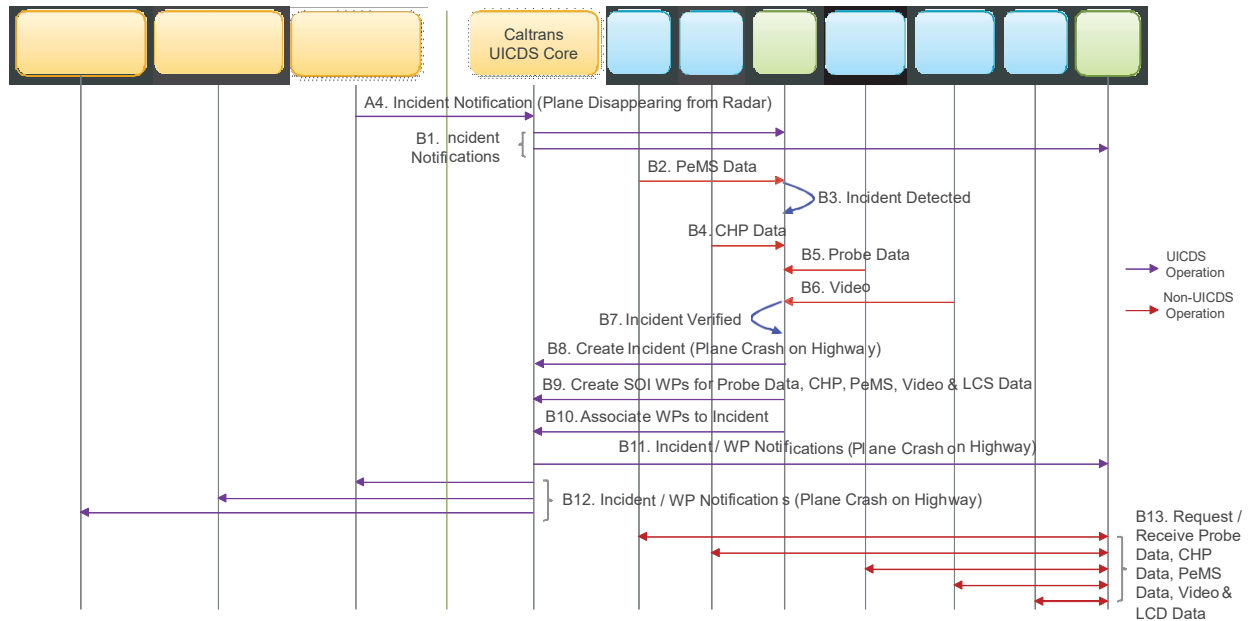


Figure 3: VEOC Operation Flow at Caltrans UICDS Core Level

5 Prototyping

The prototyping work involves implementing a scaled-down version of the VEOC architecture using UICDS. Figure 4 shows the architecture of the prototype. The prototype involves two UICDS cores. The UICDS Core 1 connects to the PeMS system, and Historical PeMS system at FIRST Testbed that contains historical PeMS data. The UICDS Core 2 connects to the LCS system. Each UICDS core also connects to a Viewer application that provides viewing of incident and traffic data, and a UICDS Administration Console.

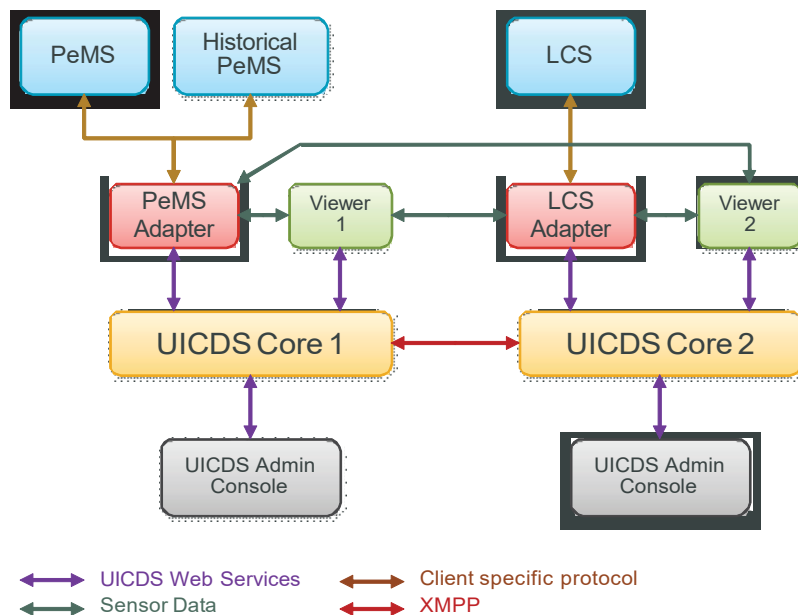


Figure 4: Architecture of Phase I Prototype

5.1 Components

The components included in this prototype are the PeMS Adapter, LCS Adapter, and Viewer application. The UICDS Administration Console is provided by UICDS.

PeMS Adapter

The PeMS Adapter is a bridge that connects the PeMS system to the UICDS Core 1. It supports automatic data retrieval and processing from PeMS through an FTP interface. It also provides additional data analysis and incident identification capabilities. Upon identifying an incident, the PeMS Adapter will create a UICDS incident and publish this incident in the UICDS Core 1. The PeMS Adapter also provides an interface for the Viewer application to access the PeMS data.

The PeMS Adapter also connects to the Historical PeMS system at the FIRST Testbed. When PeMS is not available, the PeMS Adapter is able to retrieve historical data from the Historical PeMS system.

LCS Adapter

Similar to the PeMS Adapter, the LCS Adapter is a bridge that connects the LCS system to the UICDS Core 2. It supports automatic data retrieval and processing from LCS via an HTTP interface. It also provides additional data analysis and incident identification capabilities. Upon identifying an incident, the LCS Adapter will create a UICDS incident and publish this incident in the UICDS Core 2.

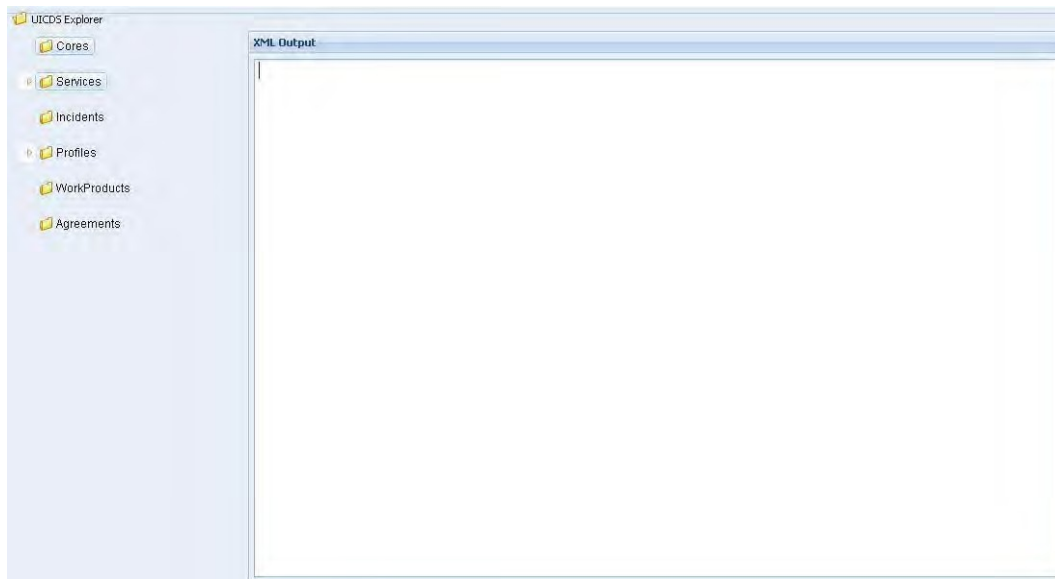


Figure 5: UICDS Administration Console

Viewer Application

The Viewer application is a web-based application that retrieves data from the PeMS Adapter and LCS Adapter to create a common operation picture of an incident. It provides VEOC users with a single portal for viewing data from PeMS and LCS, as well as viewing of UICDS incidents. In this phase, users could view the following data using the Viewer application:

- Loop data from PeMS
- Lane closure incident data from LCS
- Incident data from the UICDS core

UICDS Administration Console

This is the administration system for managing the UICDS core. Figure shows a snapshot of the system. The administration functions available include:

- Managing agreements with other UICDS cores, such as creating, rescinding and modifying agreements. A mutual agreement needs to be established for UICDS cores to share information with one another.

- Managing resource profiles, such as creating, deleting and updating resource profiles
- Viewing of incidents, work products, etc.

5.2 UICDS Services

The PeMS Adapter, LCS Adapter, and Viewer application interact with the UICDS core using web services provided by the UICDS core. These UICDS services include Resource Instance Service, Resource Management Service, Work Product Service, Sensor Service, Incident Management Service, and Notification Service. The services accessed by each of the prototype components are described below.

PeMS Adapter

Using the Resource Instance Service, the PeMS Adapter registers itself with the UICDS core as a resource instance. It uses the Sensor Service to create a Sensor Observation Information (SOI) work product. The SOI work product contains information that is needed by other applications to retrieve the PeMS data directly from the PeMS Adapter. The PeMS Adapter also uses the Incident Management Service to create and publish UICDS incidents in the UICDS core.

PeMS Adapter also publishes the raw data retrieved from PeMS system to a web-based user interface.

LCS Adapter

The LCS Adapter uses the Resource Instance Service to register itself with the UICDS core as a resource instance. It also uses the Sensor Service to create a SOI work product that contains the information needed for other applications to retrieve LCS data from the LCS Adapter. In addition, the LCS Adapter uses the Incident Management Service to create and publish UICDS incidents in the UICDS core.

LCS Adapter also publishes the raw data retrieved from PeMS system to a web-based user interface.

Viewer Application

The Viewer application uses the Resource Instance Service to register itself with the UICDS core as a resource instance. It is notified through the Notification Service when incidents or work products that it subscribes to are created or updated.

Viewer Application publishes the received incident notification messages and associated information to a web-based user interface.

5.3 Operation Flow

The operation flow of the Phase I prototype is as shown in Figure 6. In this operational scenario, both the PeMS Adapter and LCS Adapter retrieve data from PeMS and LCS respectively, and analyze the data in real-time for traffic incidents. The PeMS Adapter detects a traffic incident

and creates (or registers) an incident in the UICDS Core 1. The Viewer 1 application is notified of the incident. The incident information is also sent to UICDS Core 2, and then onto the Viewer 2 application. Both Viewer applications then retrieve data from the PeMs Adapter and present it to users for viewing.

The LCS Adapter detected another incident and creates an incident in UICDS Core 2. The Viewer 2 application is notified of the incident. This incident is also sent to UICDS Core 1. As a result, the Viewer 1 application is also notified of the incident. The Viewer applications then proceed to retrieve data from LCS and present it to users.

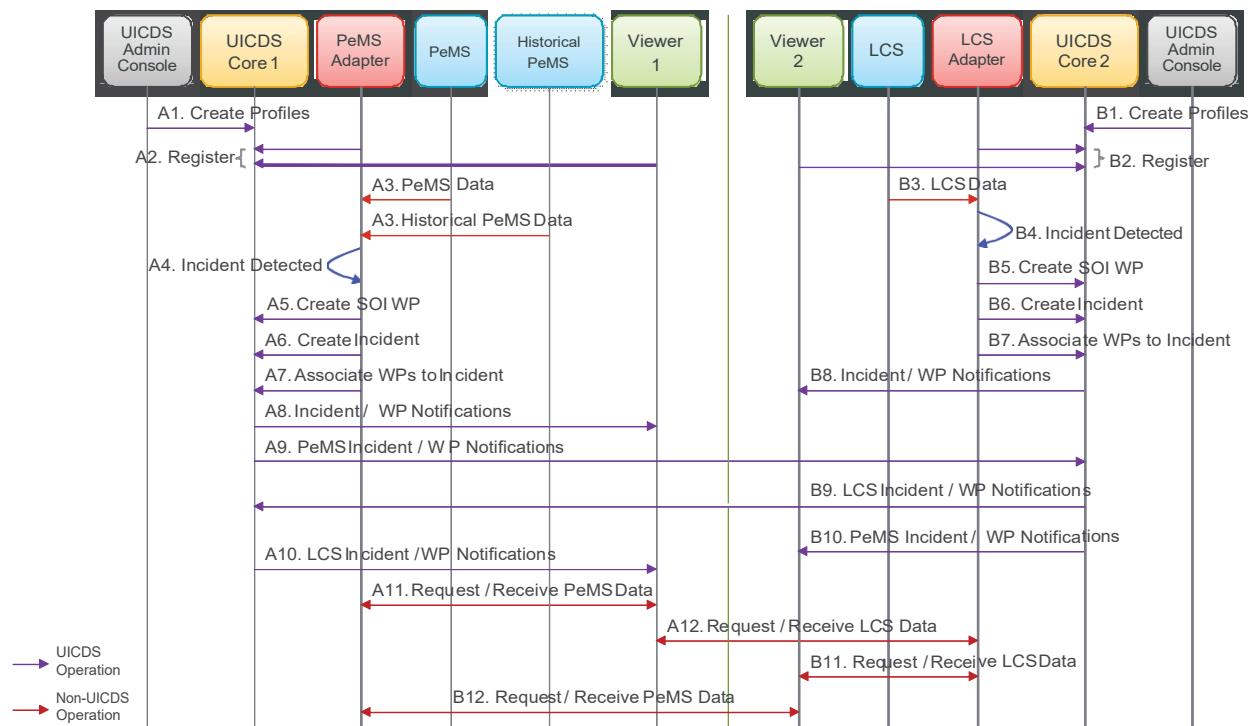


Figure 6: Operation Flow of Phase I Prototype

Details of the operation flow at UICDS Core 1 are as follows:

- A1. UICDS Administration Console creates profiles in the UICDS Core 1 for the PeMS Adapter and Viewer 1 application.
- A2. Upon starting up, the PeMS Adapter and Viewer 1 application register with UICDS Core 1.
- A3. The PeMS Adapter receives data in real time from PeMS. In the event that the PeMS system is not available, the PeMS Adapter will retrieve data from the Historical PeMS system which contains historical PeMS data. (non-UICDS operation).
- A4. In analyzing PeMS data, the PeMS Adapter detects a traffic incident.
- A5. The PeMS Adapter creates a Sensor Observation Information (SOI) Work Product (WP) for PeMS data.

- A6. The PeMS Adapter creates an incident in UICDS Core 1.
- A7. The PeMS Adapter associates the SOI WP with the incident.
- A8. The UICDS Core 1 sends Incident and WP notifications to the Viewer 1 application.
- A9. The UICDS Core 1 also sends Incident and WP notifications to the UICDS Core 2.
- A10. The UICDS Core 1 receives (LCS) incident and WP notifications from UICDS Core 2, and sends them to the Viewer 1 application.
- A11. The Viewer 1 application retrieves PeMS data from the PeMS Adapter and presents the data to the user (non-UICDS operation).
- A12. The Viewer 1 application retrieves LCS data from the LCS Adapter and presents the data to the user (non-UICDS operation).

Details of the operation flow at UICDS Core 2 are as follows:

- B1. UICDS Administration Console creates profiles in the UICDS Core 2 for the LCS Adapter and Viewer 2 application.
- B2. Upon starting up, the LCS Adapter and Viewer 2 application register with UICDS Core 2.
- B3. The LCS Adapter receives data in real time from LCS. (non-UICDS operation).
- B4. In analyzing LCS data, the LCS Adapter detects a traffic incident.
- B5. The LCS Adapter creates an SOI WP for LCS data.
- B6. The LCS Adapter creates an incident in UICDS Core 2.
- B7. The LCS Adapter associates the SOI WP with the incident.
- B8. The UICDS Core 2 sends Incident and WP notifications to the Viewer 2 application.
- B9. The UICDS Core 2 also sends Incident and WP notifications to the UICDS Core 1.
- B10. The UICDS Core 2 receives (PeMS) incident and WP notifications from UICDS Core 1, and sends them to the Viewer 2 application.
- B11. The Viewer 2 application retrieves LCS data from the LCS Adapter and presents the data to the user (non-UICDS operation).
- B12. The Viewer 2 application retrieves PeMS data from the PeMS Adapter and presents the data to the user (non-UICDS operation).

5.4 High-Level Systems Requirements

The high-level systems requirements of VEOC are described in this section.

Generic Functionalities

- VEOC-SR 1. VEOC shall provide a Common Operating Picture (COP) of incidents to system users and shall keep the COP up to date throughout the incident management process.
- VEOC-SR 2. The COP shall support user access through standard Web browsers on desktop computers, laptop computers and mobile devices.
- VEOC-SR 3. The user interface of the COP, including presentation, data type and content, shall be customizable to fit the different user requirements and user device capabilities.
- VEOC-SR 4. The COP shall support user-configurable monitoring on authorized and interested types of incidents.
- VEOC-SR 5. The COP shall support incident monitoring with user-configurable threshold values and methods of notification.
- VEOC-SR 6. The COP shall support multiple options to deliver notifications, including SMS and email at minimum.
- VEOC-SR 7. The COP shall support dashboard-like user interface and provide access to information of system resource and incidents based on user account authorization and configuration.
- VEOC-SR 8. VEOC shall support critical communications, such as real-time chatting, status update, streaming video, streaming audio/voice, between incident management agencies, personnel, applications and other entities.

System Management

- VEOC-SR 9. VEOC shall provide system management functionalities that include, at a minimum, system configuration, user account management, access control system and data back-up, system resource allocation.

Interconnection

- VEOC-SR 10. The VEOC shall be able to interconnect multiple incident management applications and entities across all levels of jurisdictions, including local, state and federal. Examples of incident management entities include traffic management centers, incident management centers, traffic management centers, police, fire departments, hazmat, and emergency medical services.
- VEOC-SR 11. The VEOC shall be able to interconnect geographically distributed incident management applications and entities.

Information management and dissemination

- VEOC-SR 12. The VEOC shall support creation of new incident information, update to existing incident information, and archiving and deletion of incident information.
- VEOC-SR 13. The VEOC shall enable incident management applications and entities to share incident related information.
- VEOC-SR 14. The VEOC shall be able to disseminate incident information to only a select group or groups of incident management applications and entities.
- VEOC-SR 15. VEOC and COP shall provide means to dispatch notifications on COP dashboard, through Short Message Service (SMS), email, or voice call.

Information types and standards

- VEOC-SR 16. The VEOC shall support heterogeneous incident information including binary and structured text data.
- VEOC-SR 17. The VEOC shall support heterogeneous incident information including structured and unstructured data, and multimedia content such as voice, video, and images.
- VEOC-SR 18. The VEOC shall support dissemination of sensor data, such as data from video cameras, traffic, weather, environmental sensors, etc.
- VEOC-SR 19. The VEOC shall support dissemination of traffic information from existing sources, including California's PeMS (Performance Measurement System), CHP (California Highway Patrol), and LCS (Lane Closure System).
- VEOC-SR 20. The VEOC shall support dissemination of vehicle probe data based on SAE J2735 and adopted by IntelliDrive.
- VEOC-SR 21. The VEOC shall adopt common formats for information exchange between incident management applications and entities.

Incident notification

- VEOC-SR 22. The VEOC shall be able to send notification to one or more incident management application and entity.
- VEOC-SR 23. The VEOC shall be able to send notification to a select group of incident management applications and entities, such as those in the same jurisdiction.
- VEOC-SR 24. The VEOC shall be able to send notification to more than one select group of incident management applications and entities, such as those in different jurisdictions.

Network

- VEOC-SR 25. The VEOC shall adopt the Internet Protocol (IP) as the network layer protocol.
- VEOC-SR 26. The VEOC shall be able to operate in both IPv4 and IPv6 networks
- VEOC-SR 27. Communication within the VEOC shall be fully functional over both wireline and wireless networks.
- VEOC-SR 28. Communication between the VEOC and connected incident management applications and entities shall be fully functional over both wireline and wireless networks.
- VEOC-SR 29. The VEOC shall support communication with incident management applications running on fixed devices (such as desktop computers), portable devices (such as laptop computers), and mobile devices (such as mobile phones).

Availability, scalability, and performance

- VEOC-SR 30. The VEOC shall be scalable to interconnect incident management applications and entities from local to national level.
- VEOC-SR 31. The VEOC shall be able to recover to its prior operating state from partial or complete system failures.
- VEOC-SR 32. The VEOC shall have the ability to backup and restore critical system data.
- VEOC-SR 33. The COP shall maintain up-to-date incident information, whereby the latency in updating information shall not be greater than 1 minute.

Security and privacy

- VEOC-SR 34. Incident management applications and entities that connect to the VEOC shall be authenticated before access is permitted.
- VEOC-SR 35. Incident management applications and entities that connect to the VEOC shall be permitted to only access incident information that it has authorization for.
- VEOC-SR 36. The VEOC shall refuse unauthenticated Incident management applications and entities to connect to the VEOC.
- VEOC-SR 37. Personal identifiable information, if any, disseminated through the VEOC is strictly accessible only to authorized incident management applications and entities and on a need-to-know basis.
- VEOC-SR 38. The VEOC shall be able to control the type of information shared by different groups of incident management applications and entities, such as those in different jurisdictions.

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- VEOC-SR 39. The VEOC shall provide means for authorized personnel to obtain information stored by the VEOC.
- VEOC-SR 40. The VEOC shall monitor, detect, report, log, and respond to security incidents.
- VEOC-SR 41. The VEOC shall be able to remove access to the VEOC by any incident management application or entity.
- VEOC-SR 42. The VEOC shall be able to reinstate access to the VEOC by any incident management application or entity.
- VEOC-SR 43. Information exchanged between the VEOC and incident management applications and entities shall be protected from tampering and unauthorized access.
- VEOC-SR 44. The VEOC shall provide a means to authenticate messages originating from connected incident management applications and entities.
- VEOC-SR 45. Information exchanged within the VEOC shall be protected from tampering and unauthorized access.
- VEOC-SR 46. The VEOC shall be able to authenticate messages originating from connected management applications and entities.
- VEOC-SR 47. The VEOC shall be protected against physical intrusion.
- VEOC-SR 48. The VEOC shall provide physical access control for VEOC system elements.
- VEOC-SR 49. The VEOC shall implement management, operational, and technical security measures to protect assets, elements, and information within the VEOC.
- VEOC-SR 50. The VEOC shall provide a means for encrypting and decrypting data.
- VEOC-SR 51. The VEOC shall provide mechanisms for creating, updating, and revoking security credentials.
- VEOC-SR 52. The VEOC shall be protected against Denial of Service (DoS) attacks.
- VEOC-SR 53. The VEOC shall have at least industry-standard security measures for protection against cyber security threat such as software virus, malware, intrusions, and denial of service attacks.

5.5 Requirements Mapping

A subset of the VEOC high-level system requirements has been implemented in this prototype. Details of requirements mapping are shown in Table 1.

Table 1: Requirements Mapping for Phase I Prototype

Requirement	Phase I Prototype Implementation
VEOC-SR 1.	Implemented
VEOC-SR 2.	Partially implemented. User access is currently provided through desktop and laptop.
VEOC-SR 3.	Not implemented
VEOC-SR 4.	Not implemented
VEOC-SR 5.	Not implemented
VEOC-SR 6.	Not implemented
VEOC-SR 7.	Not implemented
VEOC-SR 8.	Not implemented
VEOC-SR 9.	Not implemented
VEOC-SR 10.	Implemented
VEOC-SR 11.	Implemented
VEOC-SR 12.	Implemented
VEOC-SR 13.	Implemented
VEOC-SR 14.	Implemented
VEOC-SR 15.	Not implemented
VEOC-SR 16.	Partially implemented. Structured text data is currently supported.
VEOC-SR 17.	Not implemented
VEOC-SR 18.	Not implemented
VEOC-SR 19.	Partially implemented. Traffic information from PeMS and LCS are currently supported.
VEOC-SR 20.	Not implemented
VEOC-SR 21.	Implemented
VEOC-SR 22.	Implemented
VEOC-SR 23.	Implemented

VEOC-SR 24.	Implemented
VEOC-SR 25.	Implemented
VEOC-SR 26.	Partially implemented. IPv4 is currently supported.
VEOC-SR 27.	Partially implemented. Wireline network is currently supported.
VEOC-SR 28.	Partially implemented. Wireline network is currently supported.
VEOC-SR 29.	Partially implemented. Fixed and portable devices are currently supported.
VEOC-SR 30.	Not implemented
VEOC-SR 31.	Not implemented
VEOC-SR 32.	Not implemented
VEOC-SR 33.	Implemented
VEOC-SR 34.	Implemented
VEOC-SR 35.	Not implemented
VEOC-SR 36.	Implemented
VEOC-SR 37.	Not implemented
VEOC-SR 38.	Implemented
VEOC-SR 39.	Implemented
VEOC-SR 40.	Not implemented
VEOC-SR 41.	Not implemented
VEOC-SR 42.	Not implemented
VEOC-SR 43.	Not implemented
VEOC-SR 44.	Not implemented
VEOC-SR 45.	Not implemented
VEOC-SR 46.	Not implemented
VEOC-SR 47.	Implemented
VEOC-SR 48.	Implemented
VEOC-SR 49.	Not implemented
VEOC-SR 50.	Not implemented
VEOC-SR 51.	Not implemented

VEOC-SR 52.	Not implemented
VEOC-SR 53.	Not implemented

5.6 Test Scenarios

The following test scenarios have been defined for the VEOC prototype.

Test Scenario ID		P-001
Purpose		Verify that users can access the COP application through a web browser on a desktop and laptop.
Requirements Number		VEOC-SR1, VEOC-SR 2 (partial)
Test Step	Action	Results
1	Open a browser on a desktop computer and type in the URL of the Viewer 1 application	Browser displays latest incident information
2	Open a browser on a laptop computer and type in the URL of the Viewer 1 application	Browser displays latest incident information

Test Scenario ID		P-002
Purpose		Verify that VEOC is able to interconnect multiple incident management applications and entities
Requirements Number		VEOC-SR 10, VEOC-SR 11
Test Step	Action	Results
1	Start UICDS Core 1 and UICDS Core 2	Confirm UICDS Core 1 and UICDS Core 2 are running using the UICDS Administration Console
2	Start Viewer 2 application	Viewer 2 application started
3	Start PeMS Adapter	PeMS Adapter started
4	Open a browser on a desktop computer and connect to Viewer 2 application	Browser displays incident information or PeMS data as they become available

Test Scenario ID		P-003
Purpose		Verify that VEOC is able to support creation, update, archival and deletion of incident information

Requirements Number		VEOC-SR 12
Test Step	Action	Results
1	Start Viewer 1 application, then PeMS Adapter	Viewer 1 application and PeMS Adapter started
2	Open a browser on a desktop computer and connect to Viewer 1 application	Browser displays new incident when it occurs
3	Using UICDS Administration Console, close the incident	Message confirm incident is closed
4	Using UICDS Administration Console, archive the closed incident	Message confirm incident is archived
5	Using UICDS Administration Console, delete the archived incident	Message confirm incident is deleted

Test Scenario ID		P-004
Purpose		Verify that VEOC is able to share incident information with a select group of incident management applications and entities
Requirements Number		VEOC-SR 13, VEOC-SR 14
Test Step	Action	Results
1	Create agreement to share incident information between UICDS Core 1 and UICDS Core 2	Agreement created
2	Open a browser on a desktop computer and connect to Viewer 1 application	Browser displays LCS incident information
3	Using UICDS Administration Console, disable the sharing agreement	Browser will not display LCS incident information

Test Scenario ID		P-005
Purpose		Verify that VEOC is able to support structured text incident information
Requirements Number		VEOC-SR 16 (partial)
Test Step	Action	Results
1	Using UICDS Administration Console, select a work product	XML representation of the work product is displayed

Test Scenario ID		P-006
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		Verify that VEOC is able to disseminate information from PeMS and LCS
		VEOC-SR 19 (partial)
1	Open a browser on a desktop computer and connect to Viewer 1 application	Browser connected to Viewer 1 application
2	Select PeMS tab, then a district	Browser displays PeMS data
3	Select LCS tab, then a district	Browser displays LCS data

		P-007
		Verify that VEOC support common formats for incident information exchange between incident management applications and entities
		VEOC-SR 21
1	PeMS Adapter and LCS Adapter create incident information in XML format	PeMS and LCS incident information created
2	Using UICDS Console, display PeMS and LCS incident information	PeMS and LCS incident information displayed in XML format

		P-008
		Verify that VEOC is able to send notifications to incident management applications and entities in the same or different jurisdictions
		VEOC-SR 22, VEOC-SR 23, VEOC-SR 24
1	Open a browser on a desktop computer and connect to Viewer 1 application	Browser displays PeMS incident information after Viewer 1 application receives PeMS notification
2	Create agreement to share incident information between UICDS Core 1 and UICDS Core 2	Browser displays PeMS and LCS incident information after Viewer 1 application receives PeMS and LCS notifications

Test Scenario ID	P-009
Purpose	Verify that VEOC operates over a wireline IPv4 network and communicates with incident management applications running on desktop and laptop

	computers	
Requirements Number	VEOC-SR 25, VEOC-SR 26 (partial), VEOC-SR 27 (partial), VEOC-SR 28 (partial), VEOC-SR 29 (partial)	
Test Step	Action	Results
1	Connect a laptop computer to the computer running UICDS Core 2 using a wireline IPv4 network	Laptop computer and computer running UICDS Core 2 connected by a wireline IPv4 network
2	Start LCS Adapter and Viewer 2 application on the laptop computer	LCS Adapter and Viewer 2 application started
3	Open a browser on a third desktop computer and connect to Viewer 2 application	Browser displays LCS incident information when it occurs

Test Scenario ID	P-010	
Purpose	Verify that the COP application maintains up-to-date information whereby the latency in updating information is not greater than 1 minute	
Requirements Number	VEOC-SR 33	
Test Step	Action	Results
1	Open a browser on a desktop computer and connect to Viewer 1 application	Browser displays PeMS incident information when it occurs. PeMS incident timestamp is not older than 1 minute from the Viewer last update timestamp

Test Scenario ID	P-011	
Purpose	Verify that VEOC only allows access by authenticated incident management applications and denies access by unauthenticated incident management applications	
Requirements Number	VEOC-SR 34, VEOC-SR 36	
Test Step	Action	Results
1	Configure Viewer 1 application with valid credential for accessing UICDS Core 1, then restart Viewer 1 application	Viewer 1 application restarted with valid credential
2	Open a browser on a desktop computer and connect to Viewer 1 application	Browser displays PeMS and LCS incident information when they occur
3	Configure Viewer 1 application with invalid credential for accessing UICDS Core 1, then restart Viewer 1 application	Viewer 1 application restarted with invalid credential
4	Open a browser on a desktop computer and	Browser unable to display PeMS or LCS

	connect to Viewer 1 application	incident information
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Test Scenario ID		P-012
Purpose		Verify that VEOC is able to control the type of information shared by different groups of incident management applications
Requirements Number		VEOC-SR 38
Test Step	Action	Results
1	Using UICDS Administration Console, add 'incident' to the list of interests in Viewer resource profile, then restart Viewer 1 application	Viewer 1 application restarted with resource profile that includes 'incident' in the interests list
2	Open a browser on a desktop computer and connect to Viewer 1 application	Browser displays PeMS incident information when it occurs
3	Using UICDS Administration Console, remove 'incident' from the list of interests in Viewer resource profile, then restart Viewer 1 application	Viewer 1 application restarted with resource profile that does not have 'incident' in the interests list
4	Open a browser on a desktop computer and connect to Viewer 1 application	Browser unable to display PeMS incident information

Test Scenario ID		P-013
Purpose		Verify that VEOC permits authorized personnel to access information stored by VEOC
Requirements Number		VEOC-SR 39
Test Step	Action	Results
1	Login as administrator to the UICDS console, using an incorrect password	Login is denied
2	Login as administrator to the UICDS console, using the correct password	Access is granted
3	Select an incident	Information of the incident is shown in XML

Test Scenario ID		P-014
Purpose		Verify that VEOC is protected from physical intrusion and by physical access control
Requirements Number		VEOC-SR 47, VEOC-SR 48

Test Step	Action	Results
1	Check that VEOC can only be physically accessed through designated entrances	VEOC can only be physically accessed through a designated door to the secured room housing the VEOC
2	Check that a physical access credential is required at designated entrances	A security batch is required at the designated door to enter the secured room

5.7 Installation

This section describes the prerequisites and procedures for installing the VEOC prototype.

5.7.1 Prerequisite

Install JRE 6. Installation procedure is available at:

<http://www.oracle.com/technetwork/java/javase/index-137561.html>

Alternatively, user may install JDK 6. Installation procedure is available at:

<http://www.oracle.com/technetwork/java/javase/index-137561.html>

5.7.2 Install UICDS core

UICS installation procedures are described in:

UICDS System Installation Plan
 UICDS-PLN-SIP-R02C02
 September 27, 2010
 SAIC

5.7.3 Install Tomcat

Tomcat installation procedure is available at: <http://tomcat.apache.org/>

Please note that this Tomcat installation is in addition to the Tomcat used by UICDS core. The path to this Tomcat installation is referred to as [TOMCAT_INSTALLATION] in the installation procedures below.

5.7.4 Install PeMS Adapter

- A. An instance of Tomcat is required to support PeMS Adapter. Both software should collocate on the same computer
- B. Unzip the provided pems.zip to get one war file, PemsData.war, and one directory, "PeMS".
- C. Move the PemsData.war to the [TOMCAT_INSTALLATION]\webapps\

- D. Go to the unzipped directory and find the configuration file, config.prop.
- E. Update the following parameters according to the PeMS access credential and local configuration
 - a. PemsFtpServer => fully qualified domain name of PeMS FTP site
 - b. PemsFtpUser => User name to access PeMS system
 - c. PemsFtpPwd => Password to access PeMS system
 - d. PemsOutputPath => [TOMCAT_INSTALLATION]\webapps\PemsData\web\

5.7.5 Install LCS Adapter

- A. An instance of Tomcat is required to support LCS Adapter. Both software should collocate on the same computer.
- B. Unzip the provided lcs.zip to get one war file, LcsData.war, and one directory, "LCS".
- C. Move the LcsData.war to the [TOMCAT_INSTALLATION]\webapps\
- D. Go to the unzipped directory and find the configuration file, config.prop.
- E. Update "PemsOutputPath" => [TOMCAT_INSTALLATION]\webapps\LcsData\web\

5.7.6 Install Viewer Application

- A. An instance of Tomcat is required to support Viewer application. Both software should collocate on the same computer
- B. Unzip the provided viewer.zip to get one war file, ViewerData.war, and one directory, "Viewer".
- C. Move the ViewerData.war to the [TOMCAT_INSTALLATION]\webapps\
- D. Go to the unzipped directory and find the configuration file, config.prop.
- E. Update the following parameters:
 - a. Update CoreHostName according to the fully qualified domain name of the associated UICDS core.
 - b. Update ViewerOutpoutPath => [TOMCAT_INSTALLATION]\webapps\ViewerData\web\

5.8 System Startup

This section will outline the procedures to startup the VEOC systems. Depending on the system configuration, some procedures may be repeated on multiple computers. For instance, if Viewer application, PeMS/LCS adapter and the associated UICDS Core are installed on separate computers, Java runtime environment and Tomcat will be needed on each of the computer. Tomcat instance on each individual computer will need to be activated separately. Please refer to aforementioned installation procedures for the prerequisite.

5.8.1 Start UICDS

The procedures for starting UICDS are described in:

UICDS System Installation Plan
UICDS-PLN-SIP-R02C02
September 27, 2010
SAIC

5.8.2 Start Tomcat

This procedure is repeated on all computers running Tomcat. Please note that this Tomcat instance is different the Tomcat instance used by UICDS, if any of the PemS Adapter, LCS Adapter or Viewer application is colocated with the UICDS Core.

- Verify that Tomcat is not running
- Go to [TOMCAT_INSTALLATION]/bin then execute “startup.bat”. (Windows environment)
- Verify that Tomcat is running
- If a war file of Viewer application, PeMS Adapter or LCS Adapter is deployed in this Tomcat, you can verify if the data viewing feature is running properly by visiting different URLs.
 - For Viewer application: [http://\[HOST_NAME\]/ViewerData/](http://[HOST_NAME]/ViewerData/)
 - For PeMS data: [http://\[HOST_NAME\]/PemsData/](http://[HOST_NAME]/PemsData/)
 - For LCS data: [http://\[HOST_NAME\]/LcsData/](http://[HOST_NAME]/LcsData/)

5.8.3 Start PeMS Adapter

- Go to [PEMS_ADAPTER_INSTALLATION]/
- Execute the following command to start a PeMS Adapter
 - java -jar target\PemsAdapter.jar -l=pems.log -c=config.prop -r=P

5.8.4 Start LCS Adapter

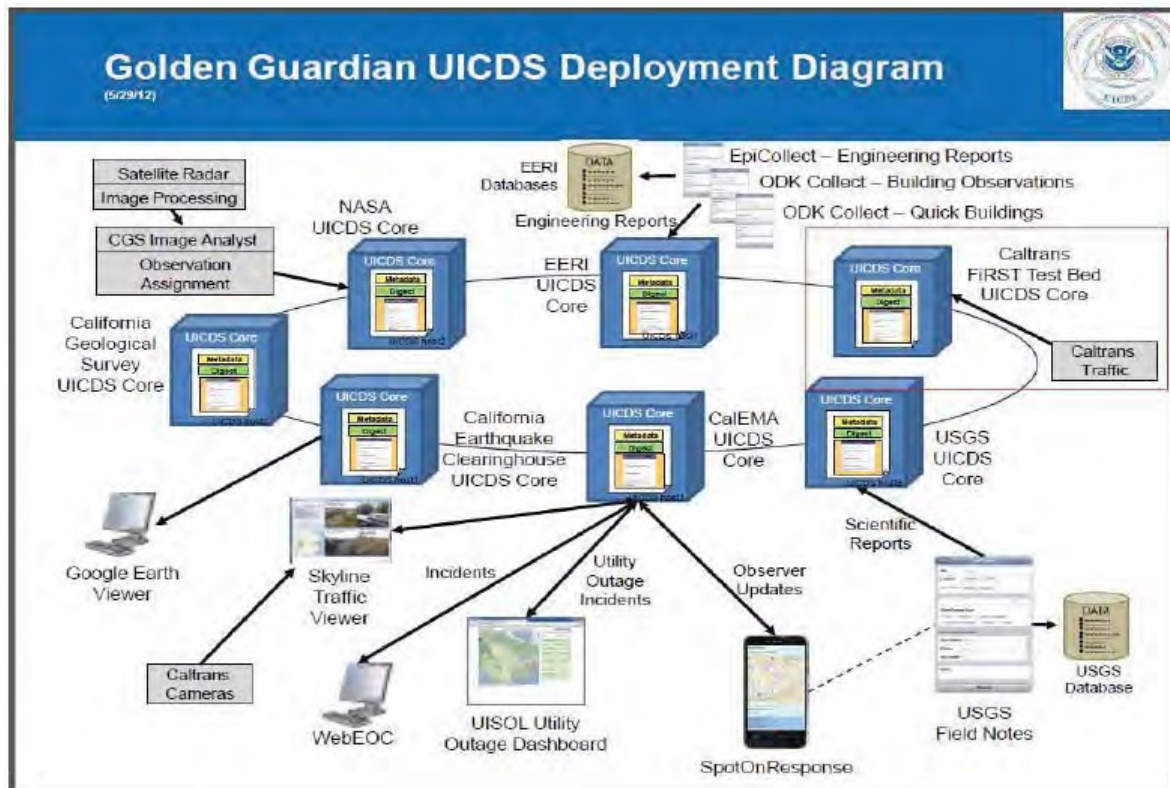
- Go to [LCS_ADAPTER_INSTALLATION]/
- Execute the following command to start a LCS Adapter
 - java -jar target\LcsAdapter.jar -l=lcs.log -c=config.prop -r=L

5.8.5 Start Viewer Application

- Go to [VIEWER_APPLICATION_INSTALLATION]/
- Execute the following command to start a Viewer application
 - java -jar target\viewer.jar -l=cop.log -c=config.prop -r=V

The Golden Guardian Demonstration

The Caltrans-FiRST Testbed participated in the California Earthquake Clearinghouse (CEC) shakeout technology demonstrations and exercise on October 2012. The purpose of the exercise was to demonstrate multi-agency cooperation during an earthquake including two-way interoperable data exchange of many types created using various applications between different participating organizations. The California office of emergency services (OES) has now added UICDS compliance to its requirement.



Caltrans, pioneered the integration of data about the status of the transportation network with emergency management functionalities in a standard based implementation developed under the virtual emergency operation center (VEOC) track of the FiRST Testbed research efforts.

The exercise participants were the Cal EMA (OES), Caltrans FiRST Testbed, US Geological Survey (USGS), Earthquake Engineering Research Institute, NASA, San Diego County and the California Geological Survey. The exercise was coordinated by SAIC representing the Department of Homeland Security (DHS).

The Caltrans' FiRST Testbed at UCSB has been the first operating UICDS core in California capable of core-to-core communication with the DHS infrastructure. The FiRST-VEOC core, demonstrated the capability of processing the Caltrans PeMS data and simulate traffic conditions and highway closures at the identified hazard areas defined for the exercise anywhere in California.

Related Systems

This section presents a high-level comparison between VEOC and WebEOC.

WebEOC is an incident management system from ESi Acquisition, Inc. that enables users to view and post information through a number of status boards. Its functionalities include monitoring and updating events status, tracking and managing tasks and resources, report generation, mapping, messaging, and other utilities. WebEOC servers may communicate with one another through ESiWebFUSION which acts as a communication hub. WebEOC also supports CAP for alerts.

VEOC enables different incident management systems from different vendors and incident management organizations to interoperate, share incident information, and monitor and manage incidents in a distributed and collaborative manner. Its functionalities include creating and updating incidents, incident command organization structures, and incident action plans; tracking and managing tasks and resources; mapping; and disseminating sensor data and incident information.

A major difference between VEOC and WebEOC is that VEOC acts as a middleware to enable incident management applications from various vendors, and those that perform different incident response functions, to interwork transparently as single integrated virtual incident management organization. WebEOC has various incident response functions all built into the system and allows communications only amongst WebEOC servers. Further, VEOC adopts a number of open standards related to incident management in implementing the functionalities and services it provides. These include:

- NIEM for incident management, incident command, incident action plan and tasking services
- EDXL-RM for resource management
- OGC SOS for sensor service
- OGC WMS and WFS for mapping service
- IEPD for LEITSC
- CAP for alerting service

It is to be noted that in a wide area emergency such as earthquakes in California, Internet may be out for days or even a week, and this will render cloud based applications (e.g. WebEOC) unavailable. A solution has been investigated and partially implemented under Track III, where a portable platform implementing the Hastily Deployed intranet Network (HDiN) will provide local wireless intranet services in the ITS and Public Safety bands, provide local mapping (e.g. Caltrans Earth), as well supporting the UICDS based VEOC. When The Intranet is restored the HDiN will use the UICDS core to automatically synchronize with other incident management platforms such as WebEOC.

Glossary

API	Application Programming Interface
CAP	Common Alerting Protocol
CFR	Crash and Fire Rescue
CHP	California Highway Patrol
COP	Common Operating Picture
DDS	Data Distribution Service
EXDL-DE	Emergency Data Exchange Language – Distribution Element
EXDL-RM	Emergency Data Exchange Language – Resource Messaging
EMS	Emergency Medical Service
EPA	Environment Protection Agency
FAA	Federal Aviation Administration
FBI	Federal Bureau of Investigation
FD	Fire department
HAZMAT	Hazardous Materials
IEPD	Information Exchange Package Documentation
LEITSC	Law Enforcement Information Technology Standards Council
LCS	Lane Closure System
NIEM	National Information Exchange Model
OEM	Office of Emergency Management
OGC	Open Geospatial Consortium
OMG	Object Management Group
PD	Police Department
PeMS	Performance Measurement System
SOI	Sensor Observation Information
SOS	Sensor Observation Service
TMC	Traffic Management Center
UICDS	Unified Incident Command and Decision Support
VEOC	Virtual Emergency Operation Center
WFS	Web Feature Service
WMS	Web Map Service
WP	Work Product
WSDL	Web Service Definition Language
XMPP	Extensible Messaging and Presence Protocol

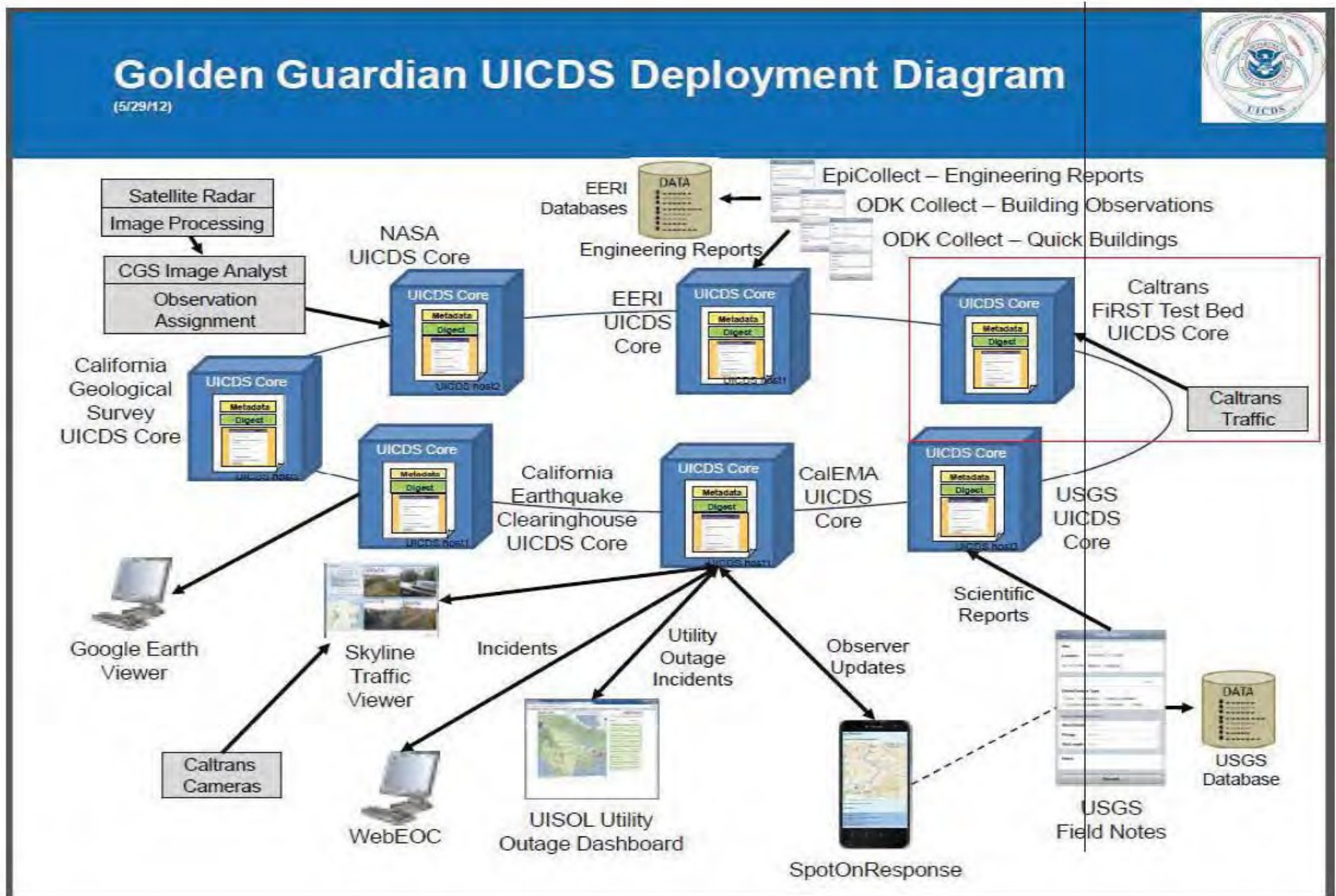
UICDS Implementation at the Caltrans-FiRST Testbed

Ramez Gerges, Ph.D., P.E.

Caltrans – DRISI

FiRST Testbed

Unified Incident Command & Decision Support



FiRST Testbed R&D Efforts

Caltrans Strategic Goal:

Provide the safest transportation system in the nation for users and workers

Strategic Objective:

To look ahead and evaluate standard based solutions to address Caltrans' mobility and safety challenges

Partners:

Caltrans – Division of Research Innovation & System Information (DRISI)

Caltrans - Office of Emergency Management (OEM)

Caltrans - Maintenance Office of Radio Communications (ORC)

UCSB - FiRST Testbed (FiRST.transcal.ucsb.edu)

FiRST Testbed R&D Efforts

Caltrans' Challenge:

- A statewide standard-based Common Operational Data (UICDS)
- A statewide web-based Common Operational Picture (COP)
- Local continuity of operation with or without Internet access
- Fail-safe operation and synchronization to cloud-based WebEOC

FiRST Testbed Solution:

Hastily Deployed Network (HDN) platform that address

- Emergency Management
 - Virtual Emergency Operation Center (VEOC)
- Emergency Communications
 - Interoperable Data-Centric Public Safety & ITS Broadband
 - Satellite SMS Communicator (anywhere, anytime)

Emergency Management

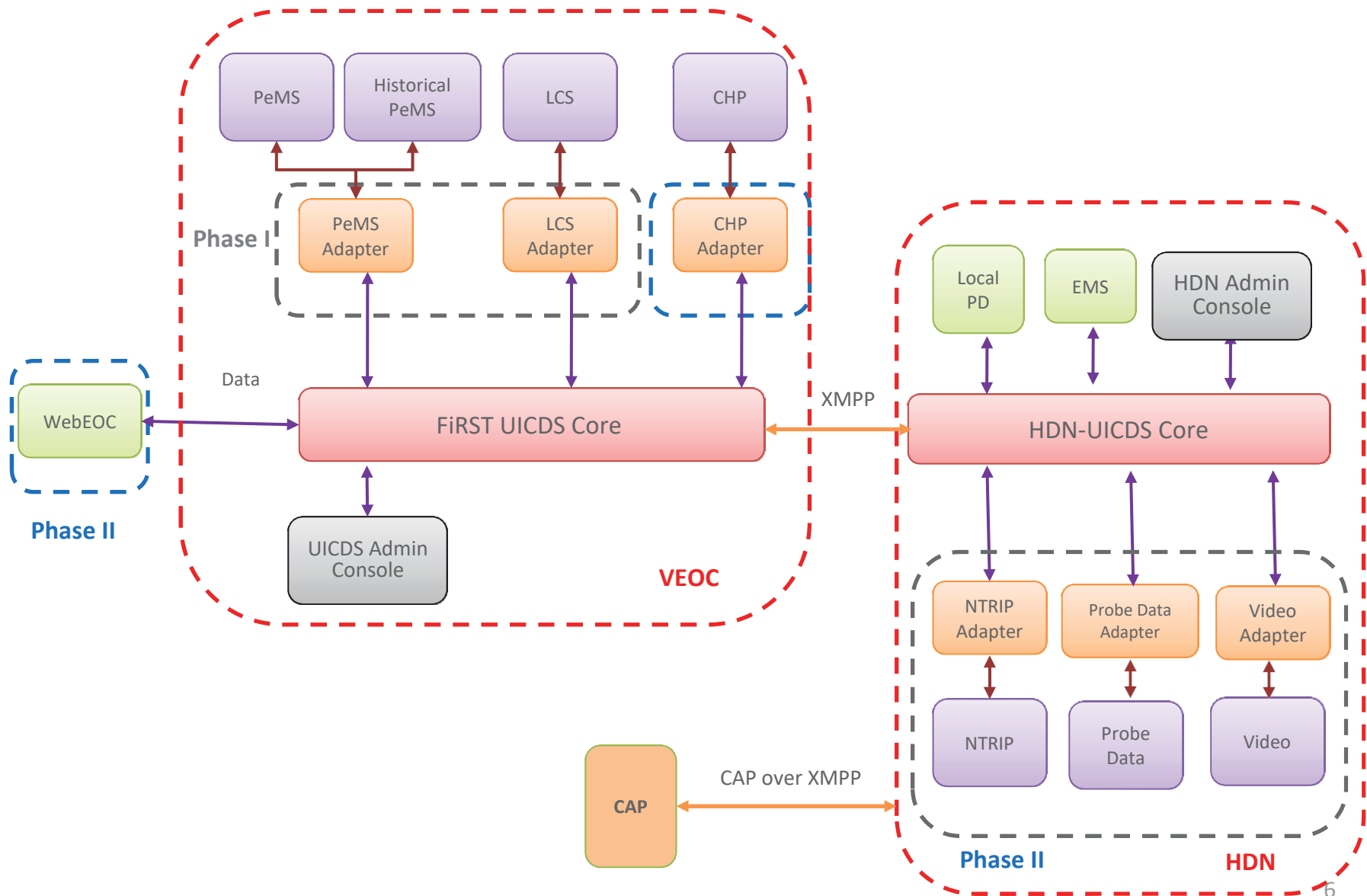
Virtual Emergency Operation Center (VEOC)

A standard-based state-wide UICDS compliant implementation:

- Support Common Operational Data
- Support Common Operational Picture (COP)
- Capture incident information without Internet Connectivity
- Provide real-time access to Caltrans local & regional resources
- Integrate data from PeMS & LCS (Caltrans) & CHP
- Support the Common Alerting Protocol (CAP)
- Replace the D4-Bay Area Incident Response System (BAIRS)*
- Replace the D7-Major Events Response Tracking (MERTS)*
- Replace the Responder developed for D3*
- Support day-to-day (e.g. urban and rural work zones)
- Embedded HDN-UICDS core for wide-area emergencies (e.g. earthquakes, tsunami, etc.)

* Phase II: Pending Funding Approval

VEOC-HDN-UICDS



Hastily Deployed Network (HDN) Platform

Interoperable Data-Centric Emergency Communications

- Broadband-over-Power (BoP)
- 3G/4G wireless router
- Satellite SMS Communicator & GPS
- ITS Radio (5.9 GHz)
- Public Safety Radio (4.9 GHz).
- Point-Point & Mesh topologies
- WSN Gateway (6LoWPAN)
- Embedded UICDS Core
- Embedded Google Earth Enterprise

HDN_ITS Station



Standard-Based HDN – ITS Station

UICDS /HDN Service	Standard
Incident Management Service	NIEM 2.0
Incident Command Service	NIEM 2.0
Alert Service	CAP version 1.1 specification
Map Service	OGC WMS, WFS
Resource Management Service	EDXL-RM 1.0 PR3
Sensor Service	OGC SOS
High Accuracy GPS (NTRIP)	RTCM STANDARD 10410.0
Wireless Sensor Network	IETF 6LoWPAN
ITS Wireless Broadband	IEEE 802.11p/1609.x
Public Safety Broadband	California Public Safety Radio Communications (CAPSCOM)

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Homeland Security

July 19 , 2013

Ms Coco Briseno
Cheif

Division of Research Innovation and System Information
California Department of Transportation (Caltrans)
1227 O St. 5th Floor
Sacramento, CA 95814

Dear Ms Briseno:

The Department of Homeland Security, Directorate of Science and Technology, is pleased that the California Department of Transportation (Caltrans) FiRST Testbed at the University of California Santa Barbara has been participating in the implementation of the Unified Incident Command and Decision Support (UICDS) information sharing middleware.

In September 2011, the California Emergency Management Agency made UICDS compliance a requirement of its procurement for the Response Information Management System (RIMS). The FiRST Testbed was one of the early adopters of the UICDS architecture as part of their virtual emergency operation center (VEOC) project. We appreciate the fact that Caltrans developed and deployed the UICDS-PeMS adapter to provide real-time status of the transportation network, and enable incidents simulation anywhere on the California highways. DHS values Caltrans continuing research in extending the UICDS architecture, its resiliency and ability to detect, alert, and share common operational data about other hazards.

The collaboration between DHS, Caltrans' FiRST Testbed and the California Earthquake Clearinghouse partnership - representing its five constituent founders: California Geological Survey, United States Geological Survey, Earthquake Engineering Research, Institute, California Emergency Management Agency, and the California Seismic Safety Commission - has resulted in impressive improvements in technology applications to earthquake hazards.

The Caltrans' FiRST Test Bed has been an integral part of the growth of the UICDS implementation and we value their installation of one of the first UICDS cores in California, becoming a leader across the nation among departments of transportation.

DH will continue supporting expanded UICDS participation in 2014 and we hope that the FiRST Testbed will continue their fine work to benefit the citizens of California in an emergency.

Sincerely,

A handwritten signature in blue ink, reading "Lawrence E. Skelly II". The signature is fluid and cursive, with the last name "Skelly" being particularly prominent.

Lawrence E. Skelly II
Program Manager
Department of Homeland Security
Science and Technology Directorate

CC: Dr. R. Church
Associate Dean Division of Mathematical, Life and Physical Sciences
UCSB-FiRST Testbed
1832 Ellison Hall Santa Barbara CA 93106-4060



**First Responder Support Systems & Technologies (FiRST) Testbed
Contract # 65A0257
Cross-Cutting Cooperative Systems**

TRACK II – Cross Cutting Modeling & Simulation

Final Report

**Principal Investigator: Dr. Richard Church
Dr. Micah Brachman
Carlos Baez
University of California Santa Barbara**

Contract Manager: Ramez Gerges, Ph.D., P.E.



First Responder Support Systems & Technologies (FiRST) Testbed

TRACK II – Cross Cutting Modeling & Simulation

Models are one of the most effective forms of testing transportation system plans. Such plans could involve the conversion of a highway lane to a high occupancy/toll (HOT) lane or the operational settings of a series of signals. The focus of this task was centered on the development and testing of models to support evacuation planning. This research was requested by Caltrans to support statewide disaster response operations and management and was directed at the problem of evacuation. Several major concerns have been raised with Caltrans personnel, including the potential risk from a nuclear power plant disaster at Diablo Canyon, a tsunami impacting a coastal area such as the northern coast of California, the Ports of LA and Long Beach, and Marina Del Rey, a major wildfire, flood, or earthquake. All of these events may trigger a massive evacuation along corridors that may have been compromised by the event. We began this task with a literature review focused on the issue of disaster response, mitigation, and capabilities. This literature review is given in the enclosed report called “Planning for a disaster: a review of the literature with a focus on transportation related issues.” This literature review gives several examples of how California’s capabilities in responding to a crisis could be easily thwarted. For example, it is documented that many hospitals have limited supplies of drugs and food, existing on regular, daily shipments for resupply. Without an intact transport system, it is clear that regular care as well as emergency care would come to a halt. As another part of this work, we developed a prototype evacuation simulation model for a large scale evacuation involving the Diablo Nuclear Power Plant. The nuclear plant triggered evacuation was modeled using a state of the art micro-simulation model called PTV VISSIM. The simulation results demonstrated that a mock plan based upon contra-flow operations could significantly reduce the time it would take to evacuate San Luis Obispo as compared to a baseline scenario. This is reported in enclosed document titled “Simulating an evacuation event: a test case involving the Diablo Canyon Power Plant.” Several elements were raised in the development of this evacuation model, including when will people make the fateful decision to leave and what route will they take. To better understand the decision to leave an area being hit with a disaster as well as estimate when individuals might leave, we surveyed people who were given mandatory evacuation ordered during the Jesusita fire in Santa Barbara. Our results indicated that up to 10% of the people did not evacuate even when they were under a mandatory evacuation order to do so. We found that a Rayleigh Probability model could be used to estimate the frequency of when people begin their exodus. This work is reported in “Modeling the evacuation decision.” We also wanted to better understand the



First Responder Support Systems & Technologies (FiRST) Testbed

TRACK II – Cross Cutting Modeling & Simulation

decision affecting the pathway chosen when someone leaves. Our survey suggested that a number of people were somewhat sophisticated in the route choice, taking routes not part of their daily routines, but likely to be ones which avoided traffic jams and thus aiding in them getting out quickly. This survey and work is reported in “Cognitively Engineered Evacuation Routes.” As a part of this we show that a multi-commodity flow optimization model can be used to model multiple exit choice, congestion behavior in terms of route avoidance, and route choice without the need to use a micro-scale traffic simulation model, which can be nearly cost prohibitive to perform in most areas. One of the tasks that was envisioned as a part of this work was the evacuation of an area triggered by a Tsunami. Initially, this was selected by District 7 to be the Marina Del Rey area that is comprised of Venice and the Marina communities. The evacuation flood risk maps show that this area could be inundated by a large tsunami. At risk I a relative large population, a peninsula comprised of homes and apartment complexes and even a school where many must travel north on only one of three roads before heading inland for safety. The second area of interest was the Ports of LA and Long Beach. Either one is of great interest and of potential significance to California. This final work element was not finished as the support funds for this project were cut as a cost saving measure by Caltrans. Additionally, the Division of Research, Innovation, and System Information requested that we make no contact to nay Caltrans Districts for information or support, even though this work was originally suggested by District 7 staff. Although, we respect the leadership of DRISI and their decisions this last task element could not be completed without closer ties with District 7.

Following this introduction, the Track II final report includes the following sections in reverse chronological order:

- 1) Simulating an evacuation event: A test case involving the Diablo Canyon Power Plant
- 2) Summary of Dynamic Traffic Assignment in VISSIM
- 3) Cognitively Engineered Evacuation Routes
- 4) Modeling the Evacuation Decision
- 5) Modeling for Emergency Preparedness Literature Review



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Simulating an evacuation event: A test case involving the Diablo Canyon Power Plant

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FiRST Project
GeoTrans Laboratory
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January 31, 2014

This report has been developed as a part of the First Responders System Testbed (FiRST) project at the University of California, Santa Barbara. The FiRST project investigates the integration of transportation and communication modeling and simulation to improve understanding and techniques of emergency preparedness and response. Please cite this report as: Brachman, ML, RL Church, and CA Baez (2013) “Simulating an evacuation event: a test case involving the Diablo Canyon Power Plant” (Report #01-2014-01), GeoTrans Laboratory, UCSB, Santa Barbara CA.

1. Introduction

Caltrans has two major transportation objectives: 1) improve public safety, and 2) reduce congestion and improve transportation efficiency. The typical focus is to improve daily operations of the state and federal highways within the context of safety and efficiency. However, it is also important to plan for unusual events, like floods, earthquakes, and tsunamis. Disasters are often accompanied by the need for evacuation. Recent evacuation events in California include the Station Fire (Altadena, La Canada, Sierra Madre, La Crescenta, etc.), the Jesusita Fire in Santa Barbara, and the Witch Fire in San Diego. These evacuation events can be time consuming and life threatening. Figure 1 shows traffic flow on Interstate 15, during a wildfire evacuation in San Diego County in 2007. An important objective in mitigating an



Figure 1: Evacuation traffic

evacuation event is to develop evacuation strategies that maximize effectiveness, minimize clearing times, and reduce risks. Modeling area-wide evacuation has been an important issue, since the development of evacuation plans for hurricanes and nuclear power plant disasters. In order to develop modeling techniques and to test possible evacuation scenarios, it is important to develop appropriate strategies for modeling and simulating traffic in an emergency. The Diablo Canyon Nuclear Power Plant was selected as a test case for evacuation modeling and planning. This test case is somewhat unique in that a “mock” contraflow plan had been developed. The basic premise was to use the Diablo Canyon Evacuation Plan (DCEP) as a starting point in which to compare and test strategies, evaluate modeling approaches, and focus on critical resource and personnel needs. It should be stated that traffic control in an evacuation event involving state and interstate highways is under the control of the California Highway Patrol (CHP). In the event that a DCEP is imposed, CHP would be in charge and Caltrans would be required to support their actions by providing appropriate levels of equipment and manpower. Supporting an event like a DCEP should not be undertaken lightly. In fact, the current plan itself appears to lack detailed instructions as well as estimates of clearing times. That is, current plans are not specifically geared to clearing the area as quickly as possible, as no comparison of strategies has been proposed or tested. Even though CHP is in charge of the operation, Caltrans does share responsibility for ensuring the plan and its possible execution utilizes the latest understanding and strategies. Figure 2 depicts the region surrounding the Diablo Canyon Power Plant. The largest center of population is the City of San Luis Obispo and the main traffic corridor is Highway 101, both shown in the red box in Figure 2.

One of the more notable evacuation events in the US involved hurricane Katrina and New Orleans. This evacuation operation was very successful for those who did not rely on public transportation and those who took the storm as a serious threat. Although most of the news about Katrina and New Orleans involved the stories of those who did not evacuate, the majority of people were able to evacuate from the region in a timely manner. The reason for the successful evacuation of the majority of the population of New Orleans was because of the implementation of a contraflow plan. A contraflow plan involves reversing traffic in a direction leading away from the event. For New Orleans, this involved reversing the west-bound traffic on I-10 East (which heads East from New Orleans), reversing East-bound traffic on I-10 West (which heads

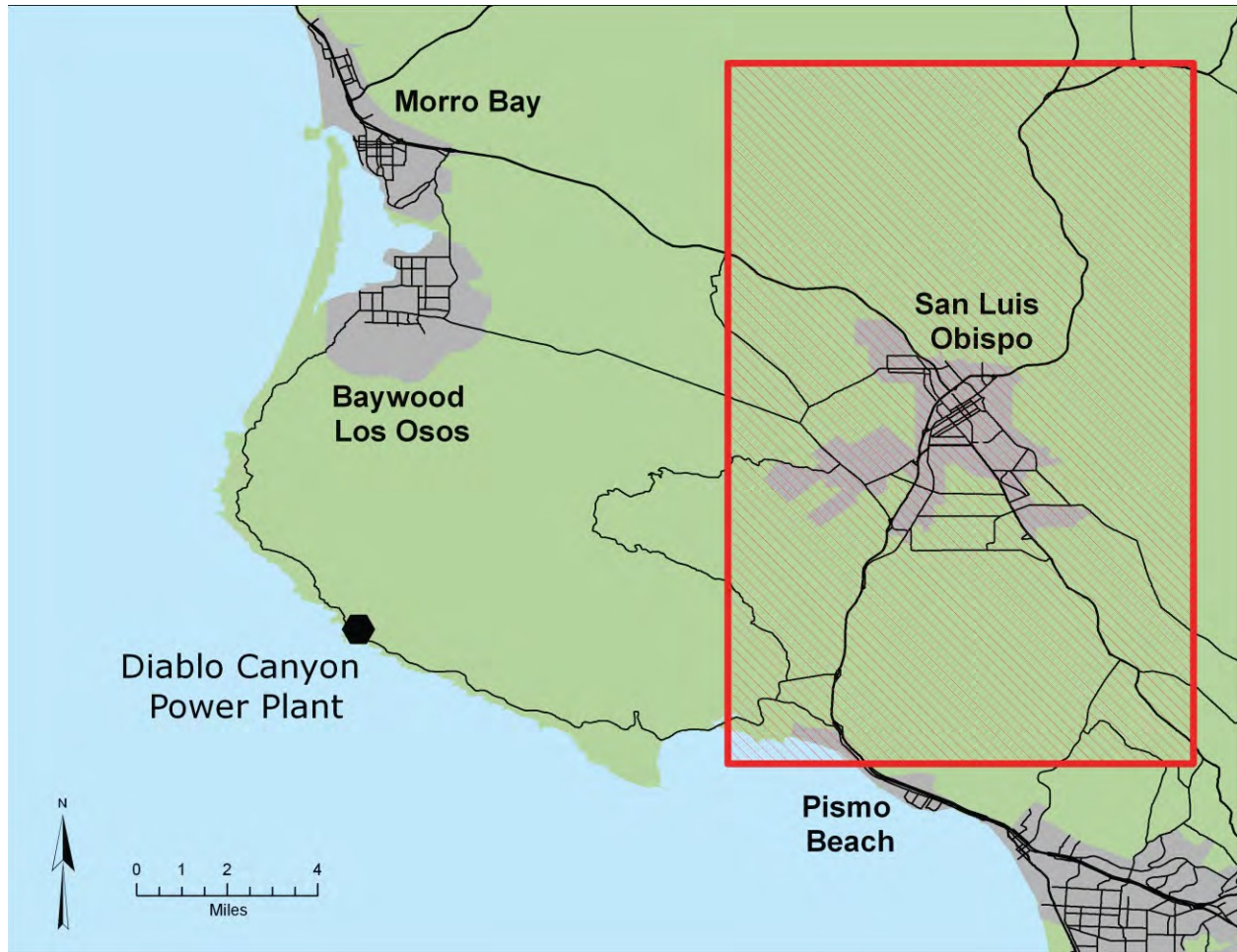


Figure 2: DCEP study area (red box), Diablo Canyon Power Plant location and surrounding cities

west from New Orleans), reversing south-bound traffic on I-55 (heading North away from New Orleans), and reversing direction on several bridges (including one causeway across Lake Pontchartrain). This evacuation plan took considerable resources and personnel to set-up, operate, and decommission. However, the plan and its operation were considered important factors in the successful evacuation of hundreds of thousands of people. There are other elements of this evacuation event which will be discussed at the end of this report that could be addressed in future work.

Given that contraflow operations can help to increase the effective capacity in a specific direction, it makes sense to consider at least the possibility of using contraflow operations in California emergencies. In light of this, District 5 traffic engineers drafted a mock plan that involves a contraflow operation along the Highway 101 corridor in San Luis Obispo County. This mock plan demonstrates foresight on the part of Caltrans, as the use of “contraflow” operations may substantially reduce clearing times in a disaster. But, Caltrans and CHP lack the appropriate tools to test and compare the existing DCEP with the contraflow based DCEP or the information in which to support changing the existing DCEP to a contraflow-DCEP. Further, contraflow plans need considerable resources to set up and operate, and such resources may not

exist locally within the time frame needed to set up and operate such a plan. The first step is to propose and develop a mock plan. Subsequent steps must involve testing and comparing the contraflow plan with that of the existing plan. Such a test would involve the simulation of an evacuation event using both existing and new plans, and then using the results to help inform of possible modifications to either the existing plan or the contraflow plan. To test any plan requires a modeling approach which can help estimate clearing times and bottlenecks.

The next logical step would be to develop a simulation of the base case of DCEP and a simulation of the contraflow-based DCEP to help give guidance as to whether a plan change would be valuable. This is one of the objectives of the FiRST project, a collaboration between Caltrans and UCSB. The FiRST project has begun the development of a modeling framework for evacuation based upon the use of optimization and simulation modeling techniques. This report describes the use of a micro-scale traffic simulation model in testing the efficacy of the contraflow based DCE plan drafted by Caltrans engineers and discusses issues that are problematic in simulating such events.

There are a number of techniques that can be used to model the efficacy of an evacuation plan. They involve:

- Simple flow assignment models, where demand are assigned to their shortest route in evacuating an area. Such approaches can involve simple congestion factors, so that as traffic is routed on the network, each subsequent assignment can be based upon the shortest time available route. Such a model is considered ad-hoc as the assignment of demand to routes is based upon an order that may not occur. This approach often requires the fewest resources to accomplish, but is also the most unreliable.
- Optimal flow models solved using linear programming. Such models have been developed for building evacuation and small area evacuation. This approach is useful to develop a lower bound estimate on actual clearing times. It is also useful in identifying potential bottlenecks in traffic flow. The main benefit of this approach is that the data necessary to model and support a given problem is less than what is necessary in a micro-scale simulation model. An example of this approach has been developed as a part of this project, but will be presented in a different report.
- Simulate an evacuation event using a traffic simulation model. Traffic simulation models, like PARAMICS, VISSIM, and MATSim, can be used to simulate an event. Each of these three software systems are designed with a different underlying set of rules and scale. For example, PARAMICS is based upon a map database that represents real road geometry. Vehicle speeds are in part controlled by the curvature of the roadway, sightlines, and discontinuities in direction. VISSIM, on the other hand, is insensitive to any geometry of the map shape file and uses speed limits and other parameters entered by the user to control vehicle speeds. Both systems use an OD matrix of traffic demands and car following equations. MATSim, uses a different design basis. First, like VISSIM road geometry is not important. But unlike VISSIM and PARAMICS, MATSim uses a trip diary for each traveler. The traffic is the sum of the individual trips being made. Whereas, MATSim can model trip making behavior, PARAMICS and VISSIM model traffic for a given set of demand represented by an OD matrix. In addition, MATSim models traffic along a road segment based upon a congestion function. This is used to estimate how much time a given vehicle will spend on a link, without modeling individual car jostling

along the link. Consequently, MATSim can model events much faster than the other two systems.

Thus, there are pros and cons for each of these systems, where one may be ideal for one task and another may be better for another. In this paper, we report on the use of VISSIM.

2. Data base development

In simulating an event, it is important to capture all elements that will significantly impact the functions being modeled or estimated. As a starting data base, we acquired NAVTEQ map tiles from PTV Corporation that covered the San Luis Obispo and Santa Barbara Counties. The main feature being modeled is the performance of Highway 101, using either the contraflow plan or Highway 101 without controls (there is a general split of traffic heading north and traffic heading south, and these splits are based upon the general evacuation plan). We developed a second form of the NAVTEQ network data by modifying it to match road closures, lane reversals, and route modifications as specified in the “mock” contraflow plan. The NAVTEQ data base contains center line information for road ways, lane data, and other attribute data, including the designation of a street being one-way and turn restrictions. Speed limits are not often given. It is important that all speed limits and assumed travel speeds be specified as well in the network. It is also important to capture multi-lane layouts accurately, turn lanes, and other elements. This data preparation can take a considerable amount of time to set up. In fact, setting up a data base for micro-scale traffic simulation is a time consuming and detailed task. For, VISSIM, it is absolutely necessary to have an accurate depiction of the network with respect to the attributes but not necessarily with respect to the road geometry.

As exact road geometry is not necessary for the simulation per se, one can be somewhat frugal in the time spent in generating an exact geometry as long as the attributes (like speed limits) are accurate. An example of this can be seen in Figure 3. Figure 3 depicts a short portion of Highway 101 and surrounding roads. You will note that the road segments are depicted as straight line segments drawn in blue. Logical connections are colored with magenta. Logical connections depict ramps and turn restrictions. This helps to aid in the use of the database in terms of navigation, supporting the common directions of “turn left” here and “take off ramp on right.” Note that the road network data (in blue) does not always have a connected set of lines (i.e. streets). The magenta lines represent turn and route restrictions, and without some of these restrictions, the network may not be completely connected. It should also be noted here that the network does not contain many shape points. Shape points are used in line representation to depict curves in roads. But, shape points are added features that expand the size of the data base. If one wants to use a database for navigation purposes, exact geometry with significant positional accuracy is not necessary. Consequently, a database can be reduced in size by keeping the use of shape points to a minimum, while still retaining enough data in which to provide navigational capabilities. Also note in Figure 3, that the lanes of the segment of Highway 101 in the figure are not depicted. The short portion of Highway 101 is depicted as two parallel lines, one representing the South-bound lanes and the other representing the North-bound lanes. Thus, the position and number of lanes are not depicted on the map (the number of lanes, however, is

included as an attribute). This is another element that may or not be resolved in the development of a traffic simulation model.

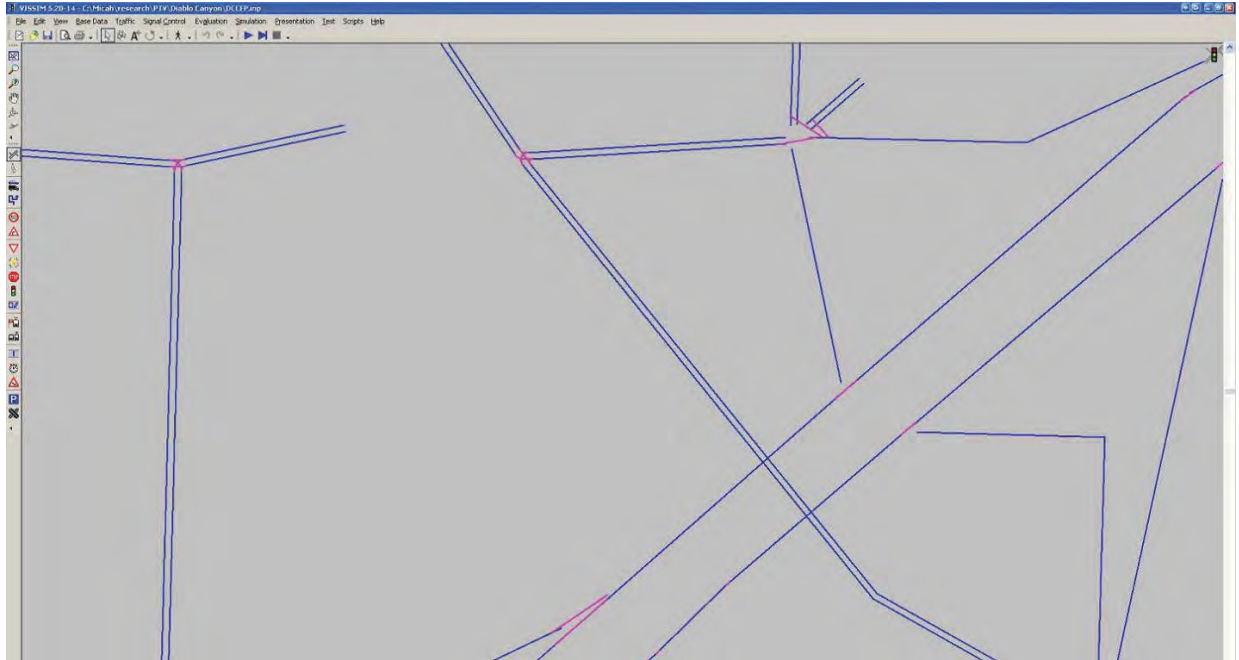


Figure 3: An example of road data layout from NAVTEQ where Highway 101 traverses from the center bottom to the top right corner of the image. The alignment of 101 is depicted with two parallel lines, depicting the South-bound and North-bound lanes. Each roadway is depicted with a line associated with a given direction of travel.

To understand this from a graphical perspective, roughly the same section of the map in Figure 3 has been resized and projected using an aerial photo as the background in Figure 4. Each roadway segment in Figures 3 and 4 is depicted with a line associated with a given direction of travel. For example, there is a somewhat vertical line segment at the bottom right corner of Figure 3 which abruptly turns left. This segment is depicted with one line segment, indicating that there is only one direction of travel. This same roadway can be found toward the center of Figure 4, where it can be seen that this line represents an off ramp for Highway 101. Note that this captures a given travel function, but does not accurately depict the roadway as it does not coincide with the image. In fact, this is not an unusual occurrence. In Figure 4, it can be seen that many of the road segments do not coincide with the image. Although the section of Highway 101 is represented by parallel lines with a reasonable level of accuracy, the major road crossing Highway 101 at the interchange is depicted with dual lines that coincide with only one direction of the separated roadway. Also observe that the intersection at the top center of the image in Figure 4 captures connectivity, but represents the roads connected to the intersection with less than what most would be considered reasonable from a graphical perspective. There are methods to automatically generate road curvatures from navigational databases, e.g. S2P, but such techniques cannot be relied upon to eliminate all issues in road representation.

One of the reasons why road depiction is discussed here is that micro-scale simulations greatest asset is the ability to depict vehicle movement along roadways in a realistic image. Such “moving pictures” of traffic help to visualize a given traffic event. The more an image departs

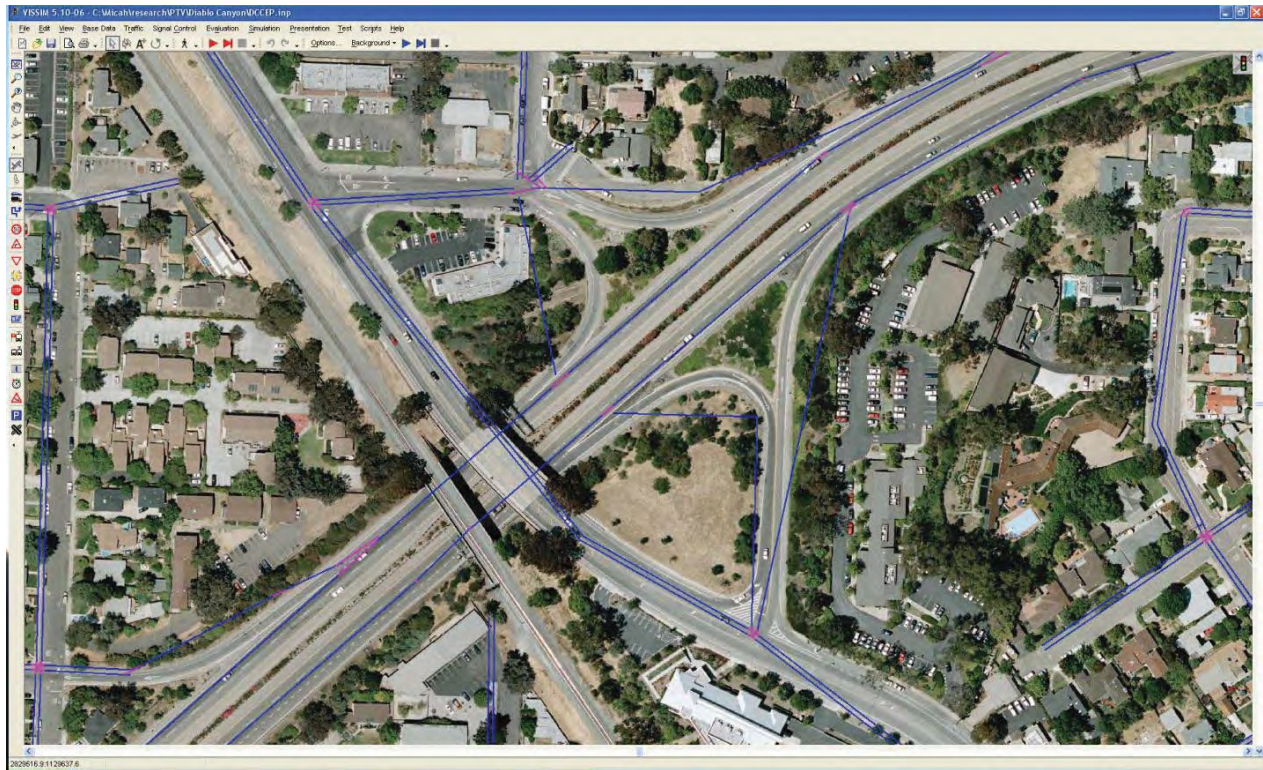


Figure 4: A portion of the road network depicted in Figure 3 superimposed on an air photo. Note the depiction of off ramps and on ramps of Highway 101 in the center of the image. Note, there is a railroad track that crosses 101 and is parallel to the roadway at the interchange.

from reality, the more one questions whether the simulation has adequately captured the movement of vehicles along a road segment. For example, if one simulated traffic along the road network in Figure 3 on the off ramp using the left angled roadway at the bottom left in the image, a vehicle would be depicted as taking the “corner” in the ramp at 20 miles per hour, without stopping! This behavior would quickly come into question by expert and layperson alike. Therefore, when depicting any event, including an evacuation scenario, one must generate a reasonable facsimile of the road system that superimposes well over an aerial photograph.

Figure 5 depicts the same image and road system after it has been edited. Editing such a network is time consuming and tedious work. This process is necessary if one intends to show any simulation movies on top of images. Consequently, using micro-scale traffic simulators with real images triggers the need for significant network editing. Such editing may be justified when a model is to be used on a frequent basis, in traffic operations and planning, but may not be justified when modeling a one-time event.

3. Estimating evacuation demand

There are a number of elements that make the simulation of an event like an emergency evacuation difficult to accomplish with any reasonable level of accuracy. One of these elements is the estimation of the demand for evacuation as well as the time frame in which this demand is

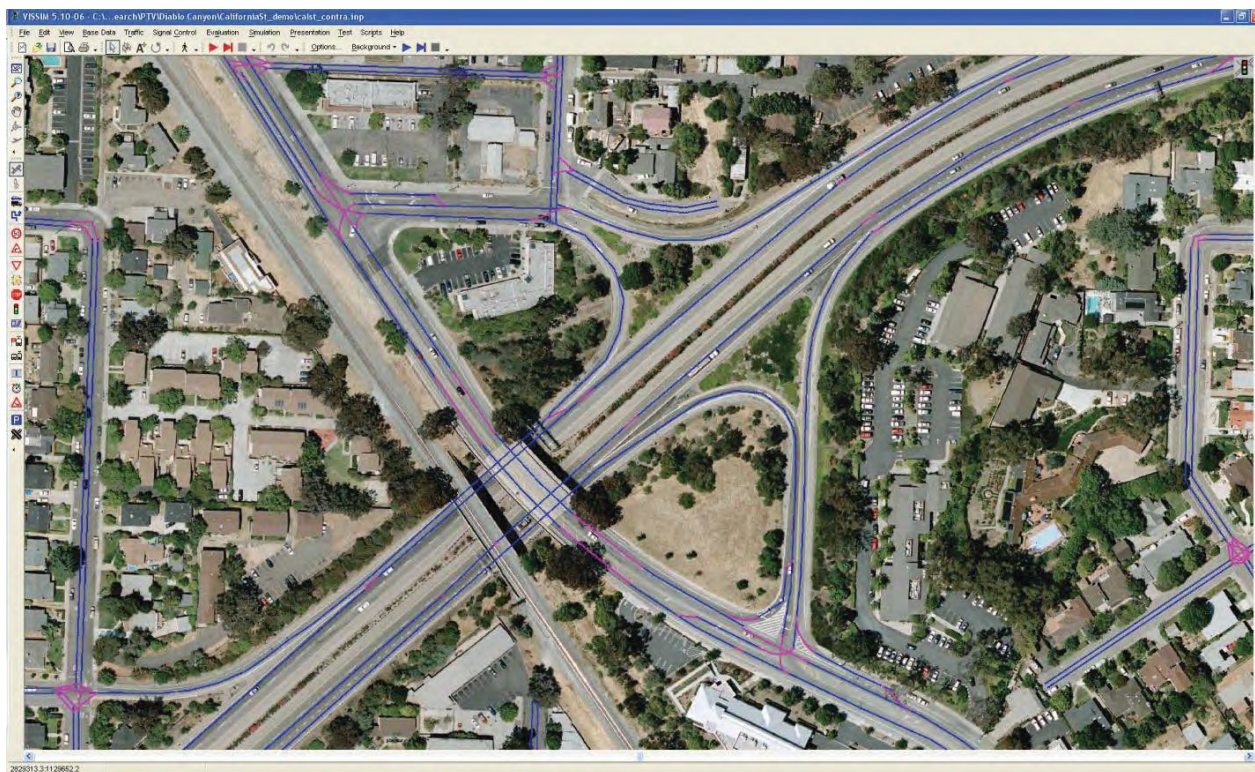


Figure 5: A portion of the road network depicted in Figure 3 superimposed on an air photo after network editing. This editing is required when movies of an event are made superimposed on an air photo image. In addition, some editing is necessary to eliminate unrealistic, abrupt changes in direction on a road segment like an off ramp.

exerted. What makes this a complicated exercise is the lack of information concerning whether an individual will attempt to first return to the area to pick someone up, like an elderly person or a “latchkey” child. Also complicating the estimate is not knowing daytime and night time populations of neighborhoods. Often one assumes that an average number of vehicles will depart per household in each neighborhood. Although this may be somewhat realistic, based upon average vehicle ownership in a neighborhood, such an estimate must be made given the lack of specific information about individual behavior during an event. For the exercise reported here, we estimated demand for evacuation to be one vehicle per household. The total number of households was identified for each census block. Each block was represented by a centroid and the total demand for that census block was assigned to the centroid point. The nearest road segment to the centroid point based upon Euclidean distance was identified. These locations became inputs for traffic during the event.

It is important to note that the evacuation scenarios modeled here do not make any assumptions with respect to school children. For example, in a daytime emergency it would be expected that many parents would want to retrieve their children by going to their schools and picking them up. In the Diablo Canyon Evacuation Plan children are to be bused to special pick up points, *e.g.* a school in Santa Maria in the event of a mandatory evacuation. If parents do not understand all of the elements of such a plan, there may be a reverse flow in traffic that is generated by parents making needless trips and needless confusion.

Another major element that needs to be estimated is the distribution of departures from a neighborhood. For example, is there an immediate onslaught of traffic generated by people attempting to flee in a panic, or is there a more organized and deliberate demand in evacuating over a longer time period? For the estimates here, we assumed that demand for evacuation was exerted randomly over a two hour period. Data exists for evacuation demand and its distribution for events such as hurricanes. In an event such as a hurricane, inhabitants often have a warning which may be hours if not days ahead of the possible disaster. But, for an event such as a nuclear power plant disaster, the distribution of demand over time is unpredictable. For example, in the recent case in Japan, the tsunami caused significant damage to all infrastructure including a nuclear power plant. In some cases, evacuations were not immediate, but took days and even weeks to accomplish. Whatever the case, it is clear that inhabitants need clear concise information and guidance. It should be noted that shorter evacuation time periods for the DCEP results in grid lock.

4. Simulation results for a non-contrafLOW evacuation plan

We used VISSIM from PTV Corporation to model traffic flow on the network. To generate information about traffic flow, we placed VISSIM data collectors on each entrance ramp in the contraflow section of Route 101. Additional data collector sets were defined:

Data Collector set 1: this totals flow per time period leaving the network, having travelled either south or north on U.S. Highway 101 to a designated point outside of the evacuation zone.

Data Collector set 2: this totals North-bound flow per unit time period on U.S. Highway 101, having reached Atascadero and a designated point outside of the evacuation zone.

Data Collector set 3: this totals South-bound flow per unit time period on U.S. Highway 101, having reached Avila Beach and a designated point outside of the evacuation zone.

Data Collector set 4: this totals North-bound flow per unit time period on U.S. Highway 101, having reached the Highway 58 junction north of Cuesta Grade.

Data Collector set 5: this totals North-bound flow per unit time period on U.S. Highway 101, just north of the last 101 entrance ramp at Monterey Street.

Data Collector set 6: this totals vehicles per unit time period having entering U.S. Highway 101, North-bound or South-bound

In addition to vehicle flow data, these collectors also captured vehicle speeds [mph] (maximum, minimum and average) and queue delay times [seconds] (maximum, minimum, and average). We also collected data on system wide information like latent demand, average speed and delays. The position of the non-ramp data collector points are given in Figure 6. Figure 6 depicts the evacuation region, major roads, and the population density of the region that is outlined in Figure 2. One can easily observe from Figure 2 that the majority of the population in the area being

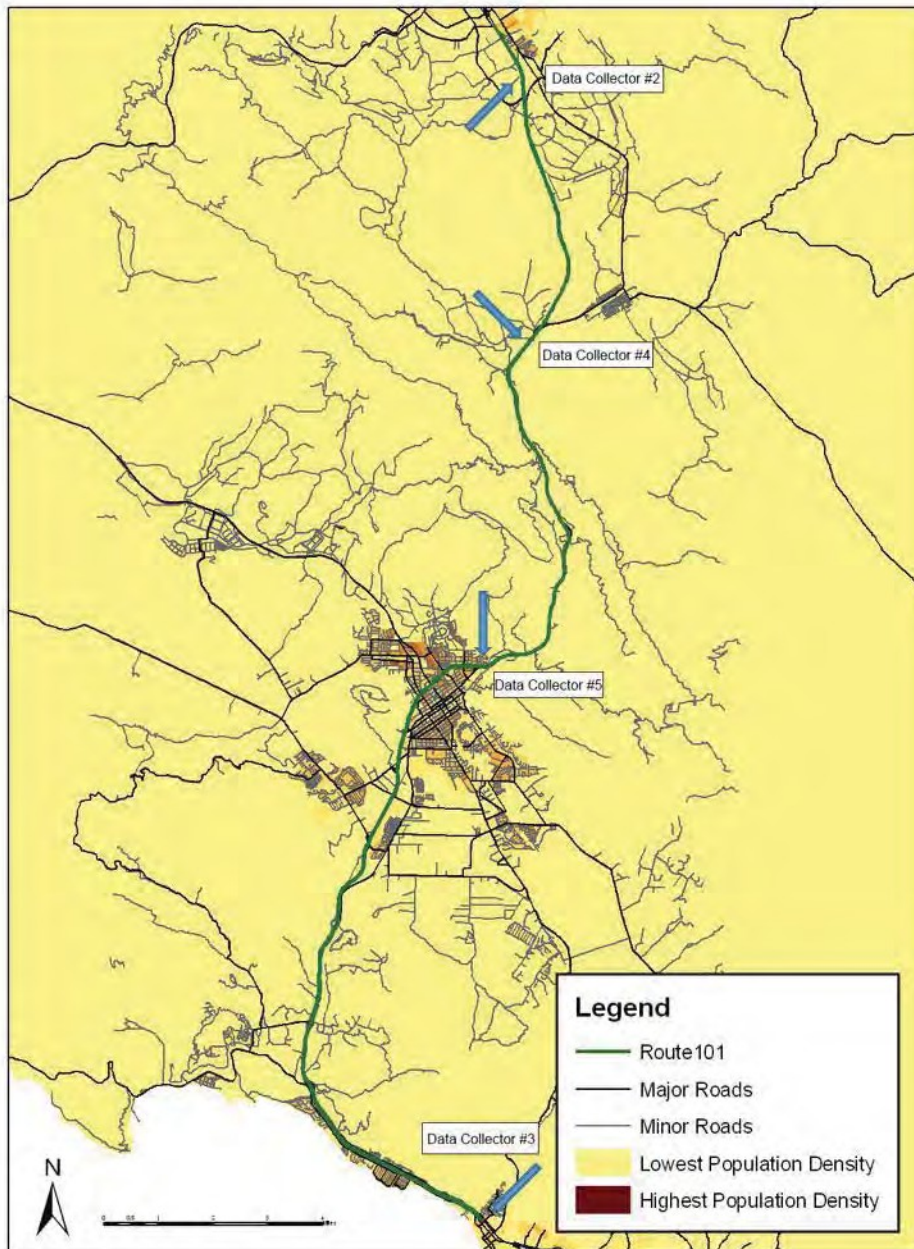


Figure 6. Location of special data collectors on Highway 101 and general region surrounding San Luis Obispo.

modeled resides in or near San Luis Obispo. Although there are communities north of Diablo Canyon Nuclear power plant that are along the coast (e.g. Morro Bay and Los Osos), these communities are supposed to evacuate by heading north along State Route 1 and Northeast along State Route 46 thereby circumventing the use of Highway 101. We assumed that this would be

the predominating flow pattern here, and because of this we did not include the north coast communities like Morro Bay and Los Osos. In addition, some eastern portions of San Luis Obispo are assumed to evacuate on State Route 1 towards Pismo Beach. These flows were not modeled, as the emphasis of this test was on the role of Highway 101 in an evacuation and on the efficacy of the design of the mock contraflow plan along the Northern section of Highway 101. The basic statistics associated with all simulations are given in Table 1. Note that the simulation exercise involved 260 census blocks in the San Luis Obispo area.

Table 1: Basic statistics associated with the evacuation event	
Basic Statistics	Basic Statistics
18,040 Total Vehicles evacuating	<ul style="list-style-type: none"> • 1 evacuating vehicle per household • Vehicles depart at random uniform time intervals over 2 hours
260 Total Vehicle Input Locations	<ul style="list-style-type: none"> • Input locations are road segments nearest to census block centroids
Vehicles are routed based upon dynamic traffic assignment	<ul style="list-style-type: none"> • Vehicles will follow a route which is updated every five minutes. This represents the driving behavior where there is not a fixed, static route for each user. • Vehicles will deviate from their originally defined route choice based upon continuously updated traffic conditions.
78.6% of San Luis Obispo households evacuate using U.S. Highway Route 101	<ul style="list-style-type: none"> • Households located close to alternate routes will utilize them for evacuation • State Route 1 and State Route 227 are the primary alternate routes

The evacuation event involved a total of 18,040 vehicles (1 per household). This amount can be easily changed as it makes sense in a real circumstance to plan using several scenarios (e.g. low estimate of demand, moderate estimate of demand, and a high estimate of demand). The departures of these vehicles were uniformly distributed over the first two hours of the simulation event. This, too, is an important variable. Earlier tests were conducted where all demand departed in the first hour of evacuation. What resulted was a grid-lock situation in which the

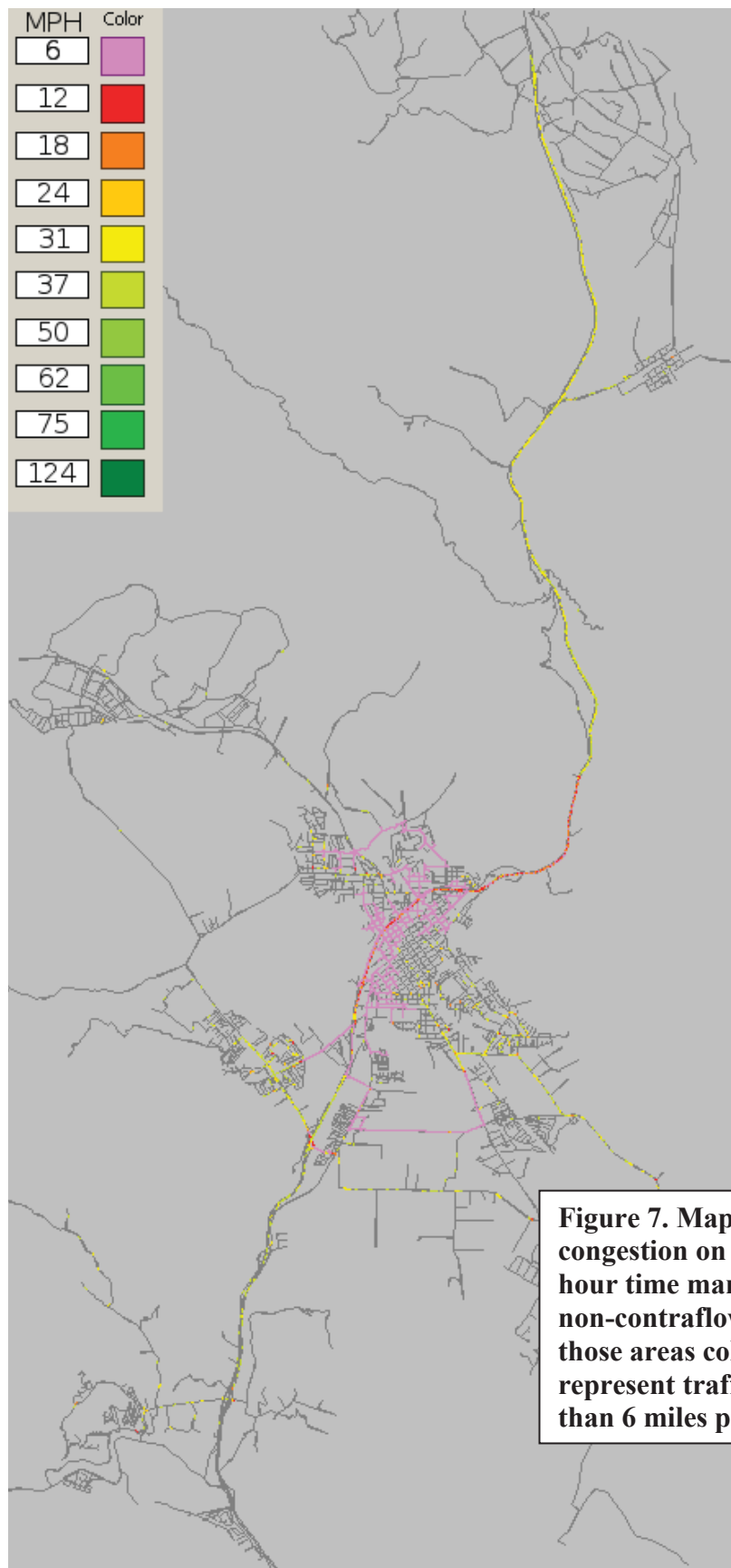
software could not reach a set of stable routes or pathways, where many vehicles traveled in circles, as capacity was limited in their movements towards on-ramps. Part of this outcome was the result of erratic routes generated when vehicles had almost no option as to where they could head. When pathways were fixed for each neighborhood in travelling towards their “assigned” highway ramp, this type of problem did not occur, however, significant traffic congestion was experienced throughout the entire area of San Luis Obispo. Examples of this are given in the appendix.

The main results generated for the base case of no contraflow options are given in Table 2. As described above, this simulation involved the use of a calibrated dynamic traffic assignment model. The results represent tabulations made at the 3-hour time mark, after the evacuation event started. At the 3-hour mark, 13,292 vehicles of the 18,040 were still in the process of evacuating.

Table 2: Simulation results for the base case (no contraflow sections)							
Data type	1	2	3	4	5	6	7
measurement	13292	4159	4923	7.2	23865.	903.87	566
1	Number of vehicles in the network, All Vehicle Types						
2	Number of vehicles that have left the network, All Vehicle Type						
3	Average delay time per vehicle [s], All Vehicle Types						
4	Average speed [mph], All Vehicle Types						
5	Total delay time [h], All Vehicle Types						
6	Latent delay time [h], All Vehicle Types						
7	Latent demand, All Vehicle Types						

Furthermore, 4,159 vehicles had successfully reached one of the evacuation exits (Atascadero or Pismo Beach). Average vehicle speed during the evacuation was 7.2 miles per hour, and the average delay per vehicle was 4,923 seconds or approximately 45% of the 3 hour period. As vehicle departures were spread out over the first two hours, an average delay of close to an hour and a half suggests that most vehicles spend the majority of their trip in some form of delay, caused by congestion. Note that at the end of the three hour period, 566 vehicles had not yet been able to depart. Overall, the statistics for the base case evacuation indicate a near grid-lock situation with significant delays such that a majority could not reach an exit of the evacuation region within three hours.

Figure 7 depicts the network at the 2 hour time mark. Each arc on the network is coded in a color that represents the average vehicle speed 2 hours after the evacuation event starts. Note many sections of Highway 101 have traffic speeds that range from 6-12 miles per hour, and that the majority of the road network within the City of San Luis Obispo experienced vehicle speeds that averaged less than 6 miles per hour. Given that the majority of the network within the city close to Highway 101 experienced such slow vehicle speeds, one can classify this condition as near grid-lock. When assessing the results of this simulation, one must keep in mind that this is a highly optimistic result for the base case. First, this does not consider any existing traffic on the network when the call for evacuation occurs. Second, this does not account for any trip chaining that may exist in a true evacuation, where a vehicle may leave a home, proceed to another



location to pick someone up, and then proceed to an entrance route on the highway to evacuate. Third, demand for those without cars, people with disabilities, the elderly, and those hospitalized have not been considered. Thus, the results underestimate the demand for those who cannot evacuate without assistance. Finally, the students who are housed on campus at Cal-Poly San Luis Obispo have not been included. Adding these other demands would add significantly to the critical nature of the event and further degrade the traffic flow.

Another way in which we can depict an evacuation is in terms of the number of vehicles that have successfully reached an outlet (or exit) of the evacuation area per given time interval. Figure 8 depicts for the base case the number of vehicles that have left the evacuation area for each half hour time interval (given in seconds). For example, in the first time interval (0-1800 seconds), only a negligible number of vehicles have reached an exit (Atascadero or Pismo Beach).

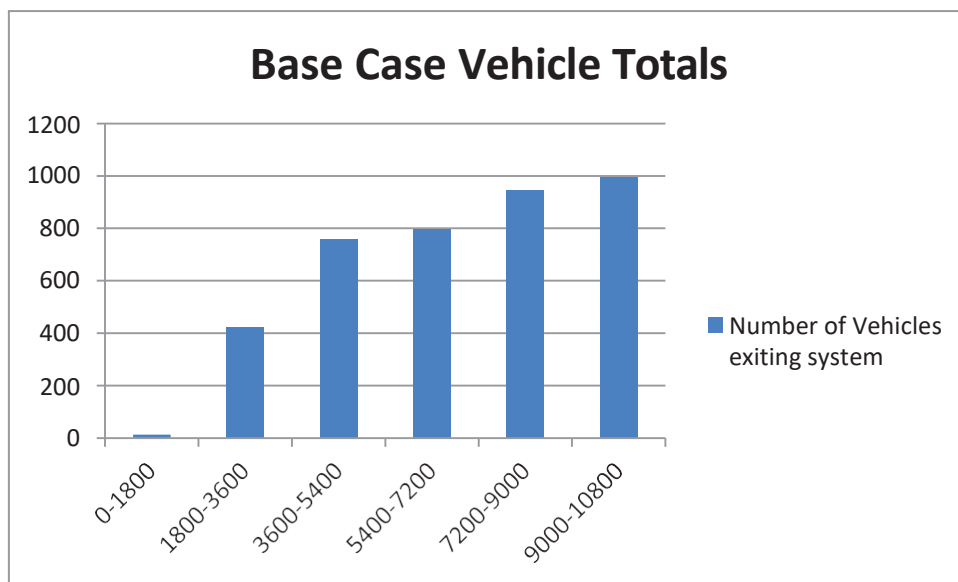


Figure 8. The number of vehicles successfully exiting the evacuation area by time intervals in seconds. Note flow totals per interval are quite low. Part of this is associated with very low average speeds on Highway 101 and near grid lock conditions in areas close to Highway 101 in the City of San Luis Obispo.

5. Simulation results for a contraflow based evacuation plan

The mock contraflow plan was based upon reversing traffic flow on South-bound Highway 101 at San Luis Bay Drive to North-bound flow. San Luis Bay Drive is south of the City of San Luis Obispo. Thus, all lanes of Highway 101 through San Luis Obispo are used to handle North-bound traffic. The end of the contraflow section is at Santa Barbara Road at the southern boundary of the City of Atascadero. The plan involves blocking specific on-ramps and off ramps to aid in directing flow for both South-bound and North-bound lanes. Other ramps are reversed

in direction of use so that vehicles can enter and travel northward on what was originally designed for South-bound use. Additionally, traffic crossing most overpasses is to be blocked, forcing traffic that reaches the highway to enter the highway. In preliminary simulations, it was found that because of a mismatch between demand generated to the east of Highway 101 and to the west of Highway 101, traffic circulated in an unusual manner that was not realistic. This situation also made it difficult to calibrate a model using dynamic traffic assignment. Accordingly, this one element was not modeled as a part of the contraflow plan. The Appendix depicts a fixed route plan which is amenable to such route closures within the simulation. The results for the contraflow plan are compared to the non-contraflow plan in Table 3. First, it should be observed that the contraflow plan resulted in average traffic speeds during evacuation of 20.3 miles per hour, whereas in the base case speeds averaged 7.2 miles per hour. From this fact alone, one can assume that evacuation is substantially aided with the use of a contraflow option. Of the 18,040 vehicles departing San Luis Obispo and evacuating using Highway 101, only 4,248 vehicles are still on the network at the end of the three hour time mark. This is substantially lower than the amount of traffic moving on the network at the end of the three hour time period for the base case (that is, 13,292)! This also means that a majority of the demand (12,855) had successfully evacuated and left an exit point at the end of the simulation period, whereas in the base case less than a third of this number had reached an exit in the same amount of time. Overall, one can observe, that in every category, the contraflow plan appears to outperform what would be achieved without contraflow operations. One telling statistic is that the average delay per vehicle for the contraflow plan is 31% of the average delay found for the base case.

Table 3: Simulation results comparing contraflow with no contraflow sections							
Data type	1	2	3	4	5	6	7
Non Contraflow	13,292	4,159	4,923	7.2	23,865.	903.87	566
Contraflow	4,248	12,855	1,528	20.3	7,262	202.71	0
1	Number of vehicles in the network, All Vehicle Types						
2	Number of vehicles that have left the network, All Vehicle Type						
3	Average delay time per vehicle [s], All Vehicle Types						
4	Average speed [mph], All Vehicle Types						
5	Total delay time [h], All Vehicle Types						
6	Latent delay time [h], All Vehicle Types						
7	Latent demand, All Vehicle Types						

Figure 9 shows the number of vehicles that have successfully left the area during different time segments of the simulation. For instance, in the time interval of 3600 to 5400 seconds (1hour- 1 ½ hours) approximately 2,900 vehicles were successful in leaving the evacuation area. Note that after the first hour the system reaches a plateau in traffic exiting the system and continues through the third hour. There appears to be a substantial gain in the numbers of vehicles successfully evacuating in each time period for the contraflow case as compared to the base case, except for the first half hour in which few vehicles exited the system in either case. The same caveats hold true for the contraflow case as for the base case, that is, with respect to the issues of

ignoring existing base-flow of traffic on streets and highways, people without cars, people with a disability that prevents them from driving, people hospitalized or in convalescent care facilities, and the student body at Cal-Poly San Luis Obispo.

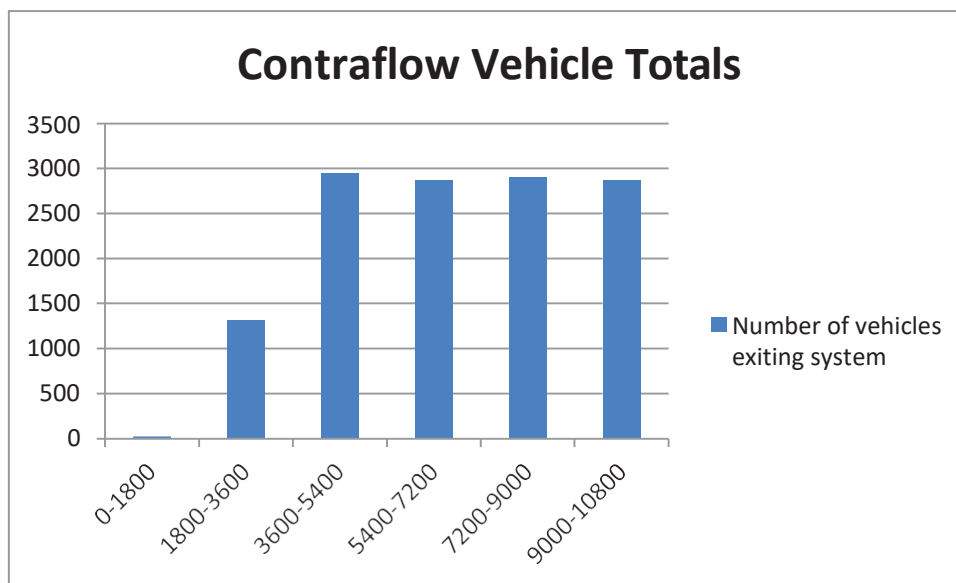
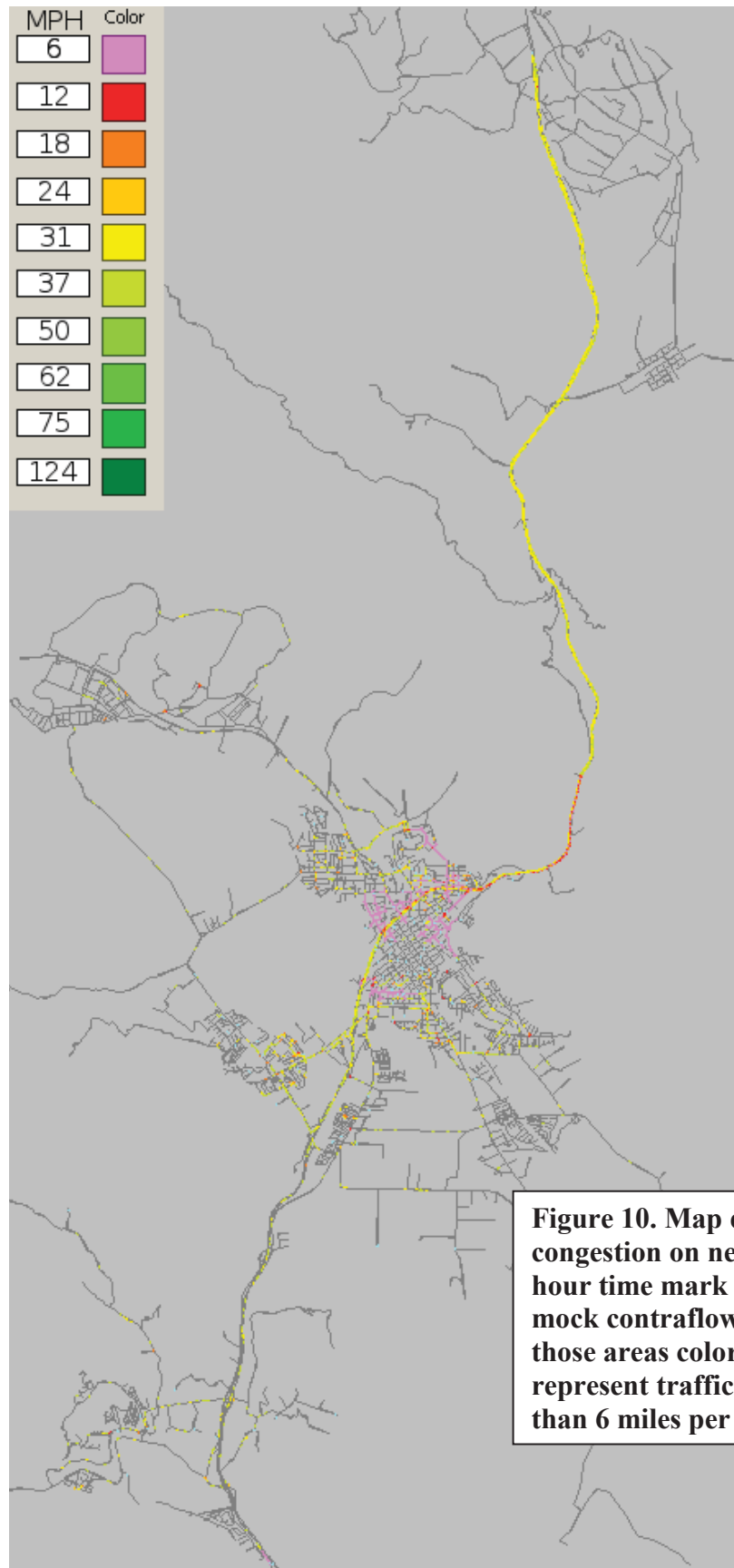


Figure 9. The number of vehicles successfully exiting the evacuation area by time intervals in seconds for the mock contraflow plan.

Figure 10 displays the network at the 2 hour time mark for the contraflow case. Each arc on the network is coded in a color that represents the average vehicle speed 2 hours after the evacuation event starts. Some of the sections of Highway 101 have traffic speeds that range from 6-12 miles per hour, and there are a number of areas within the City of San Luis Obispo that experience vehicle speeds that average less than 6 miles per hour. If one compares Figure 10 with that of Figure 7, one will see that the contraflow case appears to result in fewer areas of the City and fewer sections of Highway 101 experiencing extremely slow speeds in contrast to the base case.

In a general comparison between the base case and the contraflow case, it is clear that a majority of the residents of San Luis Obispo are able to evacuate within three hours under contraflow, but are not with base case operations. It is important to note that the results for each case might dramatically change given a different departure histogram. For example, spreading demand over a larger time frame may result in better traffic flows in comparison to restricting all departures to be made within the first two hours. Further, if such a model were to be used in fine-tuning an evacuation plan, then a number of different scenarios would need to be run in order to both fine tune a plan as well as identify major bottlenecks that might need traffic control. It is also important to note that there may be specific road issues that are part of a local knowledge base (local transportation engineers and traffic control officers) that need to be included in the traffic simulation. This “local” knowledge cannot be easily recreated and consequently, it is important that local experts be involved in such planning.



6. Discussion of results

Charts and screenshots both indicate significant queues building over time on many sections of the transportation network for the base case. Areas within the City of San Luis Obispo have the longest queues and slowest vehicle speeds which is to be expected given the high population density and corresponding travel demand (traffic inputs). The base case (no contraflow) queuing and congestion may be the primary reason that only 1/3 of the vehicles on the network make it to 'safer' areas away from the Diablo Canyon power plant in the time frame that was modeled. In contrast, the contraflow example yields demonstrably better results, where the majority of vehicles make it to an exit point of the evacuation area and where the average vehicle speed is nearly three times faster. Overall, the “mock” contraflow plan appears to be very promising. Although this is only a “mock” evacuation plan, there are appealing features to this plan in that the capacity to handle traffic heading away from San Luis Obispo has been significantly enhanced. However, there are elements in the mock plan that deserves further scrutiny. They are:

- Alternate routes should be fully utilized for evacuation, most notably State Route 1 (Northwest area of network) and State Route 227 (East area of network). This may mean that more traffic should be diverted from San Luis Obispo and Highway 101, or vice versa. Such an analysis would need to be based upon the DCEP plan and a micro-scale traffic model.
- The mock contraflow plan does not allow vehicles to utilize Highway 101 over- or underpasses, whereas the simulation model results reported here do allow that traffic to occur. This helps to relieve some disparities in travel demand between those neighborhoods on the east of Highway 101 and those on the west of Highway 101. Selected crossing locations can help to balance traffic demand entering Highway 101, fully utilizing the contraflow section and the regular flow section of the highway.
- The simulation model does not consider the possibility of trip chaining, where an individual may start at their place of work, return to their home, pick up someone and proceed to evacuate. This is a more realistic situation in an emergency, and such behavior cannot be captured in this modeling approach.
- The mock evacuation plan is far from complete. One can consider this as an exercise in thinking forward to a possible emergency. Such plans can be complicated and the requirements to fully support such a plan have not been fully analyzed within the context of setting up a contraflow segment. Operating a contraflow plan in Louisiana during hurricane Katrina took a considerable amount of state resources and time to set up. In the case of Katrina, state troopers and parish police had a considerable amount of advanced warning and time to set up the road system for contraflow operations. In a nuclear plant disaster, there may be little warning and the personnel needed to setup a contraflow system may take time to amass.

7. Limitations

The simulation presented here is a best-case type simulation. Traffic is likely to be worse as there are a number of assumptions that have been made. First, the simulation results are based upon 1 vehicle departing per household. This is likely to be a lower bound on the average number of vehicles being used in evacuation. Second, we have assumed that departure times are random with the first two hours of the event. Random uniform departures from traffic input points over the 2 hour window may not reflect trip departure timing during a real evacuation. This assumption does not necessarily match what might be expected in actual behavior, as little data has been collected for such events and a complete understanding has yet to be developed. Although, demands for major evacuation events like hurricanes are better understood, these often happen over larger time frames, and such events do not necessarily represent the urgency that might be present for a wildfire, tsunami, or nuclear disaster. Third, special demands like hospitals, nursing homes, the homeless, those who don't own cars, and those living at Cal-Poly San Luis Obispo have not been included. The bottom line is that a contraflow plan for this area appears to be beneficial, aiding in substantial increases in average travel speeds and in larger numbers of vehicles leaving considerably earlier than what happens in the base case (do nothing).

8. Suggested Future work

The objective of this project was to capture the essence of a mock contraflow plan involving an emergency at the Diablo Canyon Power Plant. Although many of the main problem elements were captured to the point that a simulation model could be applied, there are a number of remaining issues that should be considered in any future improvements to the VISSIM model addressing. They include:

- 1) Current traffic inputs should be overlaid on aerial imagery and the placement be assessed. It may be possible to move these inputs to correspond better with the actual locations of housing within each census block.
- 2) Highway 101 entrance ramp daily traffic counts supplied in the appendix of the Caltrans plan could be used to calibrate traffic flow. These counts could essentially serve as a scaling factor to help determine how heavily each entrance ramp will be used.
- 3) Network geometry should be corrected using aerial imagery. Only selected intersections at Highway 101 were corrected. This may not materially change the results of the model as the attributes of the links dictate use in a simulation but improve its use in visualization.
- 4) Traffic signal timing should be implemented, and reduced speed areas and conflict zones defined for the entire network. Also, fine tuning of merging behavior is necessary. Both tasks can be very time consuming. Collecting signal settings for the city and integrating them would help to close many of the remaining gaps in the model developed here.

- 5) Plume spread model(s) could be integrated with the traffic simulation model to assess radioactive material exposure risk during the evacuation.

Beyond the work involved with the simulation effort using VISSIM, there are several problems that should receive attention. The first of these is the development of a model that helps estimate the time it will take to amass resources and set up a contraflow plan in an emergency. In fact, Caltrans should develop supply models which estimate how much time it would take to reach any part of their system with a prescribed set of equipment and trained personnel. A second problem of major importance is the development of models which can estimate the demand for evacuation on the part of those not using personal vehicles and those requiring assistance (*e.g.* those who need public transit). Further work should also involve modeling when evacuation demand is exerted during an emergency. Finally, more accurate methods should be developed for determining the location of individuals by time of day. The simulation here is based upon the assumption that everyone starts at their home and evacuates. This is clearly a poor assumption during daytime hours, when many people are at school or work. Models like SimAgent may be employed for this purpose.

Appendix: Simulation for a contraflow evacuation plan using fixed routes

Evacuation modeling can be accomplished using linear flow models. This type of modeling technique has been used in building egress models as well as wide area evacuation, including emergency evacuation planning zones around nuclear power plants. Perhaps one of the most widely accepted approaches is one based upon paths. As an example, one form of that has been used to generate an estimate of evacuation effectiveness is the following:

- 1) Generate for each leaving vehicle a departure time.
- 2) For the vehicle that has not yet left and has the earliest departure time, identify the shortest path to leave based upon an estimate of congestion generated by those who have already left and chosen a route. Assign this vehicle to that path which is the shortest according to current trip assignments.
- 3) Have all vehicles left? If yes, stop and tally the times vehicles reached an exit to the evacuation region. If not, then return to step 2.

This approach can be used to give a rough approximate of the effectiveness of an evacuation plan. An alternate form of this is to define fixed routes for sets of individuals in leaving an area. For example, in the San Luis Obispo area there were 260 different individual neighborhoods that are used for sources of vehicles leaving the area. For each of these 260 neighborhoods (or census blocks) we can define a route that those vehicles will take to leave the area. We assume here that people will not make dynamic route changing decisions, but use what looks to be logically the route of first choice. This type of option is supported in the PTV VISSIM software as well. In order to perform a simulation using this option, it was necessary to code a fixed route for each of the neighborhoods. The simulation is then used to model congestion associated with the fixed route plan. This approach is just as efficacious as the path based model described above. In fact, in many ways it can be considered to be better than that approach as it more accurately depicts individual route congestion. In this appendix, we present the results of a simulation based upon fixed routing for each census block.

The assumptions used in the example presented here are the same as those presented in Table 1, with the exception that each of the 260 neighborhoods have a defined route for exiting the area and that all demand is set up to leave in the first hour of the simulation. Whereas, the dynamic traffic assignment results presented in the main section of this report are specified for evacuation demand spread out over two hours, we assumed for the fixed route analysis a more intense, shorter duration of evacuation demand.

At the end of the first hour of simulation, 2,005 vehicles (11.2%) have passed Cuesta Grade. This represents flow that has passed safely over the grade heading to Atascadero. At this same time 6,226 vehicles (34.9%) have passed the last entrance ramps on Monterey Street in San Luis Obispo. This means that in the first hour, approximately a third of the traffic demand has reached a point where they have merged onto Highway 101 and are traveling north from San Luis Obispo.

The evacuation event can be analyzed from the perspective of each onramp and sections of Highway 101. Rather than show details of each highway element, data in this appendix is

summarized for all ramps, those on the freeway north of Cuesta Grade and those on the highway north of the Monterey Street onramps. Figure 11 presents a chart which gives the distribution of vehicles reaching the northern most collector point over the time of the simulation. This depicts the number of vehicles having reached north of Cuesta Grade per minute. Note that the time lag in traffic reaching this collector point is approximately 22 minutes. After 22 minutes the traffic reaching this point begins to increase until it averages a flow of approximately 60 vehicles a minute. To serve approximately all 18,000 vehicles would take up to 4 hours. Figure 12 gives this same distribution for those cars passing just north of the Monterey Street exit at the northern boundary of the City of San Luis Obispo). This figure shows that the number of vehicles having merged onto Highway 101 and begin their trip to Atascadero starts with almost no lag in time from the beginning of the evacuation event. The traffic volume per minute quickly ramps up to an average that is between 100 and 110 vehicles per minute. Much of this volume is predicated on the number and capacity of entrance ramps as well as the time in which it takes to merge into the traffic lanes on Highway 101.

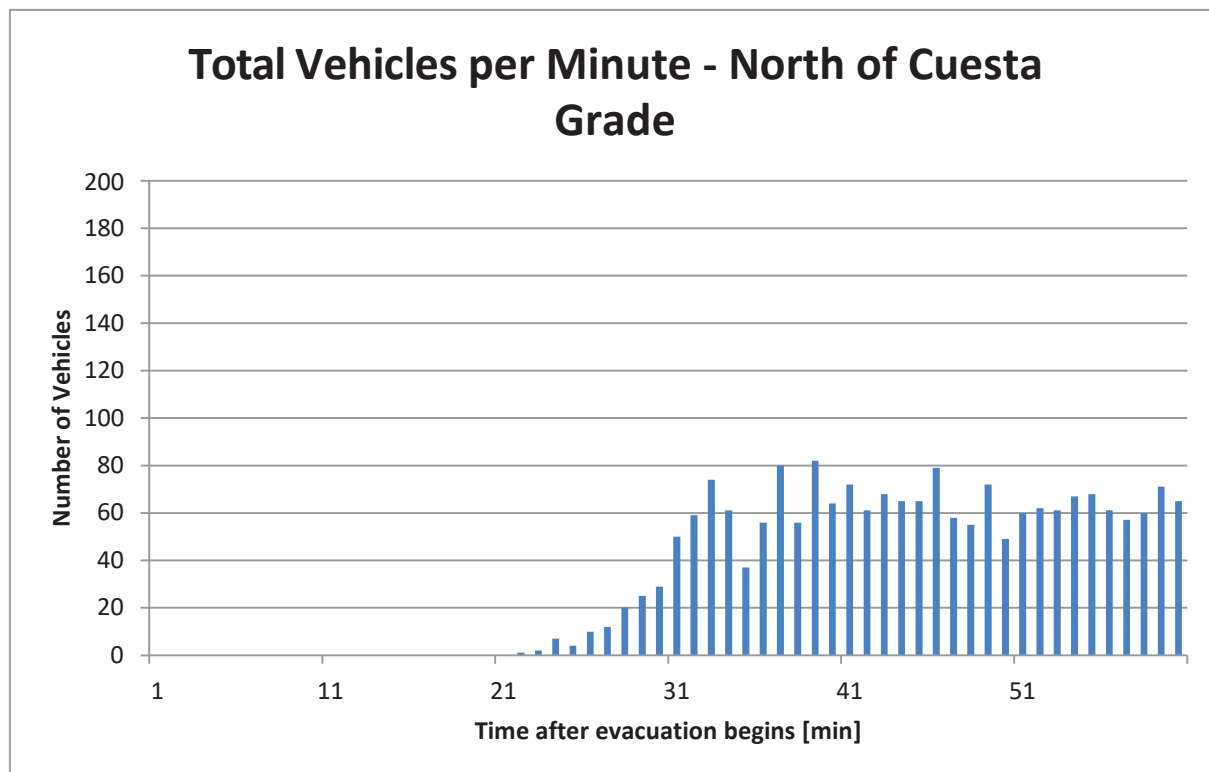


Figure 11: Total vehicles per minute passing data collector on Route 101 at end of contraflow section

Figure 13 depicts the number of vehicles merging onto Highway 101 per minute over all entrance ramps. This shows that the number of vehicles entering the system quickly ramps up to 180 vehicles per minute, but as congestion starts on Highway 101, the entrance flow begins to decline. After the first fifteen minutes the traffic entering onto Highway 101 declines to an equilibrium rate of approximately 110-115 vehicles per minute.

As the traffic begins to increase, average vehicle speeds on Highway 101 begin to decrease. This phenomena can be understood by calculating the maximum delay that is experienced by any one

vehicle entering the system. Figure 14 depicts the maximum queue delay faced by those vehicles reaching the end of the contraflow section. Note here that queue delays for cars reaching this point reach 1500 seconds at the end of the hour. This means that of the cars reaching this point, the maximum queue delay experienced was approximately 25 minutes.

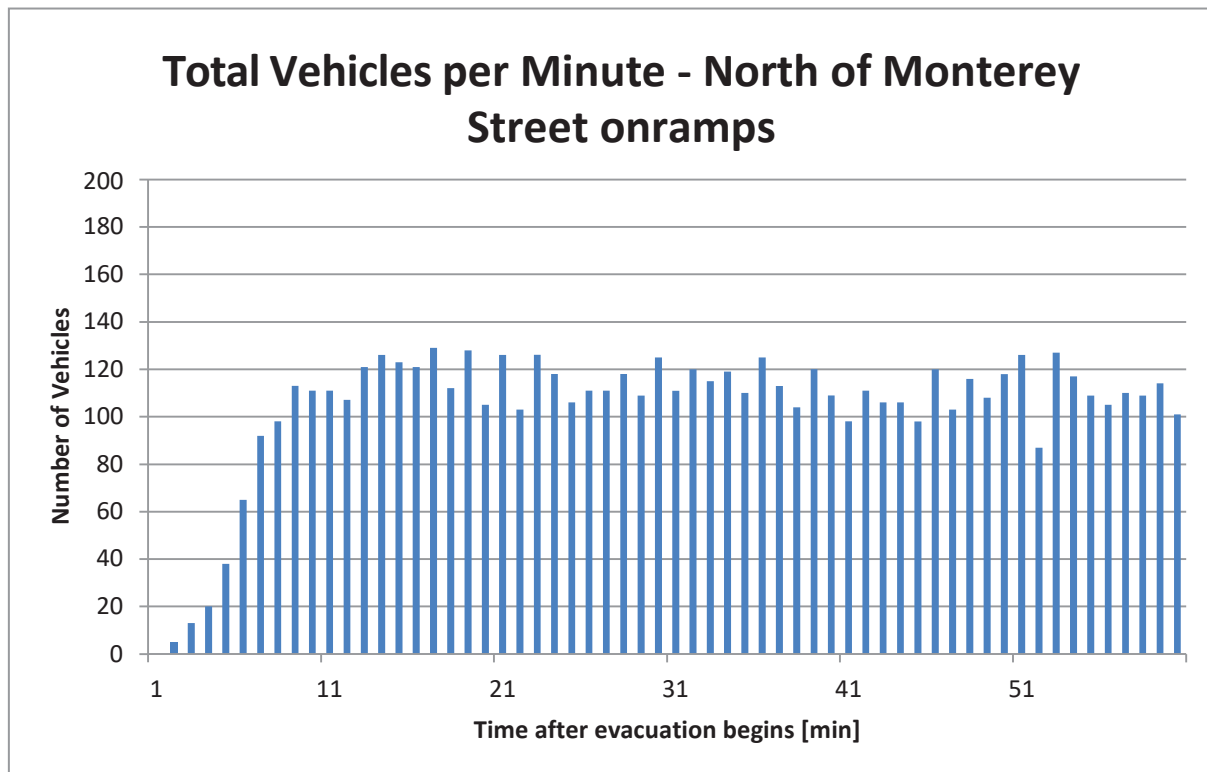


Figure 12: Total Vehicles per minute passing data collector on Route 101 after the last entrance ramp at San Luis Obispo heading north.

Figure 15 depicts a similar trend for the maximum queue delay faced by vehicles having passed the Monterey Street onramp, except that the maximum delays begin to ramp up from zero almost immediately after the start of the evacuation event. Here the maximum delay experienced by any one vehicle reaching this location at the end of the first hour is 50 minutes. That is, almost all of the travel experienced by that vehicle in that hour was queue delay! This means that there is considerable delay experienced by drivers in reaching Highway 101.

To understand where congestion occurs during the evacuation event and the fixed route scenario, maps were produced for three times: 20 minutes, 40 minutes, and 60 minutes. The images produced by VISSIM show the average speed [mph] of each vehicle on the network after 20 minutes, 40 minutes, and 60 minutes of simulation time. Highest speeds are indicated by green colors and lowest speeds by purple, with yellow at the midpoint. Figure 13 depicts the status of the system after 20 minutes. Note that the average speeds on Highway 101 are principally colored yellow, indicating that the speeds averaged 21-30 miles per hour. There are some locations on Highway 101 which experienced larger delays and are colored brown to red. In the City of San Luis Obispo, delays on a number of arterials are colored magenta or red. This means

that speeds on these streets ranged from 0 to 6 mph (magenta) and 6-12 mph (red). Thus, the traffic in the city is congested even after the first 20 minutes over many of the major streets.

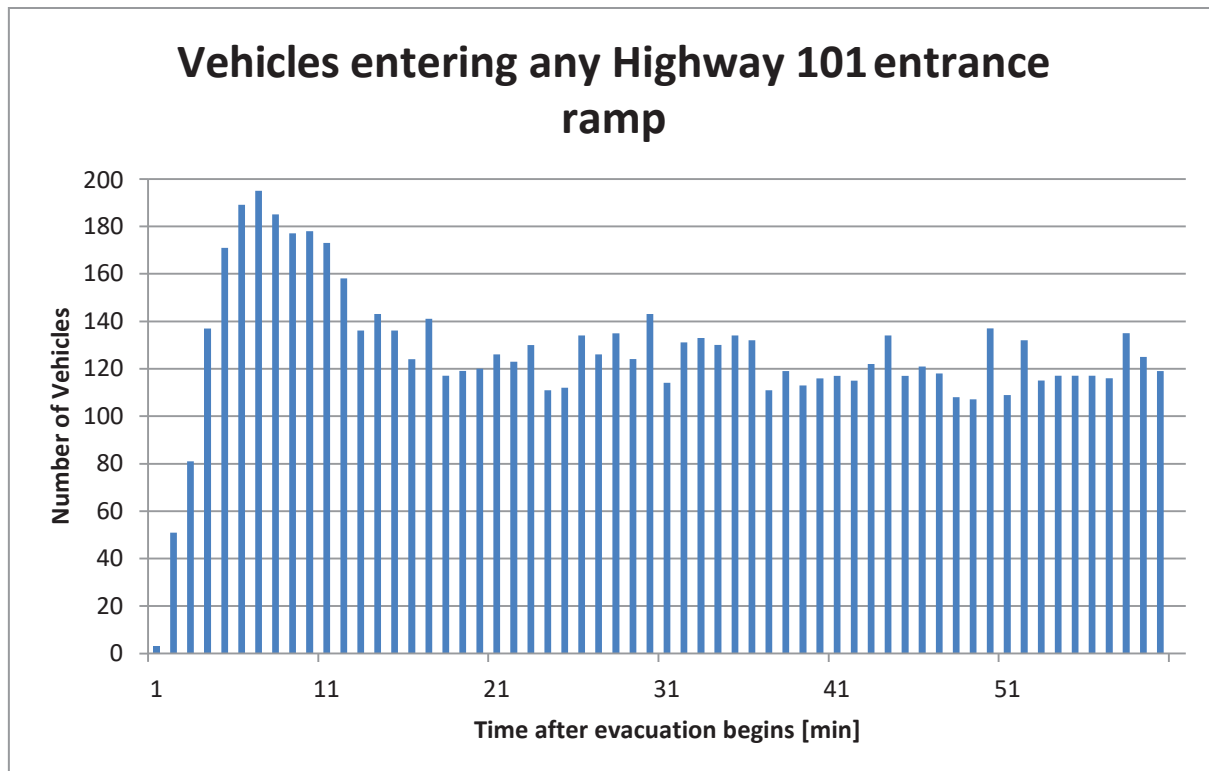


Figure 13: Total Vehicles per minute passing data collectors on all Highway 101 entrance ramps.

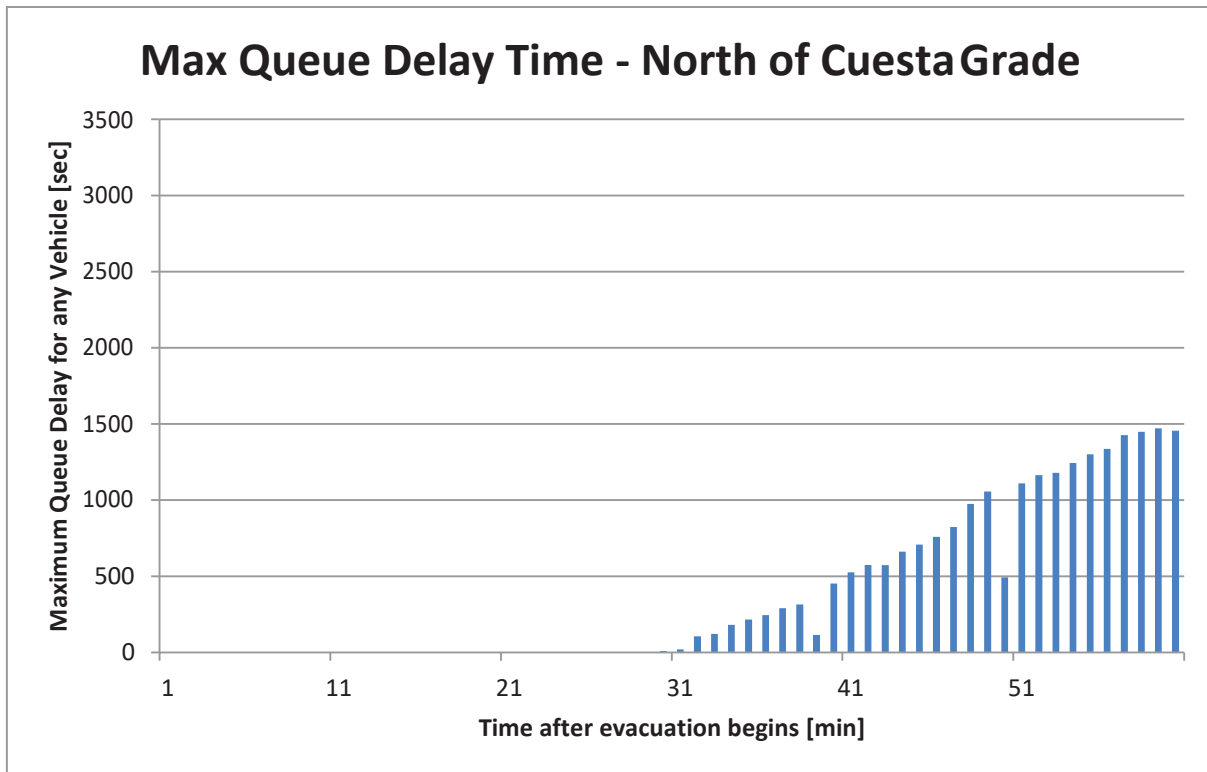


Figure 14: Maximum queue delay time on Route 101 at the end of the contraflow section

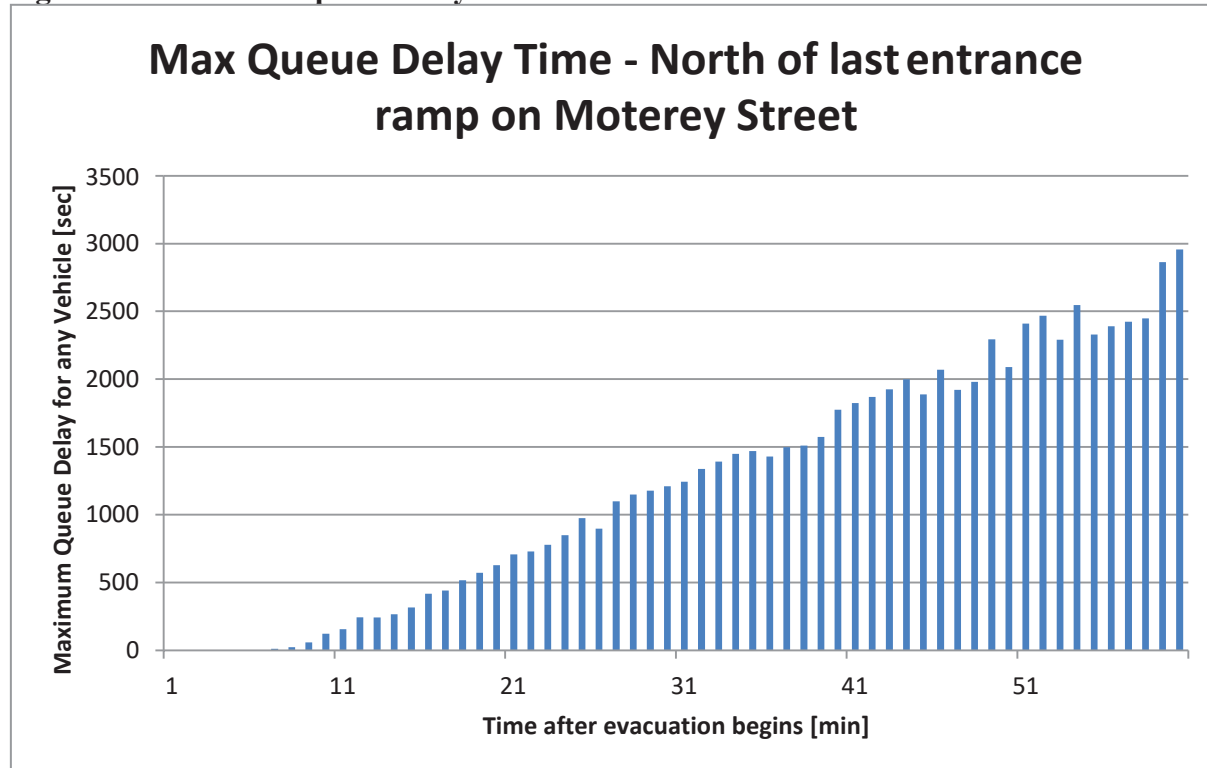


Figure 15: Maximum queue delay time on Highway 101 after last entrance ramps

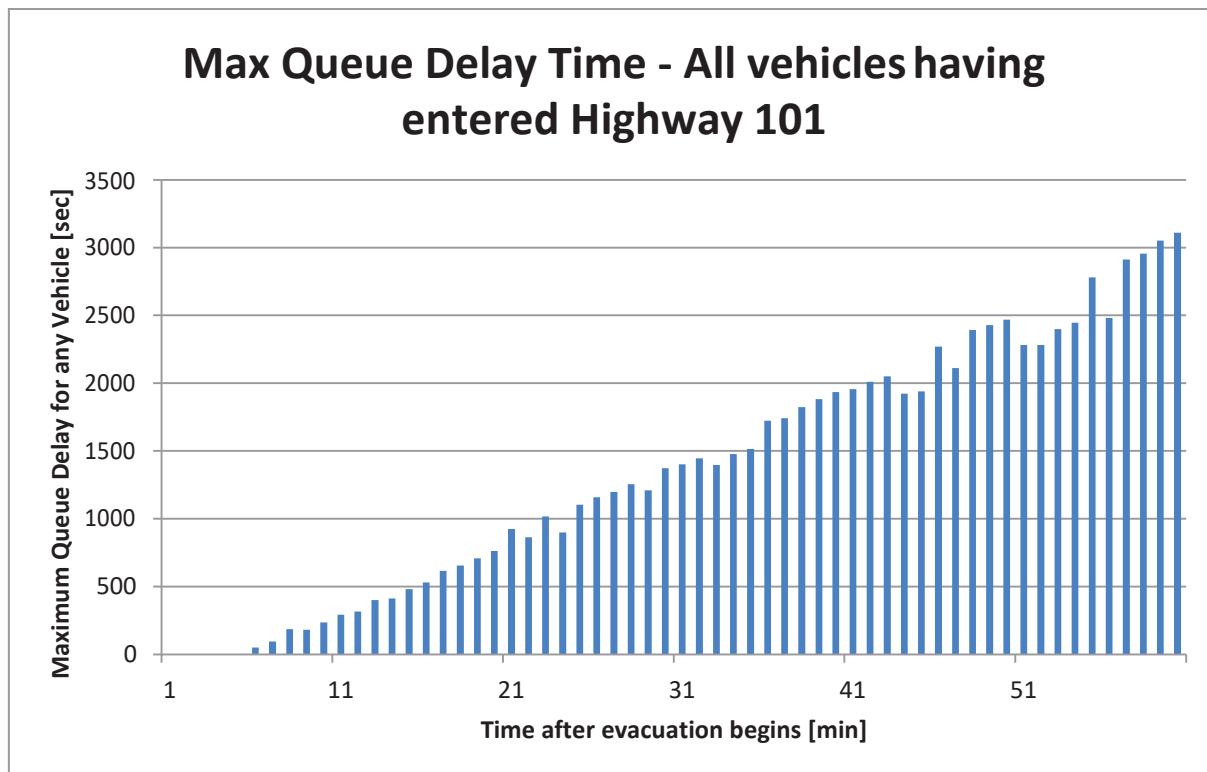


Figure 16: Maximum queue delay time on all Highway 101 entrance ramps

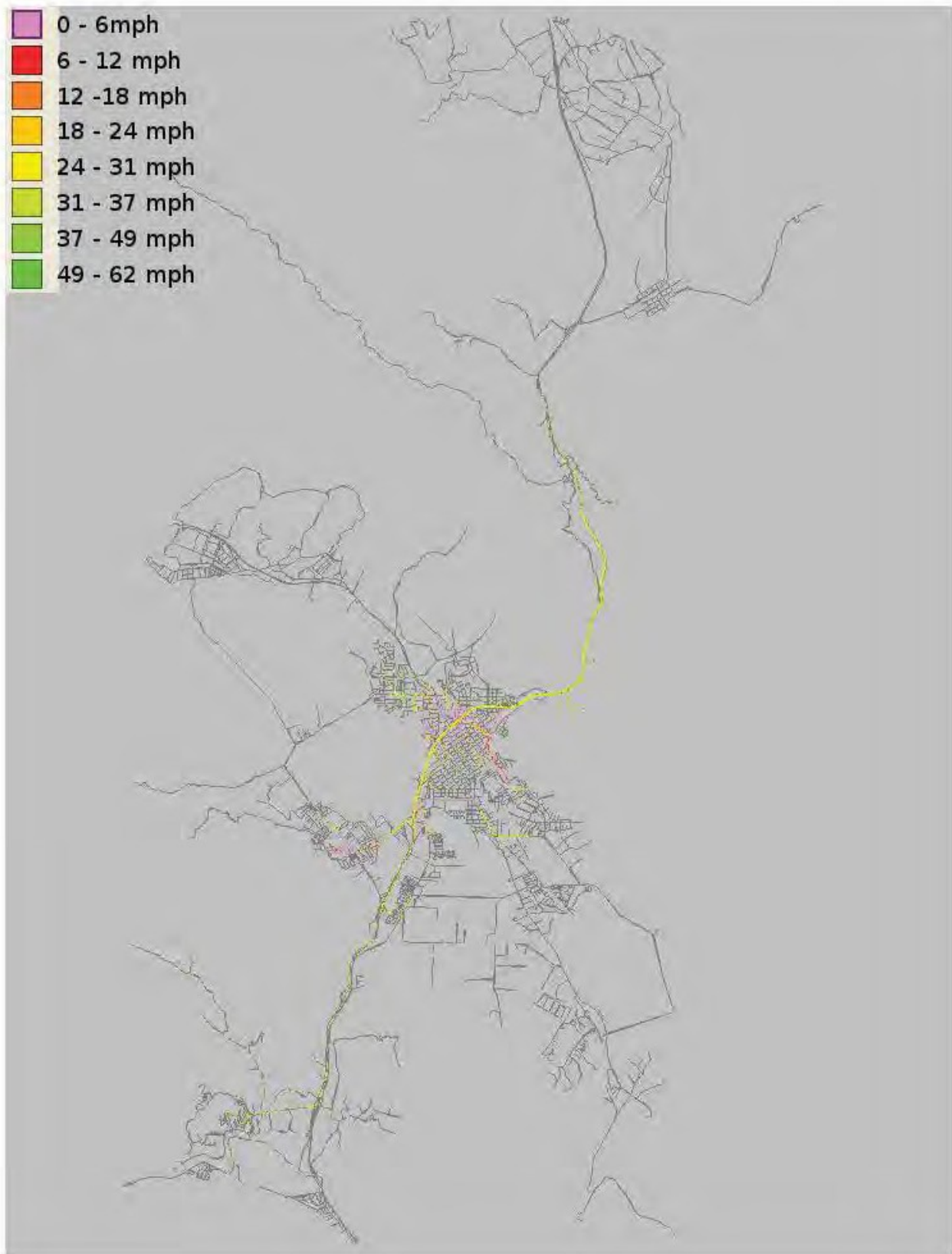


Figure 17: Vehicle speeds 20 minutes after evacuation begins

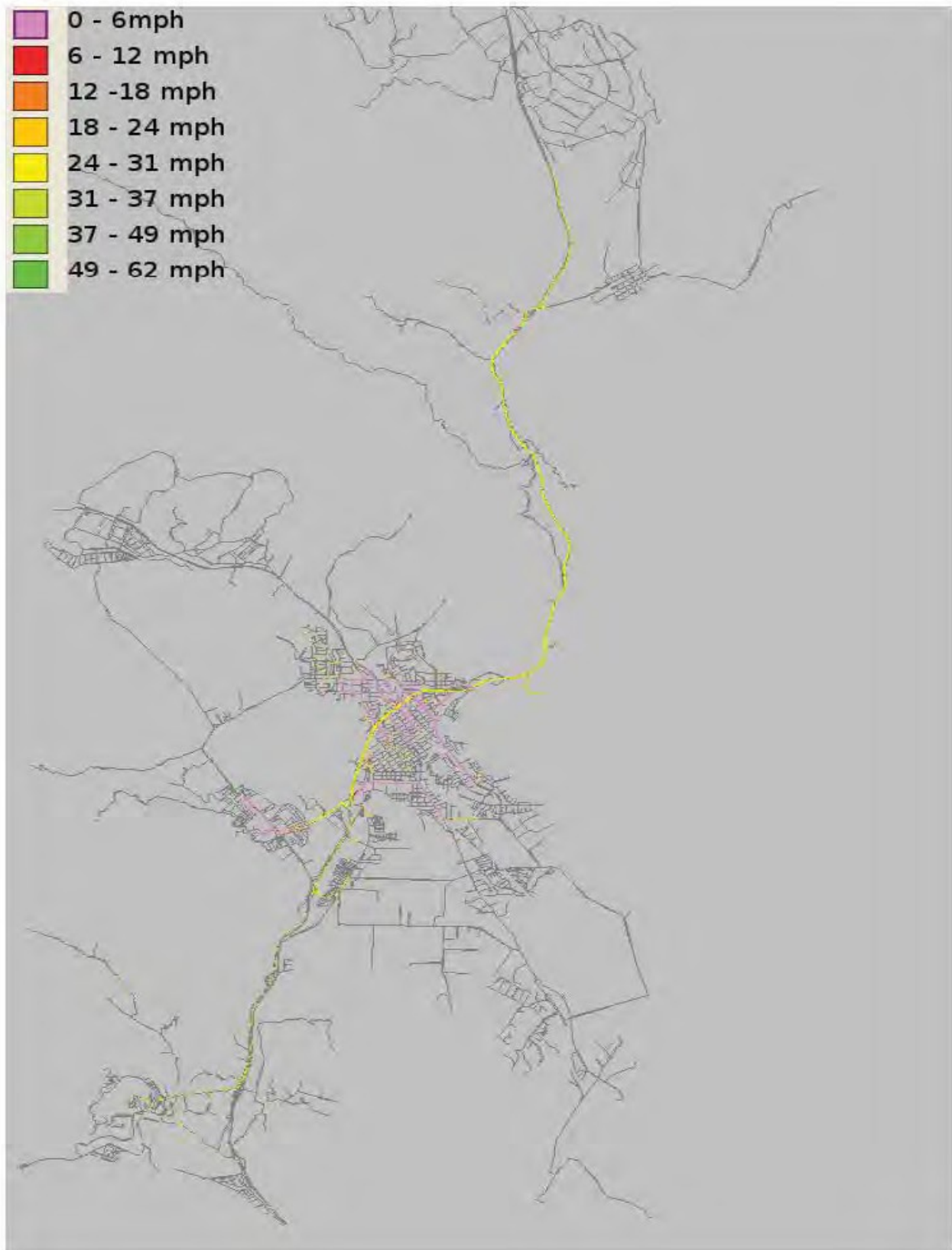


Figure 18: Vehicle speeds 40 minutes after evacuation begins

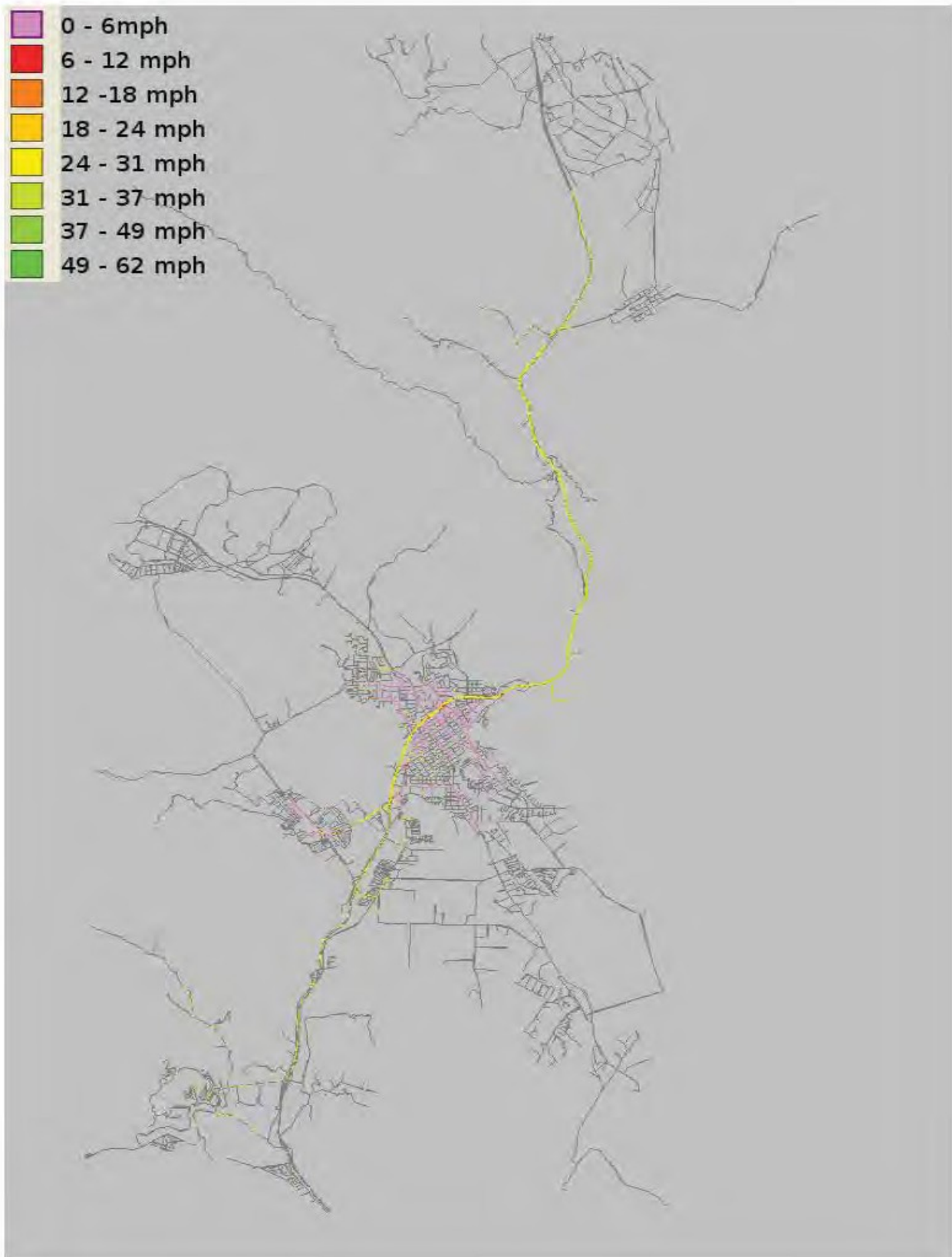


Figure 19: Vehicle Speeds 60 minutes after evacuation begins.

Figure 18 gives the view of traffic congestion at the 40 minute time period. Here it can be seen that the traffic speeds on Highway 101 have not materially changed, but congestion in the City has increased, where many street segments that were coded as red at the 20 minute mark are now colored in magenta at the 40 minute mark, indicating that traffic has been further slowed down. Note that some street segments colored in yellow at the 20 minute mark are now colored in magenta at the 40 minute mark. Also note that congestion has spread to outlying streets in the city. This pattern of congestion extends even further when moving from the 40 minute mark to the hour mark (Figure 19). It should not be a surprise that the constraints on fast evacuation are associated with the capacity of the highways to carry that traffic as well as the ramp capacities in accommodating inflow traffic. One must note that such patterns of congestion would have advanced faster with higher levels of congestion within the city without a contraflow setup.

It is important to note that this appendix presents results for a fixed route plan for all residents. This mimics the type of modeling that has been done in the past with fixed routes (without dynamic traffic assignment). The results here differ from the contraflow plan generated for dynamic travel assignment in one principal way: travel demand is spread out over one hour and not two hours. In either case (dynamic or fixed), a complete evacuation can be accomplished in approximately four hours. This estimate, of course, ignores possible delay effects of trip chaining, ignores populations needing assistance, does not include the impact of Cal-Poly San Luis Obispo, and ignores current traffic levels on streets and highways. What is important is that there appears to be a very real benefit to designing a contraflow plan, assuming local resources are ready and available to support such a plan.



First Responder Support Systems & Technologies (FiRST) Testbed

TRACK II – Cross Cutting Modeling & Simulation Summary of Dynamic Traffic Assignment in VISSIM

Summary of Dynamic Traffic Assignment in VISSIM

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TRACK II – Cross Cutting Modeling & Simulation Summary of Dynamic Traffic Assignment in VISSIM

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First Responder Support Systems & Technologies (FiRST) Testbed

TRACK II – Cross Cutting Modeling & Simulation

Summary of Dynamic Traffic Assignment in VISSIM

1. Introduction

In this summary, we will cover the use of *Dynamic Traffic Assignment* (DTA) in *transportation systems modeling* with VISSIM¹. Roughly speaking, DTA is the modeling of the interaction between a *transportation network* and its users (*network agents*) with special consideration to how these interactions evolve through time. This is in contrast to the *Static Traffic Assignment* (STA) modeling approach which does not take into account the temporal aspects of transportation network-network agent interactions in that either the nature or impact of these interactions is limited or more simply, time is omitted from the model altogether. The difference between the dynamic and static approaches will be highlighted throughout this report and presented in the context of modeling evacuations in the VISSIM environment.

1.1 Scope

The scope of this summary will be that of a general introduction as to how DTA operates in VISSIM and a general guide in how to implement DTA in VISSIM. No prior knowledge will be assumed about DTA; however, some prior knowledge about using VISSIM is required. The goal here is to allow a beginning VISSIM user with a limited background in transportation modeling to: develop an intermediate understating of how DTA works in VISSIM, know how to implement DTA in a modeling project, and how to interpret the output of the DTA model.

¹ VISSIM is a transportation modeling software product created by the PTV Group.



First Responder Support Systems & Technologies (FiRST) Testbed

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Summary of Dynamic Traffic Assignment in VISSIM

The understanding of the DTA process and its output will be the main emphasis of the main text while the implementation of DTA in VISSIM will be left to the appendix of this report.

1.2 Sources

Our main sources of information include the 2011 PTV VISION VISSIM 5.30-05 user manual² and the author's experiences working with the Mission Canyon and Diablo Canyon evacuation models in VISSIM. Thus, the bulk of the material can be presumed to have originated from the PTV manual unless otherwise noted in the text.

2. Foundations of Transportation Networks in VISSIM

Transportation system modeling in VISSIM takes place using a *micro-scale simulation* approach whereby *discrete* network agents (such as individual vehicles, bikes, buses, people, etc.) interact with each other on a *transportation network*, which consists of a set of locations and the set of connections between them (such as roads, bus lanes, bike lanes, etc.). The *micro-scale simulation* aspect of this modeling entails that the interaction between network agents is modeled at a fine resolution in terms of: 1) time, 2) the individual behaviors and attributes of the network agents (agent heterogeneity),³ and 3) the context/state/environment of the transportation network as it relates to the network agents. We now explore these concepts in further detail.

2.1 Network Agents

At the core of transportation system models in VISSIM are network agents. Fundamentally, the network agents are *realizations* of abstract entities whereby the realizations are the

² 5.30 represents a compromise for the VISSIM 5.xx versions and, unless noted, the concepts and procedures described in this summary should be compatible with and 5.xx version after 5.20.

³ In contrast, coarser approaches (such as *macro* or *meso* scale modeling) do not consider individual interactions but rather consider the aggregate behavior groups of homogeneous network agents, usually with analytical functions.



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actual individual objects that move within the modeled transportation network during the simulation. The abstract entity on the other hand, simply refers to the *vehicle type*, which specifies the range that the attributes of a realization can take. In VISSIM, the default vehicle types are (other types exist)⁴ cars and heavy goods vehicles (HGVs). As such, a simulation using the default vehicle types for generating network agent realizations will populate the transportation model simulation with realizations of cars and HGVs in accordance with parameters set by the modeler regarding the total number realizations needed and the specified proportions of each vehicle type. In VISSIM, one does not declare the population size of each vehicle type individually, but rather declares the number of desired realizations for the simulation and uses a *vehicle composition*, which is a collection of vehicle types, to specify the proportions of vehicle types. Furthermore, one is not limited to using the default *vehicle composition* of one standard car and one standard HGV vehicle type as vehicle compositions are neither restricted to only two vehicle types or to only standard cars and HGVs. In fact, additional vehicle composition classes can be generated whereby each vehicle composition can possess more, fewer, or different entity classes. Furthermore, multiple instances of a particular vehicle type are also allowed in a vehicle composition, although typically each multiple of a vehicle type possess different value ranges or distributions for single or multiple *entity attributes*, which are defined as the set of characteristics that are pre-specified (often by default or by the modeler) and immutable for all network agents. In other words, all realizations of network agents are assigned a specific value for every entity attribute it possess⁵ and the specific value assigned to each network agent (and for each of its attributes) is based upon the specifications of its vehicle type. Although these specifications are pre-defined for all entity attributes in terms of the allowable value ranges and how the allowable entity attribute values are distributed, the range and

⁴ For example, busses, trams, bicycles, and pedestrians can be modeled in VISSIM.

⁵ All vehicle types possess the same set of entity attributes.



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distribution of values can be readily modified by the modeler.

It should be noted that the specific entity attribute values assigned to all network agent realizations, regardless of entity class, are always independent of the actions or characteristics of any other network agents and of other transportation network components with which the network agent might interact.⁶ The entity attributes include: the desired speed of the vehicle,⁷ vehicle length (an attribute not modifiable by the modeler), the weight of the vehicle, max and desired acceleration, vehicle width, vehicle occupancy, and the power of the vehicle. In all, the ability to create multiple vehicle types allows for different geographic areas or time periods to have varying populations of vehicles and occupancy. Beyond entity attributes, another fundamental aspect of network agents are their *behaviors* which we define as the rules guiding how network agents react with other network agents, to certain events or components of the transportation network or components located on it. Similar to entity attributes, many parameters of *driver behavior* can be modified, although, unlike entity attributes, rather than having to specify them for every entity class, driver behavior affects all entity classes in a similar way. How these behaviors are imparted to network agents is discussed in *Section 2.2.1*. Examples of some driver behaviors include the look-ahead distance, lack of attention, looking back, lane changing, and inter-driver co-operation. By and large the implementation of these behaviors are pre-defined by VISSIM although a variety of implementation options are offered and, in some cases, they can be modified by the modeler in terms of the behavior's extent or its propensity to occur. As to how the behaviors and attribute ranges and distributions are determined for each class is beyond the scope of this report. VISSIM provides default attributes and behaviors to the standard

⁶This is in contrast to the 'state' of an entity, which describes characteristics of entities that are subject to change.

⁷This is the speed that a vehicle of this type would travel as if it was unencumbered by traffic or the nature of the road it was traveling along.



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vehicle types, but again, whether these values are appropriate is up to the modeler to decide. It suffices to say however, that the model parameters are typically selected in order to either reflect the attributes and behaviors of the network agents from a transportation system being modeled, or parameters can be selected to produce scenarios of interest. Whatever the justification for the specific parameter assignments, however, the importance of this task should not be underestimated as these parameters essentially guide every network agent's decisions during the simulation and thus play a large role in determining the nature and outcomes of interactions between agents. This is readily apparent considering that a network agent's attributes will largely guide how they will move through the transportation network subject to their behaviors when such agents encounter other agents. Typically these interactions are non-linear and thus there is a possibility that the aggregate behavior can be sufficiently non-linear (or even *chaotic*⁸) in nature such that our general understanding of the model is diminished. As a consequence, our ability to make predictions is diminished given the uncertainty surrounding how attributes and behaviors affect aggregate behavior. This is not meant to imply that every model will be problematic, but rather a strong recommendation to carefully assign attributes and behaviors to network agents despite the availability of default behaviors and attributes when conducting micro-simulations in VISSIM. This comment is especially important with systems that are large and complex or when fine measures about the network agent travel behavior are desired.⁹

⁸ Chaos entails 3 behavioral characteristics of a system, however for DTA modeling typically include only two specific characteristics of chaos, and whether they are exhibited in the model, are of interest. These characteristics include: a sensitivity to initial conditions and instances where very different initial conditions produce the same outcome. A common example in transportation modeling is a minor event such as merging into a lane resulting in a huge traffic jam.

⁹ If there is not sufficient information to guide the assignment of behaviors and attributes, performing extensive validation and verification procedures is advisable. Visual examination of the experiments and sensitivity analyses of parameters are commonly used in cases where information is scarce.



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2.2 The Transportation Network

In dynamic traffic assignment, the *transportation network* is first and foremost the domain where interactions between network agents occur and thus the network must be defined accordingly. To model transportation networks, VISSIM uses a *graph* approach. The main components of a graph are *vertices* and *edges*, whereby the vertices represent a particular location of interest on the transportation network (such as the end of a street, beginning of an intersection, transition point between a street and road, etc.) The edges represent a connection (such as roads, bike paths, or bus lanes) between vertices. Thus, when creating an abstraction of our transportation network graph (TNG) in VISSIM, *links* are created to explicitly represent the edges as well as vertices. Additionally, VISSIM allows for the creation of logical *connectors*, which are used to connect links and are often used in modeling an intersection or turn restrictions along a route. It is only on these three components that network agents can be located, travel through, or interact with other network agents given that all network agents are constrained to the transportation network until they “exit” the transportation network.¹⁰ There are special elements, called nodes, that will be discussed below which allow, for example, one to define a controls for an area. Nodes are objects that are distinct from the network vertices. This could be a point of confusion that arises with people who are familiar with network models, as the terms vertices and nodes are often used interchangeably. In VISSIM, nodes are NOT to be confused with vertices. Vertices are points of connection for edges or simply endpoints of edges. Nodes may not necessarily represent network features, but serve a wider function.

Another important aspect of the transportation network is that VISSIM’s simulation approach allows for the TNG’s links and connectors to dynamically influence network agent

¹⁰ Exiting the network usually occurs in one of two ways: network agents can “drive off” the network if the last link on their route is not connected to any other link, or they disappear from the network. The latter usually this occurs due extreme congestion not permitting a network agent to enter a new link or general transportation network after a substantial amount of time.



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decisions or actions as they move through the network. All of these objects can be assigned attributes and behaviors that can affect the actions of network agents that interact directly or indirectly with any of them. The non-link and connector network objects of interest in this report includes *nodes*, *markers*, and *routes* given their role in Static Traffic Assignment (STA) and Dynamic Traffic Assignment (DTA). The first object of interest, a *node*, is simply a component that has a defined boundary, which can be as small as an area including a subsection of a link or connector or as large as a collection of links and connectors. Its functions include inducing temporary changes in certain behaviors of network agents as they travel through such a node, with the node type determining the behavior to target. *Markers* are objects located at specific points in a network and can influence network agents at a distance or as they approach the object. They can also be used to specify source points for vehicle instantiation. Finally, *routes* are objects that can be overlaid on links and connectors and perform the function of routing network agent's from a set origin to a set destination via fixed (i.e. fixed or *static*) routes. A final note on network objects is that beyond simply influencing network agent behaviors or actions, many components also serve functions related to the way VISSIM operates in general. For instance, certain nodes help determine the ultimate topology of the graph that VISSIM will use for the simulation. Both markers and nodes are used to introduce and remove vehicles from the TNG. More details will follow in their respective sections.

2.2.1 Links and Connectors

The first way in which links and connectors influence network agents is that they can possess many attributes that directly affect the movement or travel decisions of network agents. The most obvious one is the physical capacity of the link or connector, which is a function of the number of lanes that they have and their length. In VISSIM, links and connectors have no immediate maximum length restrictions however, with respect to lanes, connectors are



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limited to a single lane,¹¹ whereas links can be created with up to 20 independent lanes. Further, link and connector attributes include: cost, gradient, lane closure status, lane change permissibility, and lane-width, all of which affect the actions of network agents as they travel through the links and connects, or, in a more indirect way, by influencing the decision making of network agents as they plan their trips. As with the entity attributes, default link and connector attributes are provided by VISSIM but many can be modified by the analyst. Lastly, links and connectors can influence network agents through their *behavior type*, an attribute that modifies the *driver behavior* of each vehicle agent as they make contact with the link or connector by traveling on it. These modifications to the *driver behavior* remain with the network agent as long as they remain on the same link or connection. If a subsequent link or connection is reached but shares the same behavior type as the previous link or connection, then the driver behavior will remain the same. Otherwise, the network agent will adjust its behavior to that of the new link or connection it has entered.

2.2.2 Nodes

To reiterate, nodes are non-point behavior changing objects or indicators located throughout the TNG. Even though links and edges are similar with respect to the graph, nodes are not analogues of vertices of a TNG. Whereas vertices are created when an edge is specified, nodes are created at specific locations in the transportation network. Nodes are used to coordinate special types of interactions between agents, directly manage the actions of agents, and/or temporarily modify the behaviors of individual network agents within the influence area of the node. Often Nodes indicate critical decision-making points/areas of the transportation network. Lastly, Nodes can be used to help VISSIM manage the topology of the TNG in an efficient manner. In the remainder of the report we

¹¹ Connectors join links by associating lanes of two links rather than just associating the links themselves. Also, a single link lane can connect to multiple link lanes on both the 'incoming' and 'outgoing' end.



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will refer to a specific Node object by capitalizing ‘Node’¹². The rationale for this is that there are a multitude of objects in VISSIM that are conceptually viewed as nodes but are not named or recognized as nodes by VISSIM¹³ thus impeding a clear, concise discussion about the structure of transportation networks in VISSIM.¹⁴ Issues of semantics aside, the three types of nodes that exist in VISSIM are zonal, indicator, and decision point nodes. This includes objects such as parking lot zones, yielding zones, conflict zones, and reduced speed areas. We will concentrate our discussion here to parking lot zones and the use of nodes in STA and DTA in VISSIM.

*Parking lots zones*¹⁵ (PLZs) are used to specify the origin, or a location on a TNG where network agents can enter the network and often, to also specify the destination or network exit point for network agents. The idea behind this is that during simulation runs, VISSIM will search for paths that can be used by the network agent to get from its designated origin to its designated destination, a process more extensively discussed in *Section 3.4.2*. In VISSIM, Nodes are essentially indicator nodal objects that are used to manage the topology of the complete TNG. The first way in which it accomplishes this is by assisting VISSIM in determining the topological relationships between non-link/non-connector network objects on the TNG. Its second and largest role, particularly when working with massive TNGs, is that nodes can help reduce the complexity of the complete TNG by transforming it into a more topologically simple *abstract graph*. This will be discussed in section 2.4.1. The size of such Nodes can be as small as that needed to cover a simple fork in a road, which would include a segment of one link’s end and those of the two other links, or, their size can

¹² The specific object ‘Node’ will always be capitalized while the conceptual class node will never be capitalized beyond the location of this footnote.

¹³ This is because VISSIM organizes and names its objects mainly by their designated function. Thus, many conceptually similar objects end up being scattered throughout the many program menus.

¹⁴ The segregation of conceptually similar objects arguably leads to many redundant descriptions, explanations or references.

¹⁵ The parking lot zones are used for modeling parking lots, but in VISSIM they also serve the function of designating origins and destinations for network agents.



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as large as would be needed to encompass a massive cloverleaf freeway interchange structure, which usually are modeled with a large number of links and connectors. Regardless of the “apparent” size of a Node, they viewed as a “vertex” within the TNG¹⁶ when VISSIM compiles the TNG for a given simulation.

2.2.3 Markers

The marker of interest is predominantly¹⁷ that of the *vehicle input marker* (VIM) whose role is that of designating a location on a link in the TNG from which vehicles can enter. The parameters of this type of marker include a set of time intervals whose number and length are defined by the modeler.¹⁸ Furthermore, each time interval is loaded with information about the volume of network agents that will leave within a particular time interval and the vehicle composition of the vehicle types that will leave that node. Purposely excluded as a VIM attribute, however, are parameters with information about the destination of the vehicles emanating from the VIMs. As previously stated, this is a function that can be handled with PLZ nodes.

2.2.4 Routes

Routes function by forcibly routing network agents, of selected vehicle types, through an entire fixed (or *static*) route upon entering the route, but only if the network agent’s point of entry was the route’s origin. Furthermore, similar to Nodes, on certain junctions of the TNG, routing decisions maybe placed whereby network agents can diverge to different connected static routes according to proportions set by the modeler.¹⁹ Also, the vehicle types that are allowed on the routes can be restricted, including places where network

¹⁶ One exception to this is that nodes can either be aggregated into a single *polygon node* or maintained as a collection of *link segment nodes*. Although both nodes have the same function, the latter approach allows for more control over the model by allowing certain nodes to be ignored for information collecting purposes or as a decision point in DTA. Furthermore, it is possible to convert between these two types if needed.

¹⁷ Other types of markers include things such as stop signs and desired speed decision markers

¹⁸ Note multiple vehicle input nodes can be placed and share the same time intervals

¹⁹ The vehicle type proportions can be set to vary with time.



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agents can diverge to different paths.

2.3 Network Agents and the Transportation Network Graph

In the previous sub-sections, much of the relationships between network agents and TNGs have been discussed. To summarize, a TNG can directly and indirectly influence network agents via the attributes of links and connectors. Furthermore, since TNGs are the only place where vehicles are allowed to be located we can expect network agent-to-network agent interactions to occur here as well, with the outcome of these interactions being dependent on the behavior, state, and attributes of the interacting network agents as well as those of the relevant TNG links and connectors. Lastly, additional objects can be located on the TNG (such as nodes, markers and routes) that can further extend the influence of the TNG in a variety of ways, including how vehicles are controlled in routing. Discussion on the issue of routing and guidance on selecting between the VIM and PLZ approaches is presented in *Section 3.4*. Nevertheless, we can begin to introduce some of the issues surrounding the PLZ and VIM paradigms by looking further into how TNGs are processed by VISSIM.

2.4 Compiling Transportation Network Graphs

Before the micro-simulations phase of the model begins, VISSIM must first *compile* the TNG, as well as any associated network components, into an *abstract TNG*, which is a secondary TNG that VISSIM uses during the simulation phase for a variety of purposes.²⁰ Exactly how the abstract TNG is compiled and eventually used, however, is largely dependent on whether a VIM or PLZ modeling approach was selected. To explain how they differ with respect to the compilation process, and the implications of these differences, we begin the discussion with the PLZ approach, as the compilation of the TNG is extremely critical for its implementation.

²⁰ It should be noted despite the creation of an abstract TNG, all direct Network Agent-Network Agent or Network Agent-Network interactions occur strictly on the original TNG.



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2.4.1 Parking Lot Zones and Network Compilation

When using PLZs there are two general issues that must be addressed due to the very nature of PLZs. First, although PLZs have explicitly defined origins and destinations for every instantiated vehicle, there are no routes that are provided beforehand by VISSIM in order to guide vehicles from their origin to their destination. As a result, VISSIM must somehow provide these vehicles with some mechanism to find routes (if they exist at all!) in a process that can be computationally challenging. Second, even if the set of routes between an origin and destination are known, the attractiveness of routes (or *general cost* - in the unattractive sense) relative to others must be established. This is further complicated when costs beyond distance are considered, such as travel time or tolls or when certain vehicle classes are subject to different restrictions.

Routes and Parking Lot Zones

Consider a sufficiently large and/or complex network with a non-trivial number of PLZs. In this case, routing can be an extremely daunting task as the set of all possible paths between an origin and destination, or even just the subset including only reasonable paths, might be incredible in size and thus making the route search process computationally infeasible considering an incredible amount of computational power would be required to find and search through an enormous set of possible routes, and not to mention, the amount of memory that would be required to store these route sets would be extremely large. This is further complicated by the fact that since not all vehicles leave at the same time or from the same place, a naïve approach to routing becomes more impossible as the number of modeled vehicles increases. In order to reduce the severity of these computational issues, during compilation, the PLZ approach attempts to reduce the complexity of the route issues by forming a less complex, and thus more computationally manageable, abstract TNG via vertex and link reductions. The goal here is for the abstract graph to retain only the information from the original TNG that is needed in order to efficiently find and store



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routes.²¹To reduce the vertex set size for the abstract TNG, rather than having vertices where every link begins and ends (following the VISSIM's graph approach), vertices are limited to locations where critical routing decisions occur and around certain network components, which can potentially obstruct routes (such as PLZs). As hinted to in *Section 2.2.2*, this process involves the use of Nodes, which are created on critical decision points, such as over intersections, or they simply surround the network component – such as is the case with PLZs.

As for the link reduction procedure, it largely follows the vertex reduction as VISSIM will merely combine a series of sequential links segments, from the TNG, that connect two Nodes in order to create a new link, known as an *edge*, for the abstract graph. Thus, when searching for routes or storing them, only the edge information will be analyzed or recorded. Therefore, after this graph reduction procedure, the resultant abstract graph should contain far fewer vertices and links than the original TNG which in turn should result in a set of paths that is also smaller. This, in turns, reduces the computational burden.

Route Attractiveness

Within VISSIM, the issue of keeping track of route attractiveness is largely addressed by the use of the abstract TNG. In addition to simplifying the TNG by generalizing it to a set of routes through the use of edges, the abstract TNG maintains information about the generalized costs/ attractiveness of these edges. Thus, as the simulation unfolds, the edge information is continually computed and updated so as to reflect the most current state of the various parts of the network, which in turn will assist vehicles in navigating efficiently through the network.²²

2.4.2 Vehicle Input Markers and Network Compilation

²¹ The exact way in which these routes are found are discussed in *Section 4*.

²² The process of agents (vehicles) choosing between routes and the manner in which edge cost are calculated is presented in more detail in *Section 3 and 4*.



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In contrast to the PLZ modeling approach, VIM (Vehicle Input Marker) is the least complicated in terms of compiling the TNG. With the VIM approach, VISSIM will depend mostly on the topology of the original TNG²³ rather than an abstract TNG during the simulation phase. This is mainly due to not having any destination explicitly specified. This eliminates the need for VISSIM to find an explicit route set, and their associated general costs, for any vehicles starting from a VIM. In fact, in this paradigm VISSIM will simply release vehicles onto the TNG and then leave it to other network objects (such as paths) to guide vehicles, but only if such network objects happen to interact with the VIM instantiated vehicles. In fact, in the absence of any interaction with a network object capable of routing vehicles will aimlessly travel through the network until it somehow exits the network, or disappears from the network due either severe congestion or it reaching a dead-end.

3. Transportation System Modeling with Traffic Assignment²⁴

Formally, a transportation system model consists of the three parts: a *supply* component, a *demand* component, and a component concerning how these two components interact with each other - the component of *traffic assignment*. The first component, supply, consists of the structure of the transportation network to be modeled and how such a network responds to congestion generated by the vehicles.²⁵ The *demand* component on the other hand, is concerned with the task of modeling vehicular trips, which includes the trip origin, destination, and departure times. Also, part of the demand component involves determining the general routing preferences of drivers within the model. As such, the *traffic assignment* component then consists of primarily of how vehicles will select their routes from an origin to a destination given the preferences and decisions made by the agents

²³ Assuming no origin and destination PLZs are used in the model.

²⁴ This section is based heavily on the book *Transportation Systems Analysis: Models and Applications* (2009) by Ennio Cascetta and the FHWA's *Traffic Analysis Toolbox Volume XIV* (2012).

²⁵ Some authors refer to this as the *level of service* attributes.



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(vehicle drivers). It is important to note that the nature of each component of the model is in some way largely driven by the intended scope of an associated transportation project. In turn, the transportation project's scope is often the outcome of negotiations between a variety of stakeholders, which may have different goals or visions for the project – often because of some vested interests related to the project. Without knowing the scope of a project beforehand, it is rather difficult to generate a set of general guidelines. For instance, the *level of effort* that should be devoted to defining certain aspects of components is one aspect that can widely vary from project to project. Some projects might call for an extreme amount of detail and accuracy of a certain aspect of one component, while other projects might see the very same aspect as unimportant. Therefore, the discussion of each component in this report will try to focus on outlining the general characteristics of each component rather than attempting to describe a plethora of special circumstances about them. For this section, the goal is for this guide to serve more as a starting point rather than a solution manual.

3.1 Supply Models

In relation to the other two components, the supply model can be thought of as a foundation for the other two components in the transportation systems model. While the relationship with the traffic assignment component is trivial, the modeling focus begins with recognizing the organization of the supply model as it will serve as an input for the demand model, both for functional reasons and in order to determine how the demand model can be structured. Unless a transportation network is planned and built from scratch, it is difficult to make sense of the nature of the demand component of the model. This is not to say that every other aspect of the supply model should be specified before addressing any issues of demand, such as determining the relationship between link capacity/type and travel times, but nonetheless, without first understanding the organization of the transportation network, understanding any of the other model's components, let alone



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determining what they should look like, is an arduous if not impossible task. Finally, it should be noted that the modeling of supply can be conducted with one of two approaches, that is, from a prescriptive approach or through a descriptive approach.

3.1.1 Network Information

The core components of a supply model are the network topology and geometry and thus, acquiring or constructing a representation of the network is the first order of business. The network is generally based on information from one of three sources: a GIS database, data from existing models, or from aerial or ground level photography. In the first two cases, a network representation can be obtained from a variety of sources ranging from public institutions ranging from Federal institutions to more local ones, such as city or regional planning departments, often for little or no cost. Alternatively, academic institutions and commercial entities can also provide either GIS databases or model data but often at a price. In either case, the advantages of pre-existing data sources are such that much less effort is often needed to produce a supply model, although the quality of the data can be a serious issue if the data is outdated, incomplete, or is flawed in that key networks connections are absent or that the data is simply inaccurate.

The photography option allows the modeler to directly digitize a transportation network to the modeler's specifications. Even though the topology may be easily digitized from an aerial photograph, it is still necessary to acquire a large amount of ancillary data, including speed limits, sight lines, turn restrictions, etc. Much of this can be collected manually, increasing the level of effort required, or be acquired from a third-party source. Another key component of the transportation network involves the control data, which includes information about traffic signal information, stop sign locations, and ramp meters. Compared to the other required pieces of information, control data can be extremely difficult to obtain due to the fact that such information is often held only by the jurisdictions or agency managing the signal. Even if the agency grants access to control



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data, the quality or type of the information delivered might pose problems. Some databases might be easy to access, but they can also be difficult to use or simply absent or outdated thereby limiting their utility.²⁶

3.1.2 Network Capabilities

Many of the types of network objects and their characteristics were previously discussed in *Section 2* and section 3.1.1. Most capabilities of the transportation network are described by the characteristics of network links, traffic controls, and the pricing mechanism used to charge for use of certain components of the transportation network. As for link characteristics, the most important attribute is the capacity, which is closely associated with its speed limit as well as the number of lanes involved. Other factors include whether link lanes have any use restrictions, such as with HOV lanes or when trucks are restricted to use the right-most lanes. These characteristics are particularly crucial to encode in the network. Although they may have little influence on traffic at free-flow, when a significant amount of congestion occurs their role is greatly increased with respect to helping maintain the fidelity of the model.

Traffic controls, too, are important, especially for critical components of the network. Missing or incorrectly specified signal controls for instance can undoubtedly affect the behavior in unintended ways. If a key set of signal controls or a sufficient number of signal controls are missing from the network or when they are incorrectly specified, the transportation network's behavior may not be consistent with the existing transportation flow. In this case, any decisions concerning network development may be misguided. The final key component of supply models involves pricing. The appropriate pricing scheme needs to be implemented as it will principally manage the key parameter of this component

²⁶ This issue is often addressed with the use of local knowledge or with software solutions provided in transportation system modeling software.



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of the supply model – the cost of using the corresponding network link(s).²⁷ The different price schemes include: fixed pricing whereby cost remains constant; time-based pricing which adjusts the cost according to time of day; and dynamic pricing, a system in which the cost of using a link depends on the demand for using it with higher demand translating to higher costs (and vice-versa).

3.1.3 Spatial Dimensions of Supply Models

The spatial dimensions of the supply system are defined by the geographical area involved and the scale at which every identified feature is represented. The *spatial domain* of a model and *spatial scale* of the features modeled within the domain are critical in that they largely determine the overall structure of the transportation system model. Overall, the scope or requirements of the project control the definition of the domain and necessary scale in order to create a model with a suitable level of fidelity.

Spatial Domain

The task of delimiting the spatial domain of a transportation network, which we refer to as the *primary study area*,²⁸ includes many considerations of not only the features of interest but also those which interact with them either directly or indirectly. In the transportation modeling context this includes identifying the locations and characteristics of relevant transportation network routes and of relevant geographic areas which may contain facilities, locations, or services that directly or indirectly affect the transportation network of interest, or vice versa. With respect to transportation routes, routes located outside the primary study area that are significant alternatives to any routes inside the primary study area, and vice-versa, should be included. Without including such alternative routes, a significant choice is being excluded for the purposes of routing thereby increasing the possibility of incorrectly assigning volumes or routes to vehicles. Furthermore, in sufficiently

²⁷ Note that these parameters can be modified for demand model related reasons, which are discussed later in Sub-section 3.2.

²⁸ We use this term out of pure convenience.



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complex transportation networks, the magnitude of the distortions and/or their characteristics might not be readily obvious thereby casting doubts on the scope and validity of the model. Similarly, places where queues or congestion can potentially spill out of the model's spatial domain should be included. Moreover, in models that do not prioritize the generation of unbiased routing behavior, it is important to consider a domain that captures all relevant components, which might control overall performance. Likewise, interfering with queuing behavior by poorly defining the spatial domain can result in distorted volume measurements, which in turn can result in biased transportation network performance measurements or biased route choices. As for determining which geographic areas to include or exclude from the primary study area, areas that serve as either barriers (whether natural or administrative) or as significant traffic sources or sinks should be seriously considered when determining the spatial domain of a project. Significant omissions can result in measurement biases and thereby complicate the interpretation or applicability of model results. From a more practical standpoint, knowledge of these factors are also important as data often also dictates a project's feasibility and the scope of the results produced by its models.

Spatial Scale

For micro-scale transportation models, the spatial scale is a key focal point and involves the fine details within the model. This involves a combination of capturing detailed transportation network geometry and topology, capturing interactions between highly granular model elements and capturing the interaction between these two facets by adding spatial context to the model. The motivation for such a high level of model granularity is that it provides the ability to capture a variety of potentially significant interactions. For example, a detailed topological representation of an intersection can reveal a high level of queuing in a single turning lane in what would otherwise be a moderately congested link at



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a larger scale.²⁹ Likewise, a model of a highway in a city might attempt to include complex and subtle behaviors such as acceleration behavior and aggressive or hesitant lane-changing behavior in an attempt to capture the effects or outcomes of these behaviors, which can be equally - if not more - complex than the behaviors themselves. There is a great interest in capturing the resulting vehicle behaviors and interactions in and around traffic “conflict zones” such as on and off ramps. Here the heavily congested environment and the significance of the location (with respect to role in the transportation network) allows for the actions of one or a few vehicles to have potentially large effects on operations.³⁰

The availability of the appropriate data can pose a significant challenge to modeling efforts. When considering the extensive costs of collecting data itself (let alone highly detailed data) and the technological/methodological limitations of data collection efforts, the scarcity of high-resolution data should be of no surprise. Without having data at the appropriate resolution or the ability to compute a model at a high resolution, problems of model bias arise.

3.1.4 Temporal Dimensions of Supply Models

The essential question in resolving the temporal dimension is whether the structure and characteristics of a transportation network are static or dynamic through time. Examples of varying transportation network characteristics through time include having a network link with varying speed limits or toll charges that depend on the time of day or the level of congestion. Another example is a network link capacity that can change when restricting access to certain lanes depending on vehicle type and/or the time of day. These types of

²⁹ To further elaborate on this example, a right turn lane on to a popular avenue might be congested while the rest of the lanes, incapable of making a right turn, are rather free. In a coarser model with no lanes, the model representation would assume all lanes could turn right, or at least, more vehicles would be able to turn right than is actually possible.

³⁰ The example of a single vehicle causing an entire traffic jam might be hyperbolic for this discussion, but undoubtedly, single vehicles can have a significant impact on traffic flow as when a driver has to break in order to accommodate aggressive driving which in turn affects other vehicles or vehicle-vehicle interactions and so forth.



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changes are commonly the result of operational policies, as is the case with lane management, or it can be legal in nature as with “Cruising Laws” which can result in the shutting down of entire streets or boulevards. In contrast to the previous examples, the temporal nature of the transportation network’s structure often defined over longer time periods with the addition of new links to the transportation network or the removal or reconfiguration of existing links. The length of the analysis dictates the nature of the network characteristics with shorter analysis periods being more static than longer term analysis. That is, models with short analysis periods (< 6 Hrs.) tend to be focused on the modeling of homogeneous periods such as either off-peak or high-peak periods. In contrast, models with longer temporal domain (> 6 Hrs.) often vary network characteristics in recognition that different times of days require different management strategies and policies. Lastly, in terms of modeling structural changes to the transportation network, scenario-based approaches are used whereby a set of either short or long-term analyses are conducted and compared in order to understand the nature of the current transportation network and the effect of structural changes.

3.2 Demand

Transportation demand models have two main components, one addressing the willingness of individuals to make trips between different locations and the other, concerning how trip-makers establish their route preferences. Moreover, these components include the motivation for trips, trip frequency, the time at which these trips occur, the destination of these trips, the mode by which the trip will take place, and the route that will be taken to the destination. In all, demand models attempt to connect information about vehicle trips (including their origin and destinations, and departure times) and route preferences with that of the characteristics of trip makers and the transportation network. Although much information is available about the characteristics of trip-makers, data about travel demand is problematic as it is difficult to obtain and also, the nature of available trip-maker and



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travel demand data complicates modeling efforts. First, in terms of data availability, direct collection of disaggregate travel data is desirable; however, such efforts are limited by high costs, issues of time,³¹ and technical and methodological constraints. Furthermore, when trip-maker characteristic data and travel demand data is available it is usually in an aggregate form thereby making it difficult to establish any relationships between the characteristics of trip-makers and travel. Nonetheless, many methods and models have been developed to cope with these challenges. These alternatives, however, also possess their own set of requirements and limitations, which must be compatible with the goals of the modeler, the data that is available, and the nature of what is being modeled.

3.2.1 The Spatial Dimensions of Demand Models

Defining the spatial dimensions of a demand model requires that both the spatial extent of the model be defined and that a spatial scale be determined. Here we take the spatial extent of the model to be the as previously defined for the supply model while the spatial scale refers to both the size of features that will be included in the demand model and to the extent to which the location of included features is generalized.

Spatial Domain

The definition of the spatial domain of the demand model is similar to that of the supply model. To reiterate, the study area must: include routes that interact with the primary study area (as well as significant alternatives), acknowledge significant physical and/or administrative barriers, and consider the locations of any facility, area, or service that might significantly interact with the primary study area in a direct or indirect manner. As a result, the spatial domain of the demand model should be equal in size to the supply model as the supply model has already taken into consideration the elements of the demand model. If

³¹ Large and detailed data sets are often produced; however, there is a significantly large time period between when the data was collected and when the data is in a condition to be used in models. This delay precludes the data's use in projects that require relatively recent data (such as real time modeling projects), or in projects that are modeling a constantly changing environment or one that has sufficiently changes since the data collection.



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they do not match however, two possible outcomes include the modeling of features that are not relevant to the model or the exclusion of significant features in the supply or demand model.

Spatial Scale

In defining the spatial scale of the demand model, the process is more complex as it is largely dependent on the spatial scale of the features in the supply model. We note that it is often the case that it is not possible to collect data at the desired scale. This typically implies that the demand data is not sufficiently detailed in terms of location as a result of data aggregation. It is possible to proceed with the modeling effort in this case; however, the model is likely to produce biased results and with much uncertainty surrounding the nature of the bias. This uncertainty can be reduced via external measurements, such as with the use of traffic counts, but without changing the demand data, the bias cannot be mitigated.

In the case that finer demand model elements are desired, the demand data must be disaggregated via some defined process with a general aim of reducing the amount of locational generalization and also, to have the new disaggregate demand features to be more reflective of the demand they represent. As previously discussed, this process is also potentially problematic in terms of bias and uncertainty. However, this issue can also be lessened in this case with the use of external measurements. One such example is the use of land-use or parcel data, which can be used to estimate how vehicle trip origins are distributed in a more detailed way. Another case about scale and demand data to consider is when demand data requires aggregation.³² This process, as with data disaggregation, can increase the amount of bias and uncertainty in the demand data. Furthermore, the amount of uncertainty surrounding the bias can be reduced in a similar fashion with the use of external data sources. Unlike the disaggregation process however, bias cannot be reduced as it is

³² This is often the case due to issues of privacy or the lack of computational resources.



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inherent to the aggregation process although it can be managed to a large extent. The essence of bias minimization is to establish a high degree of homogeneity of demand within the new aggregated features in terms of the aggregated demand collectively possessing very similar locations, land uses, and accessibility to the transportation system, services, or facilities. None-the-less, the effectiveness of this technique is limited by the ultimate resolution of the demand data. This is particularly evident when considering the relationship between the supply model and the demand model whereby coarse demand data can produce heavily distorted traffic patterns because of the generalization of the locational aspect of demand data.

3.2.2 The Temporal Dimensions of Demand Models

Defining the temporal dimensions of a demand model requires specifying the set of time periods we are interested in for the study of a transportation system (whether directly or indirectly) and the relationship between these periods. More precisely this includes declaring the specific periods of time that allow us to understand the system being studied (the *model period*) and also, the set of all model periods relevant to the understanding of a transportation system (the *analysis period*) and their relationship to each other. We note that the analysis period can contain multiple model periods within it and that these periods do not necessarily have to occur sequentially. Generally, the size of the analysis period is a function of the motivation for studying the transportation system and the nature of what is being studied. In other words, the study might require data about a short period or it might require data that covers an extended amount of time. For instance, an assessment the economic impact of the project over its lifetime might require an analysis period decades long whereas a performance assessment of a new on-ramp during rush hour might only require an analysis period of a few hours. Furthermore, the nature of the project itself can also determine the length of the analysis period. For example, if a new on-ramp's impact



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over time were to be studied but it happened that it was to be opened in increments over an extended amount of time, the length of the analysis period in this case would likely be considerably larger. As for the general criteria for determining the time-frame of the model period, the observed (or assumed) level of the variability in the transportation system's behavior and characteristics are of particular interest. This typically includes variations in the system's parameters, the nature of supply, demand, and how they interact, and the variables exogenous to the system. In all, if these behaviors or characteristics are observed or assumed to be stable, we consider the system to be *stationary*. Conversely, if only some behaviors or facets are observed or assumed to be stable, the system is considered to be *dynamic*. If a system is found to be stationary, it can be taken as a sign of the existence of an equilibrium of supply and demand within the system (in the broadest sense). In turn, this implies that a short model period can be used to generate results about a transportation system that are equally valid to those produced by a longer model period as the measured characteristic of the system and the time at which they are measured are independent of each other. Furthermore, it also implies that the results from a short model period can also be extended or extrapolated to any sized period including the entire analysis period. Alternatively, if a system is found to be dynamic, the system is assumed to have a partial system equilibrium. Here some of the elements of supply and demand remain in equilibrium while other elements change as the result of endogenous or exogenous factors.³³

3.2.3 Route Choice

The role of route choice models in the demand model is to establish how routes are selected by trip-makers. In all, this component is concerned with the process by which route preferences are established rather than the actual routes that are used. Moreover,

³³An example of the difference between full and partial equilibrium is a comparison of peak-hour traffic models with and without peak spreading. In both cases, the same number of cars is present during the model period, and supply and demand are in equilibrium. The key difference then is the dynamic nature of demand in terms of departure times.



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depending on the objectives of the modeler and the trip data that is available, the decision-making model in this component can consist of simple or naïve route-selection mechanisms or they can comprise a collection of sophisticated processes that model complex decision-making behaviors. Regardless of the complexity of the route choice model that is selected or the parameters that are used, the models consist of two basic components: route preferences that are established by a set of route attributes and characteristics and the information that is available to trip-makers regarding the network and its state. A variety of modeling dimensions can be defined for each of these components including: the inclusion of stochastic or dynamic model elements, the frequency of events and the order in which they occur, and the mechanisms by which the model is implemented. In terms of selecting a route choice model, their utility is, again, largely dependent on the nature of what is being modeled, the objectives of the modeler, and the limitation imposed by the lack of computational resources or data. As such, we limit the discussion of route choice models to that of a brief discussion of several key model facets: probabilistic decision-making, the nature of information about the transportation network, and trip planning and re-routing behavior. The first of these facets considers whether decisions are to be stochastic or deterministic in nature. In general, the stochastic approach is preferred as it more representative of decision-making that occurs in the real world and because it provides a more flexible modeling framework. More specifically, with respect to the latter point, in a stochastic framework, alternative choices can be more easily accommodated into the decision-making process, in both a practical terms and conceptually, in comparison to their implementation in deterministic frameworks. A drawback about stochastic approaches is that they can require substantial computational resources. The second model facet concerns determining the data that informs routing decisions and the nature of such data. For route choice modeling, the most relevant and important pieces of knowledge are that of the structure of the transportation network and that of the state of the network. The



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extent of knowledge of these features must be specified for all trip-makers. Furthermore, the nature of this knowledge must also be indicated particularly with respect to whether it can be updated and its availability. In general, the principal factor for determining the extent and nature of knowledge about a transportation network is the ability of trip-makers to learn about a transposition system or to possess historical knowledge about its structure and operations. The third issue, trip-planning and re-routing behavior, mostly addresses a combination of issues presented in the first two facets, however, it also adds an element of time. This has significant implications for the other two facets. For example, consider the addition of en-route route planning to a route choice model with stochastic decision-making. Without en-route planning, a stochastic route decision model will have trip-makers use different routes according to some probability distribution that is based on the relative attractiveness of the various route choices. With en-route planning, however, the stochastic nature of the route choice model is practically eliminated if the route adjustments are always adhered to. Also, if an efficient route has been found and learned, what would be the purpose of route planning technology? To conclude, the key components of route choice establishes a preference for routes, and the extent and nature of the knowledge of trip-makers with respect to the transportation system. Furthermore, it is possible to implement a variety of behaviors into a route choice model, however, the impact of the additions are often closely tied to other aspects of the model. Consequently, the development of general rules/guidelines for building or evaluating route choice models without knowledge where they will be applied is extremely difficult.

3.2.4 Demand Modeling Data and its Collection

Traditionally, trip data was collected through the use of massive survey studies where participants were asked for information about their trips. This data usually contained information about trip origin, destination, and trip-type and was used to create origin and destination (OD) matrices at the scale of transportation analysis zones (TAZs). Such surveys



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however were plagued by their high cost, were difficult to implement, and if data was collected, its uses and scope were very limited. In light of these limitations, other methods were developed in an attempt to measure or estimate OD matrices. One general approach involved the collection of traffic data whereby various traffic-measuring instruments were placed throughout a transportation network. Then upon the collection of sufficient traffic data (in terms of both volume and locational coverage), the collected data was *directly* used to produce “synthetic” OD matrices using a set of techniques known as *Origin and Destination Matrix Estimation* (ODME) Techniques. A second approach is the development of OD matrices via the use regional travel demand models. Here, coarse OD matrices are extracted from the travel demand model³⁴ and are then disaggregated with the use of traffic data. Finally, regardless of the approach that is taken, after the initial OD matrices are created they require calibration of some form to ensure that the OD matrices (or their more refined derivatives) can be relied upon for use in transportation models. The details of this process are covered in Section 4.2, however, we note here that this process often requires the collection of additional data. Depending on the calibration approach that is taken the data collection efforts might include: OD matrices generated by other models, traffic datasets not used in the OD matrix generation process (including those generated by different studies or with different technologies), or the collection of new traffic data. In terms of new data collection, we note that attempting a traffic-data collection effort similar to the initial one is an option, however, other alternatives exist and might often be more appropriate. In contrast to trip data, data for route choice models was both easy and difficult to collect. Data about the attractiveness of routes can be derived from the attributes and characteristics of their links. This data would then be assessed in a cumulative manner and then compared to the assessment of a different route.³⁵ As a result, the data requirements

³⁴ The coarseness of the OD data is the result of the scale of regional demand models.

³⁵ For instance, some methods calculate a weighted sum of a route’s travel time and the costs associated with traveling and compare them to one or more route alternatives in a standardized way (so as be able to



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for basic route choice models (those that only consider travel time and travel cost) are easy to meet. Enhancing these models is also possible through the use of econometric techniques and discrete choice models in order to establish the relative importance of each link attribute and property, as well as other factors. This requires additional data and might not be easily procured. The most difficult aspect of route choice model building involves collecting data about the knowledge of trip-makers concerning the structure and operational performance of a transportation network as well as the use of route planning technologies. Without survey data about the trip-makers in the study area, either existing datasets can serve as a proxy to generate an estimate or assumptions can be made about the use of route planning technology.

3.3 Traffic Assignment

The traffic assignment stage of the transportation system model is where we model the interaction between the components of supply and demand. More specifically, this involves the actual routing of vehicles on the network - a process that is subject to the trip demand (the trip origin, destination, and departure time), the structure of the network, and to the routing preferences and choices of the trip-makers. Traffic assignment models estimate the present state of a transportation system or some component of it (such as the levels of travel demand and its spatial nature), or attempt to measure the potential impact of changes in land-use or in transportation system. Underlying traffic assignment is the concept of an assignment equilibrium, which for now can be simply thought of as a stable pattern of vehicle routing, in the transportation system as a whole, which emerges after routing choices from trip-makers become gradually more consistent. The theoretical significance of assignment in equilibrium is that these patterns develop as the result of all trip-makers finding their best and stable route choices. This then allows modelers to

establish the relative attractiveness between paths). The path that had the lowest total weighted sum is considered the most attractive.



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measure the impacts of changes to the supply or demand by simply comparing the difference between systems when they are at their respective equilibrium.

3.3.1 Equilibrium in Traffic Assignment

Although the concept of equilibrium provides a solid theoretical foundation for transportation system analyses, there are various types of equilibrium that can occur given the nature of what is being modeled and the nature of the model itself. The implications of this is that a lack of knowledge about the relationships between what is being modeled, of how the model was constructed, or the modeling methods can result in the misinterpretation of a model outcome or simply result in the generation of a meaningless outcome.

User-Equilibrium and System-Equilibrium

The first important concept about equilibrium is to recognize the difference between *user-equilibrium* and *system-equilibrium*. The latter is based on the premise that maximizing the performance of a transportation system is the ultimate goal and as such, routing policies must be followed by trip-makers to achieve system equilibrium. Since compliance is expected from trip-makers, a regular pattern of vehicle routing occurs from which no one deviates, thereby forming a condition of equilibrium.

To understand the significance of this, consider that the underlying premise of user-equilibrium is that users are allowed to change their routing decisions so that route selection maximizes their own interests/utility. Consequently, this implies that in a user-equilibrium, a stable pattern will only develop once every trip-maker has made a routing decision such that no single trip-maker has an incentive to change their route choice. In other words, in user-equilibrium any unilateral³⁶ switch to another route by any trip-maker can only result in the trip-maker being at best no worse off. System-equilibrium requires the development of a routing policy, a very challenging task, in which the cooperation of

³⁶ It is assumed here that coordination and cooperation (even between two trip-makers) is not possible.



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trip-makers is required. This is unlikely due to incompatible incentives (trip-maker might be better off by deviating from the routing policy), and because of this it is not a model framework that is present in most transportation systems. Thus, we shall focus on *user-equilibrium* throughout the rest of the report with the exception of one particular model.

Static and Dynamic User-Equilibrium

The simplest version of user-equilibrium is formalized in *Wardrop's User-Equilibrium principle*³⁷ which states that *given a connected transportation network and a set of trips that correspond to the transportation network,*³⁸ *for all trips that have the same origin and destination, the generalized cost associated with their route choice will all be equal. Also, that cost will also be the lowest possible cost and no user will be able to unilaterally switch their route choice so as to lower their trip cost.*

We note that in Wardrop's User-Equilibrium principle there is no mention of time despite the fact that this principle can be extended into transportation networks with a temporal dimension. In effect, the issue of time in relation to Wardrop's User-Equilibrium principle results in the emergence of two conceptually distinct modeling approaches, *Static User Equilibrium* (SUE) and *Dynamic User Equilibrium* (DUE), with the latter approach incorporating time in Wardrop's principle and the former approach excluding it.

As previously mentioned, DUE incorporates time into Wardrop's principle through the addition of a temporal dimension to the transportation network.³⁹ This is achieved by appending temporal information to the transportation network by creating additional sets of nodes that represent the original nodes through time. This allows the possibility of trip-makers occupying the same location without co-locating by simply being there at different

³⁷ Wardrop, John Glen, and J. I. Whitehead. "Correspondence. Some theoretical aspects of road traffic research." *ICE Proceedings: Engineering Divisions*. Vol. 1. No. 5. Thomas Telford, 1952.

³⁸ Meaning that trips have a one defined origin node, one defined destination node, and that both of these nodes are located on the transportation network.

³⁹ So long as the temporal network is logically connected (e.g. no time travel, etc.) Wardrop's principle also holds as we can simply solve an isomorphic atemporal graph.



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times. As for links, the atemporal spatial links between nodes are removed and replaced with forward directed spatio-temporal links that preserve the spatial connection but only after crossing some time-period. This type of networks is commonly referred to as *diachronic networks*.

As for the Wardrop's principle through time, we only need to amend the principle to state that the *experienced travel time* would be the same for all trips that depart from the same location at the same time and that have the same destination. In other words, the trips leave from the same place at the same time and they arrive at the same destination at the same time.

Static and Dynamic Traffic Assignment

Although the SUE and DUE assumptions describe a condition of equilibrium regarding the route choices of the trip-makers and the associated costs of certain trips, they do not completely characterize, respectively, *static traffic assignment* (STA) and *dynamic traffic assignment* (DTA). In particular, they fail to either highlight or provide context about the some key aspects about the nature of traffic assignment in both models. Concerning static traffic assignment, one significant aspect about it is that ultimately the assignment of traffic occurs as if all trips happened simultaneously and instantaneously. The implication of this set up is that travel demand is inelastic thereby precluding changes to arrival or departure times. Furthermore, in terms of solving a STA problem with SUE, uncongested and congested networks can prove to be problematic. On one hand, if the network is uncongested in such a way that volume has no impact on link costs or travel times, an *all-or-nothing assignment* would be appropriate as it would assign all vehicles with the same origin and destination to the same (and shortest) route. On the other hand, using the SUE approach for STA with congested networks can also prove to be challenging as traffic assignments are sensitive to the levels of demand. This is problematic as increases in congestion result in the path costs or travel times determined by the SUE being less



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reflective of the actual experienced travel time of the trip. Lastly, this issue is further complicated as STA generally does not generate unique solutions in terms of path flows⁴⁰ which creates uncertainty as to how vehicles are routed. With dynamic traffic assignment with DUE, there are two key properties that are integral to its approach: the treatment of travel time and the implications of DUE for determining route choice. In DTA with DUE, trip-makers are allowed to postpone their departure without incurring any penalties (costs or time) as result of an emphasis on the experienced travel time rather than the amount of time. Thus, the travel times/costs generated by DTA and DUE are likely to closely approximate the “true costs” of the trip. As to how DTA with DUE is able to operate is through the use of consistent reevaluations of path costs which are in part calculated by anticipating the actions of trip-makers and the use of historical data about the transportation system as a whole. This leads to improved predictions about the transportation system’s performance however not without the use of significant computational power.

3.3.2 The Process of Traffic Assignment

Independent of the traffic assignment approach that is adopted, traffic assignment consists of three general phases – *route search*, *assignment of trips to paths*, and *trip loading*. In the route search phase, there is a search for the shortest path between all origins and destinations pairs of interest. This search process is repeated every time the network traffic data is updated. Subsequently, the second phase attempts to assign traffic to paths with the objective of establishing an equilibrium. Many methods have been developed to establish equilibrium in a variety of situations. In DTA, these methods include the Frank-Wolfe Algorithm, method of successive average (MSA), and gradient projection. The final phase, trip loading, is tasked with evaluating the traffic assignment

⁴⁰ SUE however does produce unique solutions for link flow values if the link cost functions are strictly monotonic.



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from the previous phase and determining if the assignment has converged to equilibrium, or whether further iterations of traffic assignment are required.

To measure convergence in DTA, the *relative gap* measure is commonly used. This measure functions by comparing the current path assignments to ideal path assignments, which consists of the shortest possible route that the trip could have taken. Then, if the cumulative difference between the assignments is below a certain pre-specified tolerance, the traffic assignment is assumed to have converged and no further iterations of traffic assignment are conducted. Alternatives to the relative gap method include other measures that are indicative of stability in the transportation network but not necessarily convergence to some equilibrium. Accordingly, these alternative approaches are necessary for the analysis of transportation systems experiencing certain conditions or exhibiting erratic behaviors. Examples of these conditions and behaviors include heavy congestion (including gridlock) and highly unstable travel times.

3.3.3 Non-Equilibrium Dynamic Traffic Assignment

The approaches to traffic assignment discussed above were all founded on some principle of equilibrium, however, there are many situations where traffic equilibrium would not be appropriate. Two prominent examples of this are models of unexpected events that require trip-makers to react to such events with limited guidance as to what to expect and also, models in which trip-makers have to make route choices solely based on their experience or on navigation devices. In the first situation, equilibrium cannot be established as there is inherently no information available that would enable trip-makers to anticipate future traffic patterns and behavior. Instead, the trip-maker is left to rely on limited and potentially useless information, such as historical traffic patterns, or is left to react constantly to developments in transportation system. As for the second situation, equilibrium is implicitly not desired by the model (at least in an immediate sense) as it is designed to study situations where the development of equilibrium is either gradual, limited, or prevented. More



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concisely, the conceptual underpinnings of non-equilibrium DTA are that route choice is dynamic, in the sense that routing decisions are re-evaluated by a trip-maker at some phase of his or her trip, and that the information that is provided for the route (re)evaluation cannot be used to anticipate the future state of the network.

Developing Non-Equilibrium Dynamic Traffic Assignment Models

The development of a non-equilibrium DTA model begins with the identification and characterization of the event to which trip-makers will react.⁴¹ This process includes specifying the location of the event, the time at which it will transpire, and how it will occur. The latter aspect includes determining the nature of the stimuli that will trigger the event, as well as, how the supply model might change. For example, an event can result in the closing or the shutdown of a lane (as with a car accident) or an entire highway. Alternatively, heavy automobile traffic on a freeway might prompt a designated lane to be repurposed for general use. Subsequently, the next tasks include outlining how the various aspects of the demand model will be affected by the event, including the nature of the traffic knowledge and information travelers will possess or have access to, and then determining how the impacts will be handled within the model. For this phase, it is difficult to establish what specific issues will require attention and what the mitigation plan, if required, should look like. None-the-less, insofar as general guidelines go, they include identifying any pre-existing or new modeling conflicts, such as those related to event induced changes to the model, and also, implementing solutions that are reasonable and consistent with both the nature of the event and with a larger plan about how any and all changes will be handled, particularly those affecting the demand model. For example, an event might result in an origin and a destination becoming disconnected thereby creating an unsolvable traffic

⁴¹ In the case that there is no explicit event that occurs (such as in models that have trip makers gradually learning the nature of a transportation system), the event of interest is simply the introduction of the subjects to the transportation system.



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assignment problem unless the destination is moved to a location that is accessible to the origin. If so, the location should then be, again, consistent or compatible with the nature of the event and the reaction to this change. For instance, consider a model of an evacuation related to a sudden and severe natural disaster. In the case that a citizen was driving home but could no longer reach it due to highway damage resulting from the disaster, that citizen's new destination should follow the evacuation plan rather than a different home (the logic being that the trip's motivation should remain unchanged) unless there is a strong reason to believe that the citizen will not follow the established plan. Non-equilibrium DTA models can begin with any type of traffic assignment approach or with the lack of one. Furthermore, each assignment approach can have some type of equilibrium conditions associated with it. In contrast, the traffic assignment procedures of non-equilibrium models lack any type of equilibrium conditions and furthermore, these assignment procedures are mostly all the same or at most, closely related. This is because most non-equilibrium DTA models use a *one-shot assignment* or a derivative. Fundamental to one-shot assignment is that information about the shortest paths in the network is continually being updated but that the updates are only "assigned" to travelers that enter the network at the time that the update was created. As a result, only newly generated vehicles possess the more recent traffic/shortest path information. Furthermore, the information assigned is derived from information about state of the transportation network exclusively from the very instant that the new traveler enters the network. The paths derived from this process are known as the *instantaneous shortest paths*. The reasoning behind this type of approach is that before departing, travelers would receive a final update about the state of the transportation network and use that to choose a route. Likewise, if the traveler was already on some path and some event occurred that required re-routing, the traveler would use the knowledge of the state of the transportation network just prior to the event to make route decisions. In light of recent advances in technology as well as the prevalence of many advanced



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navigation instruments (such as smart phones and in-car navigation systems), the assumptions of a “one-shot” assignment have been questioned. Consequently, some refinements have been developed in order to relax the “static” nature of route “assignment”⁴² by allowing travelers to update their knowledge about the transportation network’s “current” shortest paths at *decision nodes* located throughout the transportation network. Furthermore, such decision nodes should be located at points in the network where at least two distinct feasible paths emanate from that point and lead to a destination. Thus, this node would be a point where the traveler could refresh his or her knowledge about the state of the transportation network and then have the option to adjust their route choice. These two facets form the basis of “dynamic” “assignment” although the procedure as a whole is referred to as “Dynamic Assignment (with Feedback) in a One-Shot Simulation.”

4.0 Transportation Model Validity, Calibration, and Validation⁴³

The focus of this section is to give an overview of issues and methods related to detecting and correcting errors in our models (*model verification*), ensuring that the models we created are able to legitimately and accurately represent the system being modeled (*model calibration*), and lastly, testing the reliability and robustness of the model (*model validation*). Although many of the issues and methods could be presented in a more inclusive manner with respect to other transportation system modeling approaches, this section will concentrate on Dynamic Traffic Assignment and Micro-scale Simulation. Nonetheless, many of the principles discussed here will have applicability beyond these two modeling approaches.

⁴² The terms are quoted here as they are widely used transportation terms that, unfortunately, are homonyms of other common transportation terms.

⁴³ This section is based heavily on and the FHWA’s *Traffic Analysis Toolbox Volume XIV* (2012) and *Traffic Analysis Volume III* (2004).



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4.1 Model Verification

The ultimate goal of model verification is to minimize the number of errors related to setting up and running a transportation model. Furthermore, this process is the first step in determining the quality of the model and of the results that it generates. If a model is beset with numerous or significant errors, there is little reason to trust or rely on the outputs that are generated, particularly if the nature of these errors are unknown. In modeling traffic assignment, there are multiple points where error can be introduced. These errors can be categorized into three main classes, which are based on when the error occurred in the modeling process. The three classes include errors that occurred during the data collection or preparation stage, errors related to the coding of the model, and errors that result from bugs present in software used to run the transportation model.

4.1.1 Errors from the Data Collection and Management Process

The first point where mistakes can enter into the modeling process is when data is being collected or managed. Common errors here include recording incorrect measurement values, which includes forgetting to record them, conducting improper data conversions (in both a mathematical and computational sense), and lastly, mismanaging data in terms of properly maintaining and documenting its collection, editing, and storage.

At this phase, the most effective way to address these issues is to have well-developed plans about data collection procedures and how to handle any collected data. Then, it simply becomes a matter of carefully executing these plans and being vigilant about any irregularities that might arise.

4.1.2 Model Coding Errors

At this point, we presume that the data the modeler receives is correct and that any errors are due solely to mistakes in the coding of the model. As a result, the verification of model coding only requires that erroneously entered parameters/measurements or incorrectly constructed model elements be rectified. The following discussion shall cover some



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significant mistakes that commonly occur or that can be significant enough to cause concern.

Errors in Supply Models

The coding errors that occur in supply models are generally related to the connectivity of the network or the result of assigning incorrect properties to links. To begin, the most common types of connectivity errors include the omission of an existing connection, the addition of a connection that does not exist, and that of incorrectly setting the directionality of an arc. The effect of the first two is rather evident, however, that of directionality errors depend on the nature of the mistake and the software that is being used. One outcome is that there is simply not a connection where one is supposed to exist and another is that an irregular and non-existent connection is established. Connectivity errors, can (and do) occur in any part of a network, however, extra scrutiny should be placed in areas of the network that have complex or uncommon geometry and also, areas of the network that experience high volumes of traffic. Examples of the former include intersections and transition zones where the number of lanes increase or decrease. It is often easy to overlook connections in and out of highways, such as off and on ramps and connections with major arterial roads. The assignment of correct properties to links is often a difficult task given that links often contain numerous properties, and because the number of links in a model can be very large. As such, the complete assessment of all links in even a moderately sized network can be extremely time consuming or resource intensive for a modeler. Thus, to use time and other resources in an efficient manner, a modeler could place a greater emphasis on verifying the more critical properties of links and limit the verification efforts to the links that are most significant to the operation of a transportation network.

For modeling dynamic traffic assignment, the most important link properties are those that are strongly connected to the travel times/costs in traveling along a link as these can affect which route will be chosen as the shortest path when making a trip assignment. Thus, the



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link properties that should be inspected thoroughly are that of its speed limit, its use restrictions and the vehicle classes affected by such restrictions, the number of lanes it has, and lastly, the presence of any traffic control devices (such as stop signs and traffic lights) on it and the properties of such devices. Finally, areas that experience a high volume of traffic, major intersections, and areas where congestion can have a significant impact on traffic flow should be prioritized for scrutiny.

Errors in Demand Models

The verification of demand models is comprised of two main tasks: 1) verifying the OD matrix; and 2) verifying the characteristics and behavior of vehicles. Common errors associated with specifying an OD matrix include loading the wrong OD matrix and entering the wrong locations for the origin or destination. The former is typically a problem when multiple time-periods are being tested and the wrong matrix is sometimes loaded by pure chance. Likewise, the latter is generally the result of a random error.

In both of these cases, these errors can be identified with a careful review, however, when working with large OD matrices this can be a cumbersome task. Thus, if time or resource budgets are limited, the verification of origin (and destinations) with a high number of outgoing (incoming) vehicles should be prioritized focused on origins and destinations with greater traffic. As with the OD matrix, vehicle attributes and behavior data should also be reviewed via a close inspection. This is likely to require considerable effort as OD each OD pair needs to be verified in relation to the amount and types of vehicles that would make such a trip. Finally, if the OD matrix is large, verification efforts would likely have to be limited to those origins and destinations associated with high traffic volumes (or passengers), areas sensitive to traffic volume,⁴⁴ and areas with a significant number of

⁴⁴ The scrutiny of areas sensitive to traffic congestion should include those origin and destination areas associated with trips that contribute to the congestion. The problem here is that the identity of these additional ODs that should be investigated might not be immediately obvious without information about traffic assignment.



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special vehicles (such as large trucks or high occupancy vehicles).

4.1.3 Model Errors Resulting from Software

Modeling software oftentimes includes bugs that might produce errors in the model results. The nature of these bugs can range from the improper implementation of algorithms to those that result in the model terminating early because of a programming bug. For the bugs related to the operation of the software (as opposed to the operation of the model), not much action can be taken besides contacting the software firm to receive assistance or in the case of an open source program, attempting to find the bug and fix it. With bugs that affect the model however, many steps can be taken to identify bugs. The first is to find the software's page concerning known issues about the software. This step allows the modeler to avoid these problems and often, to learn about workarounds. The next step then, is for the modeler to test the software. One possibility is to run simple test cases on the software and observe whether any undesirable behaviors or incorrect results are observed or generated. These tests can be tailored to test issues that commonly arise when modeling traffic or to test issues known to plague the modeling software, as well as other rival programs. Again, depending on the nature of the bug, there might be a workaround or if not, the firm or programmers associated with the software will have to fix the issue.

4.1.4 Model Review with Simulation

This phase of the model verification involves the use of visual inspection of various types of model runs (simulations) in order to identity errors that might have eluded detection in the earlier phases. The visual and animated components of this process are particularly valuable as they allow us to identify many issues that would not be readily recognizable by extrapolating from model outputs. Furthermore, they allow for a more broad verification of many of the model's components by visually scanning the model simulation.

It should also be pointed out that this phase is a critical part of the verification of the model as it is the last review before the calibration phase begins. If mistakes manage to avoid



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detection here, they might be detected only after a substantial amount of time-consuming calibration, and possibly, after validation work has been completed. Such circumstances would require the re-calibration of the model to take place thus causing the modeling project to incur significant delays.

Model Review Tests

Two general types of tests exist for evaluating simulation models: *single-run testing* and *iterative-run stress testing*. The data inputs for these tests include the transportation model data. It is encouraged to use additional datasets (either real or synthetic) in order to reduce the chance that any error remains undetected. As for the difference between these two approaches, it is rather minimal as they employ similar methods, however, because of how the tests are ordered and structured, they will ultimately allow different analyses to be performed.

Single-run tests consist of running a series of iterations of the DTA model. This begins by using only a small fraction of the traffic from the DTA model with subsequent iterations using ever-larger proportions of vehicles. A key exception in this procedure is when a network coding error is found. Under such a condition, the coding error would first be corrected. Then, the process would start all over again, beginning with a small fraction of traffic to be assigned. In all, this process is repeated until the traffic levels reach the same level as that of the transportation model. In other words, the single-run test ends when an iteration of the model simulation has handled all demand and is completed error free. The design of the single-run test is set up in such a way that the more simple and obvious coding errors are caught in the early iterations. Because early iterations only use a fraction of the traffic from the full model, finding these errors early on saves a substantial amount of time. Furthermore, because of the number of iterations involved in this process, by the time that demand levels approach full demand, most (if not all) links and potential paths should have already been used in some iteration. Thus, if no errors are identified by the last iteration, it



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is almost a certainty that all obvious network-coding errors have been eliminated. With respect to the less obvious issues, the single-run test emphasizes carefully observing the loading and full clearing of the transportation network, and watching for traffic flow that is unusual in nature. During the network-loading phase, the main behavior or condition to search for is where queuing or excessive congestion forms. It is not that these situations are inherently an error, but they are of interest because their formation at this stage of the model is often an indicator of a coding error related to the capacity of a transportation network or to the level of demand assigned to the area in terms of volume or the rate at which vehicles enter the network. While the latter can be easily rectified by correcting demand parameter values, the lack of capacity is very problematic as its impact often includes significant delay in vehicles entering the network. Moreover, some modeling software simply prevents the entry of a vehicle into the network if its entry into the network is sufficiently delayed. Just as attention during the network-loading phase is focused on observing proper vehicle entry onto the transportation network, during the network-clearing phase, attention is focused on observing whether there is proper exiting of vehicles from the network. This is typically indicated by vehicles that remain within the network for an unreasonably long time and by vehicles avoiding routes that seem reasonably superior to the actual route choice. Often, unusual routing behaviors in the network-clearing phase are indicative of connectivity errors that reduce access such as a missing link error or the misconfiguring of a link such that it is rendered inaccessible or unattractive to the point that the link is not used. Also, vehicle behavior in route choices should be collected so as to determine the location of the network coding errors. The final component of single-run testing is to monitor the network for unusual traffic flow. Situations consistently exhibiting congestion for unnecessarily long periods are of interest here and in particular are those that only begin clearing at a relatively late point in the simulation. Such situations are indicative of a connectivity error.



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In comparison to single-run testing, iterative-run stress testing can be thought of a test of longer-term behavior. The basis of the model is to monitor a network for unusual behavior all the way through the development of an equilibrium condition. At this point, the model simulations do not stop but rather continue while looking for any unusual traffic behavior. Essentially, the objective of the iterative-run stress test is to assess whether unusual behaviors are short-term artifacts of the ongoing assignment process or a more long-term event resulting from a coding error. Thus, while conducting an iterative-run stress test it is important to be observing when the transportation model converges into equilibrium and to observe whether any unusual congestion remains despite the equilibrium conditions. Only when equilibrium is confirmed and unusual congestion remains significant can events be concluded to be the result of a coding error.

4.2 Model Calibration

The process of model calibration can be defined as a process that seeks to determine the set of model parameters which best allow the corresponding transportation model to reproduce the observed behavior of a transportation system of interest. Furthermore, the selected model parameters should also be able to replicate other instances of the transportation system's observed behavior in a statistically significant manner. In the context of a DTA, model calibration is very similar to that of other transportation models in that the calibration process considers links flow measures, including speed and volume, and the amount of queuing that occurs, as well as its intensity. However, because of the nature of DTA, additional measures related to trips are also considered. These measures include a trip's departure time and the route choice. Furthermore, the calibration of DTA models requires a more extensive consideration of spatial scale. As with any transportation model, a DTA model requires the modeling of an area of interest (the primary area). However, as previously discussed in Section 3, DTA models also require that areas outside of the primary



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area of interest (*secondary areas*) also be modeled if the interaction with the primary area and any secondary areas is significant. The implication for the calibration process is that data concerning the secondary area is not as detailed in comparison to that of the primary area. As such, the calibration efforts will be required to consider the nature between these two areas in light of this type of situation. This, however, is not meant to imply that the secondary area should always be further developed to compensate for the lack of fidelity or that the secondary area should also be calibrated. Rather the calibration effort only requires that the interaction be reflective of the interaction that is observed.

4.2.1 Defining the Scope of Calibration

The definition of calibration listed above emphasized two general goals for the transportation mode: 1) the model be able to reproduce the observed behavior of a transportation model as best as possible; and 2) the model should be robust enough to reproduce observations of the transportation system for periods following the observations used in the calibration process and also of the periods preceding such observations. Such goals however, are rather vague without an accompanying framework. In the discussion below, we offer a rough framework for determining the scope of the calibration process. This framework has two main components: 1) determining the objectives of calibration process, and 2) identifying and selecting the performance measures by which the transportation model's performance will be evaluated.

Calibration Process Objectives

The process of establishing the scope of a calibration procedure begins by first defining the objectives of the project and using these principles to develop a set of validation objectives for the calibration process. In all, the structure of calibration framework is geared to ensuring that the objectives of the calibration process all directly support the objectives of the project and that there are procedures developed to verify the calibration process itself. Furthermore, the calibration process objectives are evaluated in terms of whether they are



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compatible with the objectives of the project stakeholders. This process might require that the calibration objectives be revised if objections are raised by stakeholders against certain aspects of these plans. Nonetheless, once these calibration objectives are approved, then the more specific aspects of the calibration process can be determined. This task would include specifying the performance measures to be used, the spatial and temporal dimensions of the calibration procedure, and the methods by which performance measurements would be evaluated.

Identifying and Selecting Performance Measures

The first step toward determining what performance measures will be used in the calibration process is to determine whether a performance measures can be measured in the field and whether the modeling software being used can produce them as part of the model output. Simply put, the performance measure must be both collectable and a part of the model output in order for it to be a part of the calibration process. Without field measurements of the performance measure, the model output's measurements cannot be evaluated. Formally, if a candidate measure satisfies the requirements and is compatible with the project and stakeholder objectives, the measure is adopted. Once plausible performance measures are identified, the final step is to determine how the performance measures that were collected are to be compared to the results produced by the model's output. In selecting the method to perform this task, it is important to keep in mind that an exact agreement between the model and the field observations is highly unlikely, if not impossible, due to the stochastic nature of models (including DTA) and the natural variability of the data that is collected from the field. As such, the degree of variability in field data is first determined and then statistical tools are employed in order to establish amount of error or variability that would be tolerated in the transportation model.

4.2.2 The Calibration Strategy

The primary task of the calibration process is make adjustments to a model which so that it



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is better able to reproduce the observed behavior of the transportation system. Once the calibration processes' objectives, priorities and evaluation criteria are decided, the rules and a general guide to this task are established, then the calibration process to begin. However, because of the complex nature of DTA and transportation models in general, many issues often persist that require further guidance in order to address them *effectively*. The goal of this section is then to provide one possible framework for calibrating DTA models. To begin this discussion, we begin by recalling that DTA is a complex model that requires an extensive amount of information, a large part of which consists of the characteristics or parameters of many of the features in the model. Consequently, the sheer number of parameters would greatly hinder any effort to calibrate every parameter and furthermore, the complex relationships between parameters, as is usually the case in DTA, would make any such attempt effectively impossible (with the exception of small or trivial cases). In spite of these circumstances however, DTA can still contribute to the understanding of a transportation system. Through the careful selection of model parameters to focus on and the development of a coherent and systematic calibration process, the challenges facing calibration can be greatly reduced.

Selecting Parameters to Calibrate

One starting point for evaluating model parameters for the calibration process is to eliminate from consideration those parameters that are known to be set correctly with a high degree of confidence. This approach allows for a greater amount of attention to be allocated to parameters in which there is less certainty about them being set correctly. In addition, it should be noted that this policy could be adopted in a flexible manner in that not every parameter of a certain class needs to be excluded. For instance, features located in a critical point in the transportation network can have all their parameters examined but the same feature located in an isolated area can forgo having some of its parameters being reviewed.



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Another point to consider is the nature of DTA in that it is very sensitive to parameters dealing with traffic flow (link capacity and traffic speed) and route choices.⁴⁵ Thus, one potential strategy would be to prioritize the analysis and adjustment of parameters that most likely to affect or interact with these two parameters. Furthermore, this could also be extended to prioritizing facilities that can have a large impact on traffic flow or route choices. A potential downside to this approach however, is that overly emphasizing traffic flow can reduce the robustness of a model by ignoring other factors that are also important in DTA. For instance, travel times are a main determining factor in route choice in DTA and thus should often be checked in conjunction with traffic flow. Thus, when applying the method listed above, it is important to recall that in DTA, congestion is only important in terms of how it affects travel times and route decision. Finally, it should be noted that before correcting parameters related to route choice, all adjustments to link capacity should be performed first given that path-choice is largely dependent on traffic speed.

Calibrating Traffic Flow Parameters

As mentioned above, traffic flow is vital to the DTA and the calibration process for system performance. In addition, route choice is very closely tied with traffic flow. However, calibration is a complex process that requires an understanding how these parameters are collected and how to manipulate them directly within the context of DTA. To begin, the collection of traffic flow information for calibrating DTA models should be large enough to capture the extent of the data's variability, including periods of congestion and free-flow.⁴⁶ Furthermore, the data collection efforts should be focused on collecting information at key points and should be consistent with the type of location or facility at which the measurements are made. For instance, the measurement of capacity at a signalized

⁴⁵ Given their importance, these two parameters are discussed in more detail below.

⁴⁶ In a technical and practical sense, a link can have the same amount of flow despite there being different levels of congestion. This again is related to the principle that in DTA process congestion is only important by itself but rather in how it affects travel times and route choices.



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intersection must be based upon vehicle movement through the intersection as well as information about the signal parameters. In contrast, non-signalized intersections and facilities (such as highways and rural areas) simply require identifying where queues form and measurements of the rate at which the queue dissipates at specific times of the day. With respect to determining the maximum possible flow rate of a location or facility within a model, the process is based on manipulating input demand traveling through a link in order to measure the maximum possible flow rate of that link. The process simply requires the development of a queue by temporarily increasing the input demand of areas that are upstream for the location of interest. The necessary queue length will depend on whether the location is signalized or not. The process of calibration of capacity then requires that the modeled maximum possible flow rates and that the congestion in a model run are in agreement with field observations. Two types of complications however, can arise in a model run related to the presence or absence of bottlenecks that result from a misconfigured capacity parameter. In the first case, the model run does not show a bottleneck occurring where one should occur. To fix this, the input demands of the model are further increased until the bottleneck occurs and at which point the capacity calibration resumes. These increases must be removed before any route calibration occurs. Conversely, when bottlenecks occur when they have not been observed in the field, the local capacity has to be increased. It is important that no false bottlenecks remain after the capacity calibration process.

Finally, to measure the overall fit the model with respect to capacity a variety of statistical methods can be employed. One such approach is the use of goodness-of-fit tests that compare simulated and observed modeled speed estimates. Alternatively, one can use the mean squared error of the difference between the maximum achievable flow rates estimated through the model and the capacity measurements observed in the field as a measure of goodness.



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Calibrating Route Choice

The calibration of route choice is largely driven by the assumptions made about how drivers make routing decisions in general and about how they assess specific routes. The first facet includes the decision paradigm used by drivers for route decision making. An example would be utility maximization that only takes into account travel time and cost. Further considerations include whether some type of equilibrium is required (such as static or dynamic user equilibrium), the nature of information about traffic conditions accessible to drivers, and how any traffic information will be used by drivers for path choice decisions. Examples of different approaches to information include access to real-time information when making the decision and along the route or only allow route planning to occur before the trip. The approaches that are selected should produce global route choice behaviors that correspond to those observed in the field. As for the assessment of routes by drivers, the calibration is both global and local in nature. On the global scale, the considerations include setting the parameters for utility or generalized cost functions that result in cost or travel times that match those measured in the field. For the more local scale, the route selection from the model can be compared to that of actual route choices observed in the field. This is a particularly important step if local knowledge plays a large role in the route decision-making process. In addition to visual inspections, goodness-of-fit test or mean squared error test of model generated and observed link volumes can be used to evaluate the model calibration.

Calibrating Origin and Destination Matrices

Before discussing the process of calibrating OD matrices, the nature of such matrices must be established. Up to this point, references to origin and demand matrices have mostly referred to static OD matrices, which include ODT matrices. Dynamic OD matrices have been discussed (albeit not directly) within the context of some traffic assignment approaches.



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The fundamental distinction between static and dynamic OD matrices lies in the fact that dynamic OD matrices are not fixed whereas in the static case they are fixed. For the dynamic case, trips are allowed to vary in terms of their departure times.

Dynamic OD matrices are important as they are required for models implementing a dynamic user equilibrium approach. The implementation of such matrices is complicated, however, no general procedures have yet been developed that can be used with a wide range of matrices in terms of size and congestion behaviors. Consequently, many of these matrices are calibrated using procedures developed for static matrices but in an iterative process that moves the trip departure times forward or backward until the DTA model converges. The nature of these algorithms and other aspects of the convergence process are beyond this paper. With this said, we now turn our focus to the calibration of static OD matrices.

The calibration of static OD matrices begins with the estimation of these matrices. In this process, the objective is to produce an OD matrix from data that produces traffic patterns similar to those that are observed. Potential data sources for this process include raw traffic data or other OD matrices. Subsequently, the OD matrix is implemented into an assignment procedure and the results are compared to traffic measurements collected from the field. Then, adjustments are made accordingly to the OD matrix and the process is repeated until a good fit is developed. Although this process can be conducted manually, many methods typically automate this procedure. The process is commonly referred to as *origin and demand matrix estimation*.

System-wide Performance Calibration

The final step of the calibration process is to ensure that the system as a whole behaves according to the recorded observations of the transportation system. In the discussion above, many parameters were discussed in relation to calibration; nonetheless, many other parameters might need calibration for which guidelines could be developed. The issue with



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developing general guidelines, however, is that they can vary drastically depending on the nature of the parameter. Instead of describing many specific situations, we shall discuss a situation that is more general in nature: the use of performance measures to calibrate system-wide performance. Performance measures are the criteria by which to evaluate the model, in addition to standard measures such as traffic flows and route choice.

The calibration objectives should be selected in accordance with the project and stakeholder objectives. The importance of the calibration objective is that it specifies what deviations are acceptable when comparing the model generated performance measures and the observed field measurements. Depending on the nature of the performance measure, the process of attempting to meet these tolerances might affect the calibration efforts of other measures – most importantly those of traffic flow and route choice.

4.3 Model Validation

The final aspect of the model evaluation process is to determine the robustness of the model itself. Often, despite efforts and every intention to maintain a wide model scope, the assumptions adopted in the model, the inclusion/exclusion of certain parameters, or the nature of the calibration efforts might restrict any applications of the model beyond the situation it was designed to address. In any case, before a judgment of robustness can be made, the model must be tested with a scope defined. Tests of robustness simply need a second comparable and compatible dataset that was not used to calibrate the original model. Then, depending on the results of the new model outcome, the test can support the robustness of the model or not.

We note that the scope can also be limited to the exact situation for which the original model was developed. In such case, validation can be seen as an extension of the verification and calibration process in that it can provide additional feedback for improving the parameters used in the model. By using a second dataset, it is possible that a situation develops within the model that highlights a previously unknown error, or it can also suggest



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parameters that result in a better fit. A serious obstacle for these efforts however, is that additional high-quality datasets are not very common given the difficulty of collecting data. In contrast, high-quality historical datasets are often available and barring issues of incompatibility, they can be a part of the model's validation process. Moreover, if a model is able to replicate the behaviors of the present and the past, they are highly desirable. If a model can consistently replicate past system's behavior, then this is indicative of a model's ability to predict.

5. Traffic Assignment Modeling in VISSIM

In this section, we consider the development of both static and dynamic traffic assignment models in VISSIM. For purposes of brevity, it is presumed that the previous sections have been read, however, some concepts and definitions will be revisited in order to place them in the context of traffic assignment.

5.1 Supply Models

In *Section 2.2*, we discussed the construction and nature of the transportation network in VISSIM. To reiterate, both the transportation network and how it responds to congestion is largely exogenous to our transportation system model. However, pseudo-endogenous modeling of the supply network can be implemented in VISSIM by using an iterative modeling approach. Here, the outcome of a simulation run would be used to make changes in the subsequent iteration. Similarly, many modeling elements (such as Nodes and markers) that affect the TNG can be adjusted in an iterative matter.

For DTA modeling, VISSIM's approach to supply modeling allows for the construction of a very detailed transportation model, and consequently, calibration efforts must be very targeted and specific. However, both of these tasks can be very burdensome as some link parameters cannot be adjusted directly as they are defined in terms of driving behaviors or vehicle characteristic as outlined in *Section 2.2*. Therefore, to induce specific changes to a link, driving or vehicle parameters must constantly be adjusted until the desired behaviors



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are produced in the model. In addition, because driving behaviors or vehicle characteristics are defined for classes, changes to specific links require the definition of a new driving behavior or vehicle class, which is potentially very time consuming to accomplish if many links require specific changes. Conversely, system-wide changes to links are trivial as any changes to driving behavior or vehicle classes automatically apply to all relevant links.

5.2 Demand Models

The core components of demand are the *origin and destination* (OD) information and the *route choice mechanism*. The first includes the trip departure information for all trips taken while the latter determines how route preferences are determined and how routes selections are made. In VISSIM, the selection of the traffic assignment modeling approach is dependent on how each core demand component is represented within VISSIM. Additionally, the modeling approach selection for the OD information largely drives the selection of the route choice modeling approach. As such, both modeling approaches are selected simultaneously.

OD information can be inputted into VISSIM by the user through one of two previously discussed ways – one using VIMs and the other with PLZs. The fundamental difference between these two approaches is that with the VIM approach, only origins are explicitly defined whereas with the PLZ approach, both the origin and destination are explicitly defined. The information about origins and destinations is exogenous⁴⁷ in VISSIM and any adjustments to this component performed manually.

Similar to OD information, route choice criteria is also largely exogenous and its parameters must be defined by the modeler. In turn, the adopted OD modeling approach determines the type of parameter that is required. With the VIM approach, vehicle routes are predetermined and thus no route preference parameters are defined. Some

⁴⁷ Technically, dynamic traffic assignment can have the demand component of the model determine departure time endogenously, but in VISSIM, departure time is exogenous (although stochastic in nature).



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parameters are required to be defined however, if stochastic routes are implemented with VIMs. These parameters define the proportion of vehicles that will adopt a route if they enter the route as described in Section 2.2.4. In contrast, the PLZ approach requires the definition of a general cost function to evaluate the desirability of a route. Three parameter values are required in this function to specify the relative weight of travel time, travel distance, and financial costs within the general cost of a route. Also, if a route has any financial costs associated with traveling over one of its links, these parameter values must be specified as well. As for how route choices are established with PLZs, VISSIM uses a stochastic utility based approach based on the Kirchhoff distribution formula. In this calculation, the lower the general cost of a route, the higher the probability of that route being chosen, all else being equal. This formula includes an exogenous parameter, μ , where $\mu > 0$, which determines how sensitive the function is to differences in utility. Values of μ approaching 0 imply that the relative differences in utility between routes are increasingly irrelevant. Conversely, larger μ values imply that any relative differences in utility between routes increasingly matter.

5.3 Traffic Assignment

In VISSIM, the most basic type of traffic assignment possible is static routing. Here, information about every vehicle's origin, destination, and route choice is known and is directly implemented in VISSIM. The nature of a static routing model is that vehicles are not allowed to respond to changes in the state of the network, including levels of congestion, during a simulation or any other simulation thereafter. Vehicles are simply to follow the routes they were assigned. This is not to say that static routes can never factor in congestion or other network state criteria into determining route assignments. It is only that with a static routing approach such considerations must be made outside of the model. For example, empirical route choice data from commuters is likely to reflect route decisions that



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consider congestion due to commuters being familiar with an area's congestion pattern. In any case, static routing models inform us about how trips will unfold in terms of travel times and where congestion developed in the network, but they cannot explain how or why without more information or a model. While this limited scope is fine for many applications, other uses require more explanatory power. For the modeling of traffic, traffic assignment models provided that capability.

5.3.1 Static Traffic Assignment in VISSIM

Static traffic assignment (STA) as previously defined (Section 3.3.1) is not readily feasible in VISSIM due to the incompatibility between the assumptions of STA's of instant and simultaneous path selection and VISSIM's simulation based modeling approach. STA could be implemented in VISSIM but it would require determining the route choices outside of VISSIM. Solving STA requires the calculation of the instantaneous shortest paths and a mechanism to establish route assignments that collectively possess a *static user equilibrium* property but neither of these are features accessible in VISSIM. One plausible alternative to STA is using a static routing model with routes determined by a shortest path calculation, a model known as *all-or-nothing traffic assignment*. This approach would lack SUE however, and although reaching SUE could be attempted with an iterative assignment method, the tedious nature of this process negates STA's biggest advantage – its simplicity.

5.3.2 Dynamic Traffic Assignment in VISSIM

In contrast to static traffic assignment, *dynamic traffic assignment* (DTA) allows for the consideration of time in trip departures. As a result, DTA represents relaxing STA's assumptions that all vehicles leave at the same time and are comprised of fixed route choices, thereby providing a more flexible modeling framework. For example, by relaxing both assumptions, DTA allows for traffic assignment approaches with immediate feedback in which vehicles are constantly aware the congestion in the network and update their route



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choice accordingly (*a route guidance model*). Such a model is used to model a transportation system where vehicles are equipped with devices that have access to real time information about congestion. Other possibilities include DTA models with a *deterministic user-equilibrium*, which is essentially the same as dynamic user equilibrium only that departure times are fixed, and non-equilibrium models that, as explained in *Section 3.3*, are used to model situations where sudden events occur which require drivers to react by rerouting . In VISSIM, all three models listed above can be built, calibrated, and validated.

From a practical perspective, DTA also has its advantages. For one, VISSIM includes an automated DTA procedure that spares the modeler from manually coding route information – a significant issue in complex and/or large networks. Moreover, the assignment process can have the route assignments move towards converging and with minimal effort from the modeler. All that is required is that the modeler enters a few parameters regarding convergence. Such capabilities come at a heavy price however. Assuming non-trivial route choice criteria and non-trivial transportation networks, modeling with dynamic traffic assignment is computationally difficult due to the dynamic nature of the interaction between the supply and demand components of the transportation system. For instance, in the route selection process, a set of path choices from an origin to a destination must be created and evaluated in order to select a route. Given a sufficiently large network, the path set for an origin and destination can be enormous. Furthermore, the path creation process is complicated by the fact that the state/properties of the paths (i.e. cost, congestion) is a function of the path choices of other network agents or vehicles and how these paths interact through time thus introducing an even greater amount of complexity into this approach. Ultimately, as previously discussed in Section 3, the modeler must assess the tradeoffs between simplicity and complexity and decide whether DTA is appropriate or necessary to model the transportation system at hand.



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5.4 The Evaluating Dynamic Traffic Assignment Models in VISSIM

For the tasks of verifying and calibrating models, VISSIM provides a platform and an array of tools that facilitates finding common errors. One of its most significant aids is simply being able to visualize the transportation network, particularly during the simulation phase. It is possible to catch many errors here simply by scanning the network and looking for unusual behaviors. Furthermore, VISSIM provides a couple of visualization tools and viewing modes that accelerate the verification and calibration process. The Route Visualization tool for instance, allows one to visualize the assigned paths between an origin and destination pair, as well as the path's detours and non-converging paths. This feature facilitates the search for connectivity issues or links with faulty parameter values as the tool highlights missing paths and obviously incorrect path volume and cost information.

In terms of information reporting data, VISSIM is able to provide an extensive amount of information about system, path, or vehicle measures. It is able to report information, such as traffic counts or average speeds, from specific points as well as over intervals of various lengths (e.g paths and links). Additionally, VISSIM provides information in both an aggregate and disaggregate form thereby allowing the analysis of the transportation network at different scales.

All output data can be generated in a text format or in a database format. The information remains mostly accessible although the size of the dataset can make analyses more difficult without data analysis tools. For a variety of measurements, VISSIM provides a tool (Analyzer Reports) that collects and presents model measurements in a simple and organized document. One downside to VISSIM is that it lacks the capability to visualize the collected data as a map overlay even though this capability exists while the simulation is running. In all, VISSIM provides most, if not all, the tools needed to conduct the non-software related verification and calibration recommendations laid out in Section 4.1 and 4.2 without any issues or special considerations. Furthermore, its data collection tools



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allow for a wide variety of analyses to be performed with little effort. Finally, the provided visualization tools are limited in some respects and yet, the included visualization tools in conjunction with VISSIM's simulation approach are beyond adequate for detecting errors and calibrating DTA models.

6. Setting up Traffic Assignment in VISSIM

The directions in the guide below are written to provide an overview of the set-up for a static routing model, as well as, a dynamic traffic assignment model. This guide attempts to touch on all general principles and sacrifices detail for brevity. The reasoning behind this decision was that including additional material would almost amount to re-writing the manual. As noted in the introduction, the instructions are for VISSIM version 5.30 and although they might be compatible with subsequent versions of VISSIM, significant changes in VISSIM's platform might require that these instructions be altered.

A. Introduction

For the following sections, we presume that the transportation network graph is complete, in terms of having all links and connectors are located, connected, and loaded onto VISSIM. We also assume that all relevant type of vehicles classes for this model have already been constructed in VISSIM. For information on the coding the network please see Section 6.3.1-2 in the VISSIM manual and Section 6.4.1 for information about vehicle classes.

B. Static Routing

- I. The first step here is to place *vehicle input markers* at the all origin locations for vehicles.
1. This is accomplished by first visiting and clicking the Vehicle Inputs button located in the button toolbar [the button looks like a car stacked on a truck] in order to enable the editing of vehicle input data. One is now in Vehicle Inputs editing mode.



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2. Visit the link where vehicles will enter the network during the simulation process.
 3. Right-click a particular point on the targeted link, where vehicles will actually enter, to locate the vehicle input marker. *We recommend locating this point as close as possible on the beginning of the link (that is the side opposite from where vehicles would leave the link when they travel on it).*
 4. Repeat steps ii to iii until all locations where vehicles may originate from have a vehicle input marker.
- II. Next, the volume of departing vehicles and when they depart must be set for all vehicle input markers.
1. Confirm that one is still in Vehicle Inputs editing mode (see section A.a.i if unsure about this).
 2. To see the temporal and volume data of all vehicle input markers right click any point out the VISSIM network. This is the Vehicle Inputs box
 - a. *Double clicking a link that contains vehicle input markers will display the temporal and volume data of only the links located on that link.*
 3. The time intervals for which vehicles are to leave from are to be created.
 - a. First locate the Time subsection on the far right side of the Vehicle Inputs box.
 - This subsection contains the sets of intervals for which vehicle volume and vehicle composition information can be entered for all vehicle input markers.
 - The top number on the list represents the beginning of the first interval and the subsequent number below marks the end of the interval.



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- b. To add a time interval, right-click inside the Time subsection and select 'New' from the context menu that appears after the right-click. A new line should appear at the end of the list of the Time subsection.
- c. Enter a value in this new line in order to create a new interval break value.
 - If the new interval break value is greater than all values in the Time subsection, a new interval beginning at the former highest value in this section will be created and reflected on the subsection to the left of the Time subsection.
 - Otherwise, if the new interval break value (M) is between two existing interval break values (L and H where $L < M < H$), two new intervals will be created.
 - One of the new intervals is characterized by L as its lower bound and M as its upper bound while the other new interval has the lower bound M and an upper bound H .
 - *Note: new values cannot be equal to any of the values already existing in the time subsection*
- d. Editing of time values can be accomplished by selecting the time value to change with the mouse, typing in a new time to this line, and pressing enter.
 - The possible values for new edited value are restricted to a range equal to the interval break values that were immediately lesser than and greater than the interval break value that was modified.
- e. To delete intervals select the start time of the interval to be deleted, press delete, and confirm this decision with the prompt asking for confirmation.
 - Multiple intervals can be deleted by holding CTRL and selecting multiple interval values before pressing delete.



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4. Once the time intervals are developed, the volume and type of vehicles leaving the vehicle input markers must be defined. *The vehicle type of the vehicles entering the network must be defined in order for volume to be defined.*
 - a. To edit volume information select find the row corresponding to the vehicle input marker of interest by finding the link number of the link that the marker is located on.
 - Note: if there are multiple input vehicle markers on the same link, there will be multiple rows for each link granted that they all have at least 1 time interval where vehicle composition differs from all other input vehicle markers on that link.
 - Vehicle markers with similar vehicular composition throughout all intervals will be condensed into a single
 - b. Find a time interval column that is to be modified belonging to the target row selected in the previous step.
 - Click on the upper box of row within this time interval column and enter desired volume information is entered.
 - c. While remaining on the same time interval column, click on box below the volume information. This produces a menu where the vehicle composition of the vehicles leaving is determined.
 - d. Repeat steps 2-3 for all relevant time intervals columns for current row.
 - e. Repeat this process for all rows present in the Vehicle Inputs box.
- III. Next, we create routes and routing decision procedures.
1. This begins with the creation of a route
 - a. First we must enter Routes mode which is done by clicking on the Routes button [resembles a blue snaking line] in the button toolbar.
 - b. Click on the link or connector where the beginning of the route will be.



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- c. Right-click on a point on the targeted link or connector where the new route is actually to begin. This should create a red bar (also known as a routing decision point) on the selected point and a Create routing decision box should appear.
 - A type of route will be need to be selected at this point. The two types of interest are Static and Partial Routes. Understanding their function requires more information about the route design process and thus, they will be discussed in Step XXX of this subsection.
 - To edit the location of the routing decision point left-click the link where this point is located, left-click on the routing decision point, left-click on the destination link, and left-click on the desired location
- d. Select a destination link or connector for where the route will end.
- e. Right-click on a point on this new targeted link or connector where the new route is to end – a green bar should appear (a route destination point). If a connection exists between the selected route decision and destination points, a highlighted consecutive sequence of links representing a possible connection will appear⁴⁸.
 - If no consecutive sequence of links or connectors exists, no links will be highlighted.
 - *Note: A vehicle is committed to the route belonging to the first route decision point that it encounters until it reaches a route destination point that corresponds to this route decision point. Thus if another route decision point⁴⁹ is encountered before reaching the correct route destination point, the second route decision point will be ignored.*

⁴⁸ Routes are defined as a fixed consecutive sequence of links and connectors which contain a routing decision point and at least one destination point that is accessible from the origin point of the route.

⁴⁹ The exception here is partial routing points – a point discussed in Section 8 of this subsection.



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However, once a matching route decision point-destination point is completed the vehicle can now commit to a new route.

- [Optional] Editing a route emanating from a route destination point
 - Right-clicks outside the network and bring up the Routes window.
 - Double click on the routing decision belonging to the target route to highlight the target route.
 - Single right click an intermediate point on the highlighted route.
 - Move the intermediate point to some position in a new link and allow VISSIM to recalculate the link sequence. *Note: Intermediate points can be repositioned by dragging them to a new position*
 - Accept the changes with a single left click outside the highlighted route.
- f. [Optional] Multiple routing destinations points can be created for a routing decision point by selecting another link after establishing the first route destination point and again right-clicking somewhere in this link to place an additional route destination point.
 - Same rules apply regarding connection feasibility.
 - To manage vehicles when there are multiple destinations, once all destinations have been created, we bring up the Routes window.
 - Now select the tab at the top corresponding to the type of route we selected (Static or Partial)
 - Then we find the routing decision point of interest and click on it. This should update the boxes under the Decision box.
 - Define the proportion of vehicles that are to be headed to each possible route destination point associated with the routing



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decision point of interest by filling the box in the time interval column that corresponds to the every route destination point.

- [Optional] If these proportions are to vary through time, it is possible to add additional time intervals to allow the distribution of route destinations to vary through time.
 - Repeat for all routing decisions in both the Static and Partial tabs.
- g. Repeat Steps 2-6 as needed. However, if a new routing decision point is to be defined, double click on the network before proceeding Steps 2-6.
- h. *Note: The difference between a Static route and a Partial route is essentially that while Static routes ultimately control the origin and destination of vehicles, Partial routes are allowed to reroute any vehicles, that encounters the partial route's decision point, over a set of routes regardless of the route the vehicle might be committed to or the vehicle's destination so long as the detour allows the vehicle access to its original route. This is as once the vehicles exit at the Partial route's destination point, the vehicles then continue to their original route.*
- i. Routing decision points and destination points can be deleted from the Routes window by simply selecting either of the points and pressing delete.

IV. Simulation

Our model is complete and ready for simulation. To commence the simulation, press the 'Continuous' option in the 'Simulation' menu.

V. Post-simulation analysis

A variety of analyses can be performed using VISSIM. Here we present an abridged list of useful evaluations and its general type. For reasons of brevity, no instructions on their set-up will be included. See *Section 11* of the VISSIM



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manual for more details about setting-up each analysis.

- a. Travel Times – Travel time over an interval defined by two locations
- b. Delay Times - Congestion over an interval defined by two or more locations
- c. Data Collector – Aggregate vehicle data at a point
- d. Queue Counter and Vehicle Stops – Aggregate congestion at a point
- e. Vehicle Record – Individual vehicle data over a time interval
- f. Link Evaluation – Aggregated vehicle data over a link
- g. Node Evaluation – Aggregated vehicle data over an interval starting at a node
- h. Network Performance Evaluation – Aggregated vehicle data over time interval
- i. Vehicle input – Individual vehicle data over time interval

C. Dynamic Traffic Assignment

- I. The first step in setting up a Dynamic Traffic Assignment Model is to develop the Origin-Destination (OD) matrices and then enter them into VISSIM.
 1. The OD matrices used by VISSIM are stored in a “matrix file format” with the extension (.FMA). Thus an OD file would be named [file name].FMA.
 2. Comments in the .FMA files begin with a “*”
 3. Information required in the file is:
 - a. The time interval for which the OD matrix will be used (hh.mm).
This time interval is defined in absolute time. In other words,



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although 0:00 can represent any time of the day, it represents the beginning of the simulation (unless the absolute start time is changed).

- b. A scaling factor that can be used to scale the matrix globally
- c. The number of locations that are origins or destinations (zones)
- d. An index for all zones present in the OD matrix
- e. A matrix describing for each zone the destination volume of vehicles that will depart within the time interval defined for the OD matrix.
- f. Example file:

* time interval (hh.mm)

0.00 1.50

* scaling factor

1.0

*number of zones

4

*zones

1 2 3 4

*trips between zones

0 1 5 6

7 0 2 3

2 1 0 9

9 3 6 0

An example reading from file above is: Between 0:00 and 1:50, seven vehicles will depart from zone 2 for zone 1.



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- g. Note: Multiple OD matrices can be developed for a model and the time intervals than they are relevant for can overlap.*
- 4. Once the OD matrix files are done they must be imported into VISSIM
 - a. Select the TRAFFIC menu in the VISSIM task bar. Here DYNAMIC TRAFFIC ASSIGNEMENT will be an option in the drop down menu and should be selected.
 - b. Upon the appearance of the Dynamic Assignment window, check the matrices option.
 - c. Select *New* to load a directory menu and locate your matrix file in your system. The file should now appear in the Matrices box.
 - Matrix files can be deleted by simply selecting the target file in the Matrices box and press the Delete button.
 - d. Ensure that the Traffic composition is the correct one. If not click the target matrix file and press edit to modify the Traffic composition.
 - *Note: Desired speed attributes for the traffic created by the matrix will not adopt the values corresponding to the Traffic composition specified here but rather by the properties of the corresponding to the actual node/zone (the Parking Zone in this case) which vehicles emanate from.*
- II. After the OD matrix files are loaded, the transportation network graph has to be amended with parking lot zones (PLZs) and Nodes. PLZs will serve as origin and destination points for vehicles and Nodes are required for the of the abstract transportation graph.
 - 1. Identify location for PLZ



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- a. PLZ will be located on a link edge
- b. Routes cannot be established through PLZs
 - Try establishing Nodes on border of network.
 - If they must be located in the interior of the network, construct a link that is connected to the network and place PLZ on this link

2. Create Node

- a. Enter Nodes mode
- b. Create Node on the link the PLZ will be located and next to the specific location for PLZ
 - Right click in Nodes mode just above the link on which the Node and PLZ will be created and drag mouse to second point just below link.
 - Double right click on a third point located on the same edge next to where the PLZ will located
 - Ensure Node Evaluation and Dyn. Assignment boxes are checked
- c. Create second node next to PLZ opposite to the first Node.
Remain on the same edge.

3. Creating PLZs

- a. Enter Parking Lot mode (blue icon with a P).
- b. Select a link with a left click.
- c. Create PLZ by right clicking on a link at the desired location and dragging the mouse
- d. Only one PLZ can be located between two Nodes.



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4. Set up PLZ

- a. Note the No. and Name parameters. These are the nominal identifiers of the PLZ, *not* an origin and destination zone identifier.
- b. Select Zone connector or Abstract parking lot for Type.
 - Zone connectors allow vehicles to exit the network without slowing down whereas Abstract parking lots require that vehicles make a complete stop before they exit the network.
- c. The number in the Zone box within the Dyn, Assignment section corresponds to the zone number from origin and destination matrix.

5. Check Nodes and Edges for errors

- a. Enter Nodes mode
- b. Select Edit menu and click on Check Node/Edges option
- c. If error box appears, correct error.

///. The next step in constructing a DTA model is to specify the temporal parameters of the simulation. They will control how long the simulation will last and how often the network is to be evaluated.

1. Set up Simulation Period

- a. Select the Simulation menu
- b. Select the Parameters option
- c. Adjust simulation time parameters
 - Period – length of simulation
 - Start time – the nominal start time of the simulation



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- Simulation resolution – Time step(s) per simulation second
- Simulation speed – Simulated seconds per second

d. Click OK

2. Set up an Evaluation Interval

- a. Select the Traffic menu
- b. Next to Evaluation interval select a time interval (the units are in simulation seconds)
 - This interval value should depend on the output measurement detail that is required
 - Should be no more than half the size of the Simulation Period's length

c. Click OK

IV. Before we can begin our calibration phase, we need to specify the way in which routes are searched and the way route costs are evaluated.

1. Set-Up Route Costs

- a. Cost Coefficients for Travel Time, Distance, and Link Cost determine the general cost of a path. Each vehicle class is assigned a unique set of parameters.
 - Select the Base Data menu
 - Select the Vehicle Types option
 - Select the vehicle class of interest
 - Press the Edit option
 - Move to the Special tab
 - Under Dynamic Assignment select Cost Coefficients
 - Enter the desired cost coefficients



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- Repeat for all relevant vehicle classes
- b. Link costs have to be set on a link-by-link basis. Charges are set per km traveled on the link and they have up to 2 fixed surcharges.
 - Enter Links and Connectors mode
 - Double click on link of interest
 - Click on the Other tab
 - Select the Cost button
 - Set parameters accordingly
 - Repeat for all relevant links
- 2. Set-up Route Search
 - a. Route Guidance is a feature that allows a vehicle to reconsider their route decision at a fixed interval.
 - Select Traffic menu
 - Select the Dynamic Assignment option
 - Select the Route Guidance button at the bottom left side of the box
 - Keep *new route to destination parking lot* option
 - Set Offset and Route guidance interval to desired interval
 - Select the second Route Guidance if needed
- V. The initial calibration effort consists of developing a collection of paths to be evaluated by vehicles. VISSIM requires that they be found by vehicles and as such, we will adjust the model's path related parameters to encourage path search for now. Also, we need to store these costs so that we have path cost information to go along with the paths.



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1. Path Search

- a. Select Traffic menu
- b. Select the Dynamic Assignment option
- c. Store Costs
 - Check Store cost option is on
 - Select Exponential smoothing or MSA approach and enter the desired parameter
 - Exponential smoothing and MSA are two methods that use previous cost information to generate new path cost estimates
- d. Store Paths (and volumes)
 - Ensure Store paths option is on
 - Alter Kirchhoff exponent is required
- e. Search new Paths
 - Ensure Search new paths is checked
 - Select the Dynamic Assignment option
 - Press Extend button next to Search new paths
 - *Reject paths with total higher costs higher by than the total cost of best path* is off
 - *Search for paths for O-D pairs with zero volume* is off
 - *Stochastic edge penalization for alternative paths search* is on
- f. Correction of overlapping paths is on
- g. Avoid long detours is off

2. We are almost ready to run. The following settings are going to allow the network to load slowly. If the network is fully loaded, the path



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search process becomes more difficult. Thus we start with a small amount of vehicle and gradually increase the volume until we reach full demand

- a. Scale Volume and run model
 - Select Traffic menu
 - Select the Dynamic Assignment option
 - Scale Total Volume to is set to desired level
 - Press OK
 - Go to
 - Select Simulation menu
 - Select the Multirun option
 - Enter desired Number of runs and Dynamic Assignment Volume Increment parameter
 - Press Start

VI. Once this set of model runs is completed, we begin the main calibration process. At this point, we expect to have all the route information that we need and thus can stop searching for new routes. Furthermore, we need to define the convergence criteria will use in the model and the data outputs we want.

1. Turn off route search options
 - a. Undo all steps from step *C.iv.4*
 - b. Undo all steps from *C.v.1*
 - The exceptions here are: *C.v.1.f* and *C.v.1.e.v*; they stay the same
2. Set Convergence Criteria
 - a. Select Traffic menu
 - b. Select the Dynamic Assignment option



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TRACK II – Cross Cutting Modeling & Simulation Summary of Dynamic Traffic Assignment in VISSIM

- c. Click the Convergence button
 - d. Select desired convergence criteria and parameter
 3. Scale Volume
 - a. Select Traffic menu
 - b. Select the Dynamic Assignment option
 - c. Scale Total Volume to is set to 100%
 4. Evaluations
 - a. Select the Evaluation menu
 - b. Select Files option
 - c. Select relevant measurements
 - Consider those listed in *B.v.1*
 - Paths Evaluation – Aggregate vehicle data over a path
 - Convergence Evaluation – Aggregate vehicle data
(required if looking to have model converge to an equilibrium)
 5. Run Model
 - a. Select Simulation menu
 - b. Select the Multirun option
 - c. Enter desired Number of runs
 - d. Set Dynamic Assignment Volume Increment parameter to 0
 - e. Press Start
- VII. If convergence is being sought, the multirun will stop at the iteration that reaches equilibrium. A message box will appear and ask the user if they wish to continue. Otherwise, the model will continue running until all iterations are complete. The convergence statistics in this case can be inspected by opening the Convergence Evaluation file.



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Summary of Dynamic Traffic Assignment in VISSIM

- VIII. In terms of calibration, the model can be further evaluated to verify whether traffic patterns match or whether set performance criteria were met. The general procedures to follow are discussed in Section 4. As for the analysis of model data, this process will depend greatly on the nature and scope of the project. Such discussion is beyond the scope of this guide.



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TRACK II – Cross Cutting Modeling & Simulation

Cognitively Engineered Evacuation Routes

Cognitively Engineered Evacuation Routes

Micah Brachman

Introduction

After deciding to evacuate, the next choice an evacuee must make is which route to take. The presumed goal of each evacuee is to select a route that moves quickly and safely out of harm's way. The cognitive processes that enable an evacuee to meet this goal are complex and may differ for each individual. Yet in order to determine the best routes out of a hazardous area for an entire neighborhood, we must consider the route choices that all individuals make. One approach that a transportation engineer may take for determining the best evacuation routes out of a neighborhood is to formulate a mathematical model. Such models can represent the physical characteristics of a road network with great accuracy, but may use assumptions about evacuee route choice behavior that lead to inaccurate representations of traffic flow on a system of evacuation routes. One such assumption is that evacuees will choose the shortest distance route from their route origin to the nearest exit out of their neighborhood.

A network flow model that explicitly accounts for evacuee cognition may represent a system of evacuation routes during an event with greater accuracy than a model based



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solely on behavioral assumptions. In this paper, we first use empirical evacuation routes from a survey of wildfire evacuees to test common assumptions about evacuee route choice behavior and to determine which wayfinding strategies evacuees actually used. Next, we formulate a Cognitively Engineered Evacuation Routes (CEER) model, which can measure how the cognitive processes of wayfinding and environmental perception might impact traffic flow on a system of evacuation routes. By allowing the parameters of this model to vary stochastically, we can determine the locations of potential traffic flow bottlenecks while accounting for the uncertainties associated with individual route choice behavior. In the process of building and solving this model, we address the following research questions:

- 1) Do evacuees take the shortest distance route to the nearest exit?
- 2) What characteristics of the environment influence evacuee route choice?
- 3) Can a model that accounts for evacuee cognition represent a system of evacuation routes with greater accuracy?
- 4) How does behavioral uncertainty impact this system of evacuation routes?

This research paper represents a hybrid approach for modeling traffic flow during an evacuation. We borrow heavily from the conceptual and methodological frameworks of hazards, transportation engineering, and cognitive science. This approach allows for flexibility in both the questions we ask and how we answer them, with Geographic Information Science and spatial analysis providing the basic foundation. We hope that the



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results of this research can inform the design of future evacuation routing models, and assist emergency managers in the development of evacuation plans and implementation of traffic management techniques.



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Literature Review

1. Hazard Perception and Behavior

Within the discipline of Geography, the subfield of Hazards provides a basis for understanding human interactions with the environment. One goal of the hazards approach is to better understand the variability in perception of hazards to help determine the best response (Kasperson and Dow 1993). The environment is both a source of hazards as well as a resource (White 1945), thus perception of a hazard and its potential impact may be central to understanding human behavior under risk and uncertainty (White et al. 1958). The hazards approach often rejects models of decision-making based on strict economic rationality, but rather takes a behavioral approach in which perception and awareness dictate the boundaries on a range of choices (White 1961). This does not necessarily imply that people behave irrationally when faced with a hazard, but rather that the ability of people to understand the world around them and choose from appropriate courses of action is dynamic and uncertain (Simon 1957). While modern communication and geospatial technologies have given people access to extensive information about hazards that may help them make decisions (Iwan et al. 1999), psychology under conditions of risk and uncertainty still plays a critical role in determining the course of action they will take (Stone 2006, Coleman et al. 2011).



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2. Wayfinding

Wayfinding is the process of determining and following a route between an origin and destination (Golledge 1999). Determining and following a route may be influenced by how people perceive the environment around them (Golledge et al. 1995), thus they may use one or more wayfinding strategies to simplify the route planning process (Hirtle and Garling 1992). Laboratory and field research have suggested some general wayfinding strategies, including shortest distance, least time, and movement in the direction of the destination (Golledge et al. 1995), as well as choosing straighter routes rather than routes with many turns (Bailenson et al. 1998, Bailenson et al. 2000). These wayfinding strategies may allow people to find good routes when they lack the knowledge or capacity to find the best route possible. A study of wayfinding behavior for people trying to solve the classical traveling salesman problem found that their heuristic solutions were very close to mathematically produced optimal solutions (MacGregor and Ormerod 1996). One unique characteristic of emergency evacuations is the additional stress that evacuees may be under. Stress can interact with variables in the physical environment to influence cognition, but the specific role of stress in the wayfinding process is unclear (Evans et al 1984). Experiencing a certain amount of stress during an evacuation may actually allow individuals to process environmental information more effectively, but excessive stress may lead to distortions in information processing that can hinder route choice (Ozel 2001). Mathematical models of different wayfinding strategies can be used to study emergency evacuations (Lovas 1998),



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and can be formulated to account for the impact of environmental variables such as limited visibility due to the smoke produced during a fire (Jeon et al 2011). Other models have been used to measure how cognition may impact route planning (Rahman and Mahmood 2008) and have shown how environmental conditions may lead to more complex exit and route choice behavior when compared with a shortest distance strategy (Veeraswamy et al. 2009). There have been few studies that measure the impact of environmental variability on evacuation wayfinding in human subjects. One such study found that the presence of smoke and limited exit sign visibility have a significant impact on the routes chosen by people evacuating from a building fire, and concluded that empirical data plays an important role in developing explanations of evacuation wayfinding behavior (Kobes et al. 2010).

3. Network Flow Modeling

Determining the routes evacuees choose is one of the fundamental problems in evacuation planning (Yuan and Wang 2007), and network flow models are frequently used to estimate the amount of traffic flow on a system of evacuation routes. These models are often built on Wardrop's (1952) principles of route choice, thus use the assumptions that all evacuees will take the shortest available route (Hobeika et al. 1994, Yamada 1996) and that evacuees will always choose a less congested route if the shortest path route becomes too congested (Chalmet et al. 1982, Hobeika and Kim 1998, Langford 2010). Network flow models utilizing these basic assumptions are commonly used to generate “best case” evacuation routes and clearing times; thus, they are suited more for planning purposes than for the



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study of specific evacuation behaviors.

Researchers have addressed behavioral uncertainty by considering multiple objectives such as minimizing both the length of an evacuation route and the risk associated with using it (Alcada-Almeida et al. 2009), and tried to minimize evacuation time while accounting for the needs of priority evacuees whose limited mobility make them more socially vulnerable (Hamacher and Tufekci 1987). Other models have been used to examine the impact of egress points on network clearance time (Kalafatas and Peeta 2009), determined how to optimize traffic flow during staged evacuation (Liu et al. 2006b), and assessed the impacts of different behavioral response curves (Ozbay and Yazici 2006). Researchers have also attempted to account for the non-linear processes inherent in an emergency evacuation by allowing arc capacities to vary (Choi et al. 1988), developed algorithms to improve model solution time for large networks (Lu et al. 2005, Mitchell and Radwan 2006, Tan et al. 2009), and assess the impact of data uncertainty by testing models on random networks (Miller-Hooks and Sorrel 2008). One promising advance in network flow modeling is an explicit accounting for how physical hazard characteristics, such as the depth of floodwaters, may influence evacuation behavior (Liu et al. 2006a). Very few network flow models seek to address the uncertain nature of route choice during an emergency evacuation. This uncertainty has been attributed to both the inherent behavioral characteristics of evacuees (Fahy 1995) and to the geophysical characteristics of the hazard and road network (Yuan et al. 2006).



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4. Cognitive Engineering

Cognitive engineering uses the principles of cognitive psychology and related disciplines to inform the design of person-machine systems (Norman 1986). Also known as cognitive systems engineering (Hollnagel and Woods 1983) and cognitive ergonomics (Jorgensen 1990), this set of principles has principally been applied to the design of interfaces for computers (Gerhardt-Powals 1996) and other electronic devices. Recently, it has been argued that cognitive engineering principles should be applied to the design of geospatial decision support tools as well:

"Useful and usable solutions to people's geospatial problems can only be found by considering people's cognition, abilities, and strategies brought to the problem-solving process."

(Raubal 2009, p. 2).

One of our research goals is to use the CEER model to produce solutions to the problem of evacuating a neighborhood quickly and safely that are useful for both academic researchers as well as the fire, police, and emergency management professionals responsible for evacuation traffic management. The conceptual model shown in Figure 1 clarifies what we hope to gain by using the principles of cognitive engineering to design a system of

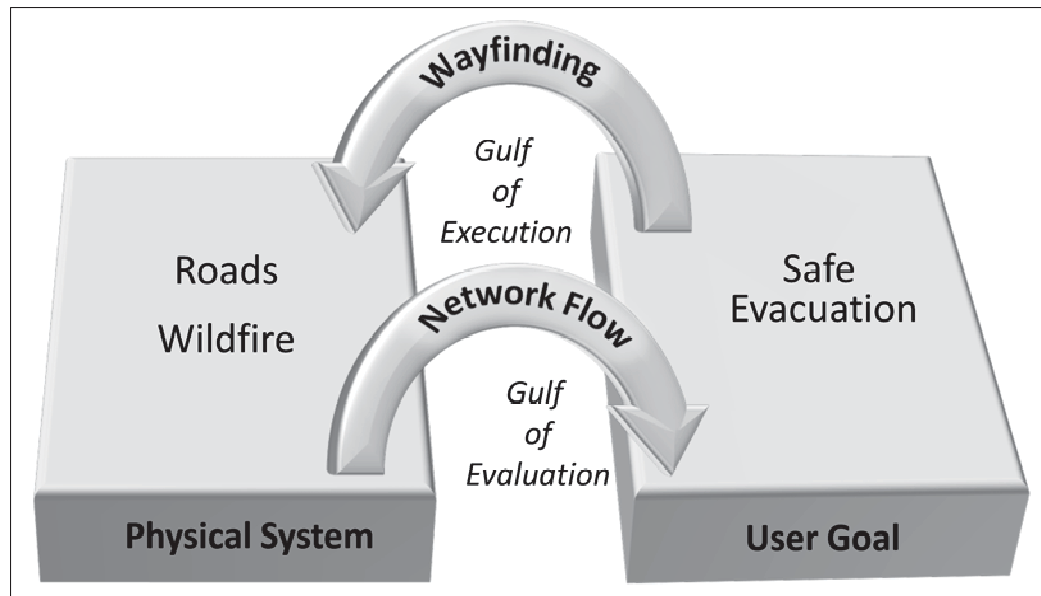
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evacuation routes. Most current approaches to modeling a system of evacuation routes consider either the route choice behavior of individual evacuees (i.e. user goals) or the physical characteristics of the road network and the hazard being evacuated from (i.e. physical system). The CEER model bridges the gap between these two approaches by considering the wayfinding strategies that evacuees may use to execute a safe evacuation in conjunction with the network flow models that academic researchers may use to evaluate the potential effectiveness of an emergency evacuation plan. By using the principles of cognitive engineering to design our CEER model, we hope to produce solutions to the problem of representing a system of emergency evacuation routes that accounts for the goals of both evacuees and those responsible for planning and managing the evacuation process.

Figure 1: Theoretical basis for the cognitively engineered evacuation routes approach, adapted from (Norman 1986).





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B. Data

1. Jesusita Fire Evacuation Routes

Our evacuation route dataset was collected using an online survey of people in Santa Barbara, CA who were affected by the 2009 Jesusita wildfire. Respondents were presented with an interactive map interface and asked to click each road segment that they traveled on when evacuating from the fire (*Survey Question QPATH*). This map interface was followed by a text box in which evacuees were asked to write a turn-by- turn description of their evacuation route (Q23)¹⁰. In order to develop a consistent dataset of evacuation routes, we established a set of rules to determine the validity of the evacuation routes provided by respondents. Our starting dataset of 141 routes includes every survey response where the respondent clicked at least one segment on the interactive map. We used two additional survey questions to help determine route validity. The first was an interactive map interface where we asked respondents to click on the road segment on which they live (QWHERE). The second was a text box where respondents were asked to enter the name of the street on which they live (QSTREET).

Route validity was determined by three basic rules: a) the route must have a valid origin node, b) all nodes in a route must be connected by a series of single links thus forming a completely connected path, and c) the route must have a valid destination node. Route origin



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was determined by applying the following four specific rules to our initial set of 141 routes:

- 1) If QPATH contains QWHERE, QWHERE is the route origin
- 2) If QPATH contains QSTREET, QSTREET is the route origin
- 3) If QWHERE is the first street named in Q23 or connects directly to the first street named in Q23, QWHERE is the origin
- 4) If QSTREET is the first street named in Q23 or connects directly to the first street named in Q23, the segment of QSTREET that connects directly to the second street named in Q23 is the route origin

These rules effectively limit selection of evacuation routes to respondents who evacuated from their current place of residence. One important group of respondents that is excluded using these selection criteria is evacuees who moved to a new place of residence after the fire, a group that includes evacuees whose homes were damaged or destroyed. To account for these people, we introduced one additional rule to establish a valid route origin:

- 5) If the first street named in Q23 is in QPATH, the first street named in Q23 is the route origin

The next set of rules was used to connect routes that had segments missing. Many respondents reported some difficulty zooming in and out with the interactive map interface, thus did not click very small street segments. These segments are needed to have a fully connected route; thus, we added these segments to the route if they meet the following criteria:



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- 6) The sum of QPATH segment distances is greater than or equal to 80% of the sum of all segment distances needed to fully connect the route
- 7) Each gap in QPATH can be filled by adding no more than two segments

We generated 61 fully connected routes using these criteria. Many of the remaining unconnected routes had gaps that exceeded the 80% distance and two link criteria, thus we used the turn-by-turn route description provided by respondents in Q23 to connect these routes using the following rules:

- 8) If the first or second street mentioned in Q23 directly connects to the route origin, the link of that street that directly connects to the origin is added to the route
- 9) If the next street mentioned in Q23 directly connects to the street added in the previous step, the first link of this street and any intermediate links needed to connect these two streets are added to the route

The previous step is repeated until either the streets mentioned in Q23 do not directly connect or a terminal node of our study area network is reached. Forty-seven routes were modified using these rules. A final set of rules were used to remove street segments that



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were accidentally clicked by respondents.

10) If an arc is not connected to any other arcs in the evacuation route, it is removed.

11) If a route contains branching arcs, these arcs were removed unless they were explicitly named by the respondent in Q23.

After applying this set of rules to our original survey responses we identified ninety-seven evacuation routes.

2. GIS Data

We collected several GIS data layers in order to assess environmental and physical road network characteristics present during the Jesusita Fire evacuation. Several fire perimeter polygons representing the location of the Jesusita Fire at different points in time were obtained through the County of Santa Barbara online GIS data catalog. These polygons were generated while the Jesusita Fire was burning by personnel from the California Department of Fire and Forestry Protection. To determine elevations in our study area, we acquired the United States Geological Survey 7.5-minute Digital Elevation Model (DEM) covering Santa Barbara. This DEM was produced as part of the National Mapping Program, and has 30 by 30 meter grid cells. We also obtained a shapefile showing private roads in our study area from the Santa Barbara County Department of Planning and



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Development, and a road shapefile with street names, address ranges, and speed limits from the Santa Barbara County GIS office. Finally, in order to estimate the population of our study area we obtained a cadastral shapefile from the Santa Barbara County assessor's office.

C. Methods

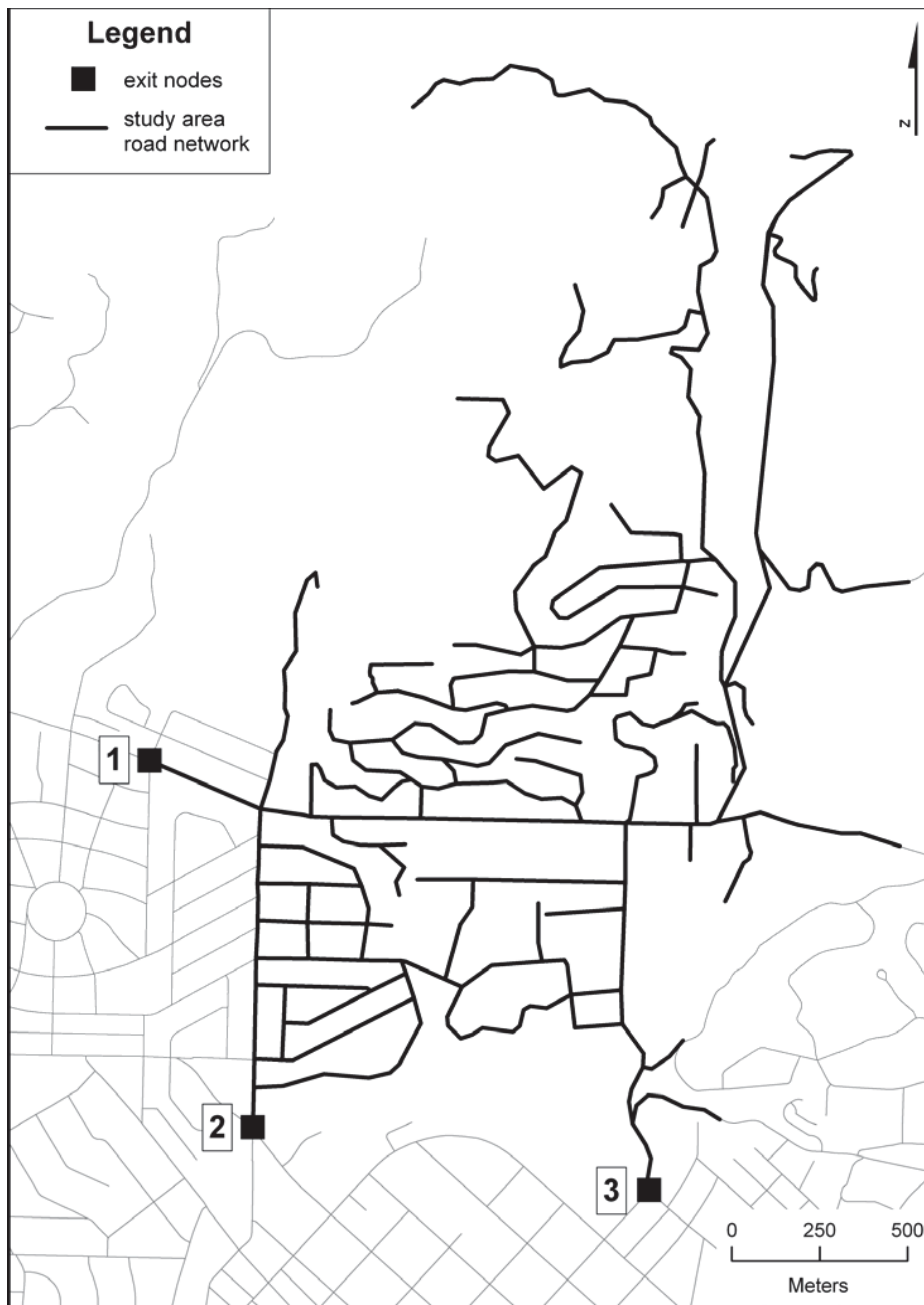
1. Route Comparison

The first research question we address is whether Jesusita fire evacuees took the shortest distance route to their nearest exit. We used Dijkstra's algorithm to calculate the shortest distance route from each evacuee's origin node to each of three different potential network exits. The network exits we selected represent the intersections of major roads in our study area (Figure 2), and were the three most heavily used exits based on our Jesusita fire survey data. We selected the shortest of these three routes for comparison to our empirical Jesusita Fire evacuation routes. Twenty-eight (29%) evacuees took the shortest distance route to their nearest exit, while sixty-two evacuees (64%) took evacuation routes that were longer than the shortest distance route to their closest exit.

The remaining seven evacuees (7%) selected network exits at a minor side street, thus traveled shorter distances than if they had selected one of our three designated network

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Figure 2: Jesusita Fire study area road network





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exits. Of the sixty-two evacuees who took routes that were longer than the shortest distance route to their nearest exit, sixteen (26%) choose the nearest exit but took a longer route to get there while forty-six (74%) choose an exit that was not the nearest to them.

From this analysis we can conclude that a majority of Jesusita Fire evacuees did not take the shortest distance route to their nearest exit, and that the primary reason for this was that evacuees selected an exit other than the closest exit to their starting location.

Why might evacuees choose a more distant exit? One factor that may have contributed to the choice of a more distant exit is traffic congestion. Although we do not have direct empirical measurements of traffic congestion at the time of the evacuation, we did ask evacuees about their perception of traffic congestion with the following survey question:

How would you describe the traffic conditions you experienced
while you were evacuating?

- a. Gridlock
- b. Heavily congested
- c. Moderately congested
- d. Lightly congested
- e. Free flowing
- f. Don't recall

Our analysis of responses to this question shows little evidence that evacuee perception of congestion contributed to selection of a more distant exit. Overall, 69% of evacuees characterized traffic conditions as 'Free flowing' or 'Lightly congested' while only 15% characterized traffic conditions as 'Heavily congested' or 'Gridlock'. Of our evacuees who



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did not choose their closest exit, 74% characterized traffic as 'Free flowing' or 'Lightly congested' and 9% as 'Heavily congested' or 'Gridlock'. Evacuees who choose their closest exit selected 'Free flowing' or 'Lightly congested' 68% of the time and the later two categories 18%. Of course the implicit assumption in this analysis is that evacuees would select a different exit node while evacuating if they experienced heavy traffic congestion. In our survey we asked evacuees if they changed their route while evacuating, and found that 84% did not.

Another factor that may have contributed to evacuees choosing a more distant exit is elevation. Our study area is in the foothills of Santa Barbara and there is a wide elevation range, with a high point of 309 meters above sea level and a low point of 70 meters. We hypothesize that evacuees selected exits that are at a lower elevation than their closest exit. One possible reason for selecting a lower elevation exit is that these exits connect to the major arterial streets of Santa Barbara, thus providing evacuees more routing options to their final destination. Another possible reason is that like many wildfires, the Jesusita Fire started at a higher elevation then spread downhill towards more densely populated areas. Evacuees may have perceived lower elevation exits to be safer because they seemed further from the fire. To test this hypothesis, we assigned each exit node the elevation value of the DEM grid cell within it falls. We find that on average, evacuees select exits that are 4.2 meters lower than the nearest exit. Although this difference is small, a one sample t-test reveals that it is statistically significant ($p\text{-value} < 0.001$), thus we can conclude that Jesusita fire evacuees selected exits at lower elevation than their closest exit.



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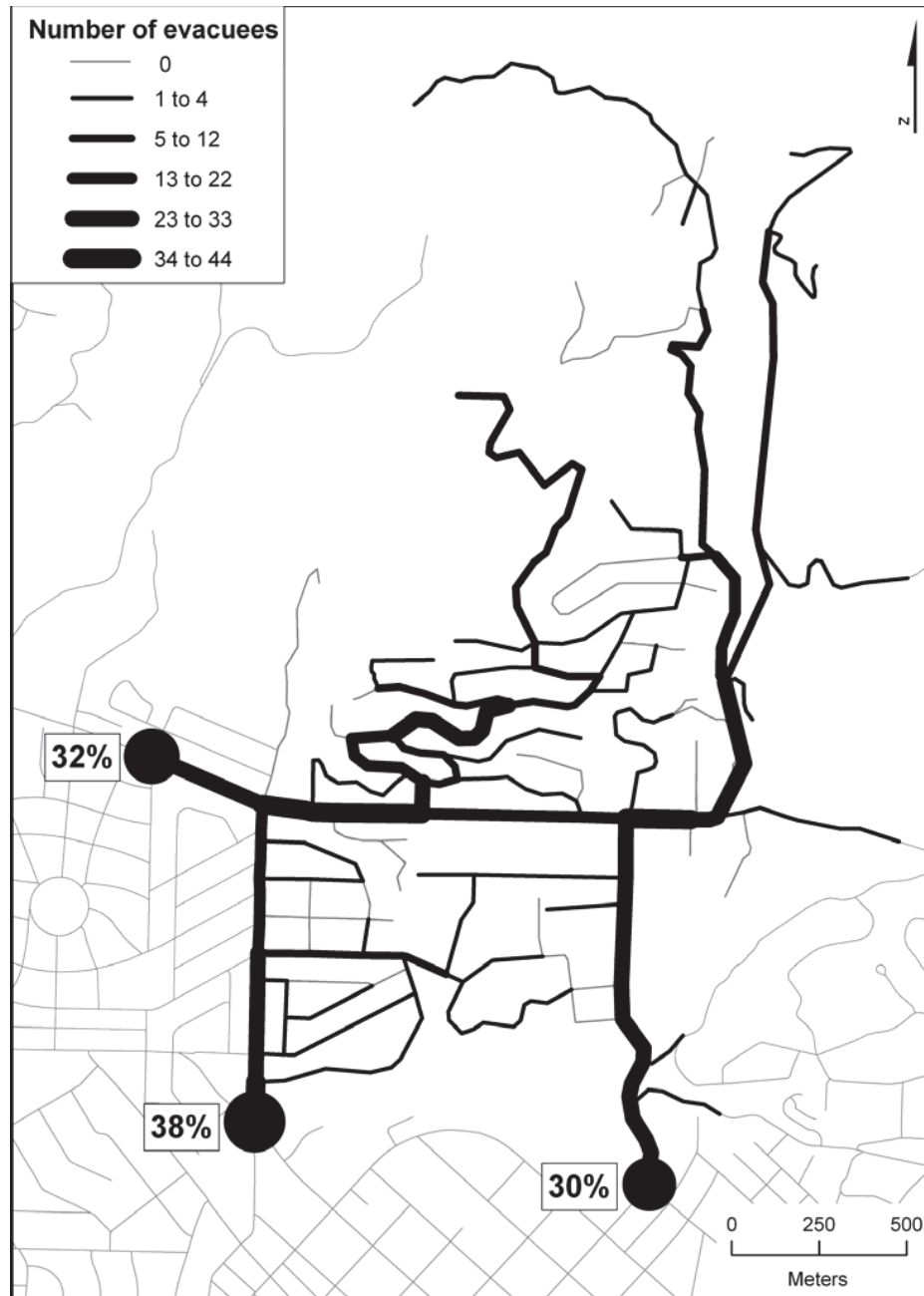
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The last hypothesis we tested is that evacuees selected exits that were further away from the fire than their closest exit. We used shapefile polygons showing the location of the Jesusita fire to calculate the distance from the fire to each survey respondent's exit node at the time of their evacuation. On average, evacuees chose exits that are 30 meters further from the fire than their closest exit. A one-tailed t-test indicates that this difference is not statistically significant ($p\text{-value} > 0.1$). One reason that this difference may be statistically insignificant is that evacuees choose exits based on their relative distance from the fire rather than their absolute distance. We determined relative fire distance values by calculating how much further away each exit is than the exit closest to the fire at that time period. Comparison of these relative values reveals that on average evacuees prefer exit nodes that are 42% further away from the fire than the exit closest to the fire. These data do not follow a normal distribution, thus we performed a Wilcoxon signed rank test, and determined that this difference is not statistically significant ($p\text{-value} = 0.11$). Based on these tests we can reject the hypothesis that evacuees will select exits that are further away from the fire than their closest exit.

The selection of an exit is a critical step in determining the route an evacuee will take. We can see from the analysis presented above that during the Jesusita Fire, the elevation of exits may have been an influential factor in the route selection process. We can visualize the impact of exit selection on evacuation routes by comparing two maps. The first map (Figure 3) shows all routes used by Jesusita Fire evacuees aggregated to each street segment in our study area.

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Figure 3: Jesusita Fire evacuation routes





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This map indicates a relatively even distribution of evacuees to destination nodes, as well as an even distribution of evacuees on the roads leading into these nodes. The second map (Figure 4) shows the shortest distance routes to each evacuee's nearest exit, again aggregated to the street segment level. We see that the distribution of evacuees to exit nodes is not balanced, but rather favors the exits at Foothill Rd and Alamar Rd (39% of total evacuees) and Los Olivos (47%) over the exit at State St and Alamar Rd (13%).

The distribution of evacuees on the roads leading into these nodes is not balanced either. Perhaps most striking when comparing these two maps is the differences in traffic flow on many streets throughout the road network. Thus, it is important to investigate not only the exit node selection process for Jesusita fire evacuees, but the street segment selection process as well.

We have established that a majority of Jesusita fire evacuees did not choose their *closest* exit. Therefore, it makes little sense to investigate the street selection process using the shortest distance routes to their nearest exit. We used Dijkstra's algorithm to calculate each evacuee's shortest distance route to their *chosen* exit. Separating out the exit node selection process may allow for a less biased measurement of factors that influence the selection of street segments along an evacuation route. Of the ninety-seven evacuation routes obtained from our survey respondents, forty (41.2%) are not the shortest possible in travelling from their origin node to their chosen exit node. The greatest distance difference between an evacuation route and a shortest distance route is 1072 meters, and the average distance difference between an evacuation route and the shortest distance route is approximately

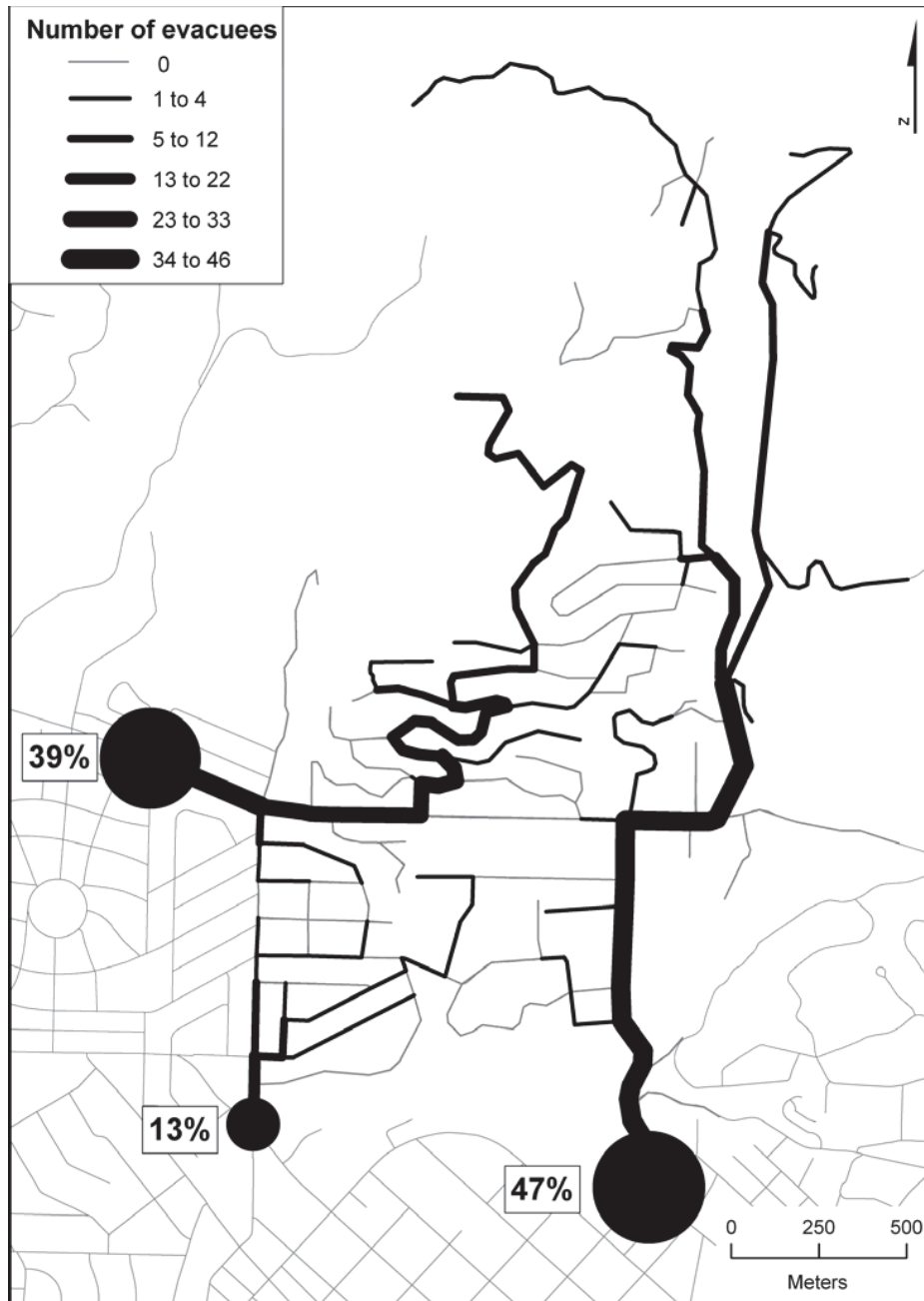
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158 meters.

Figure 4: This map shows the shortest distance routes to each evacuee's nearest exit.

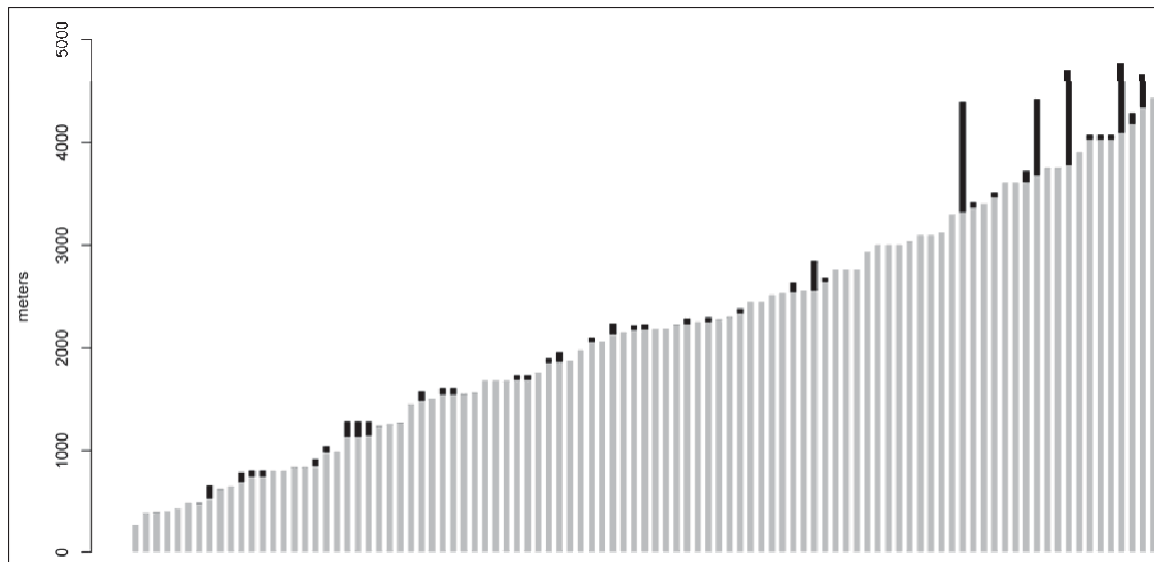


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Figure 5: Jesusita Fire evacuation routes and shortest distance routes. The grey bars show the length of shortest distance routes, and the black bars show the additional distance traveled by evacuees who did not take the shortest distance route to their chosen destination.



A plot showing the distance of each evacuation route and its corresponding shortest distance route (Figure 5) reveals that a majority of distance differences fall below this average, with a few outliers where this difference is significantly greater. From these data we may infer that most survey respondents who did not choose a shortest distance evacuation route did choose a route with a slight distance difference. It is important to note that multiple shortest paths may exist between an origin and destination, thus it is possible that evacuees chose a route that utilized completely different links and nodes than the single shortest path route we calculated with Dijkstra's algorithm. While it would be possible to assess evacuee link and node choice and determine if alternate shortest paths were used during the evacuation that is beyond the scope of this analysis.



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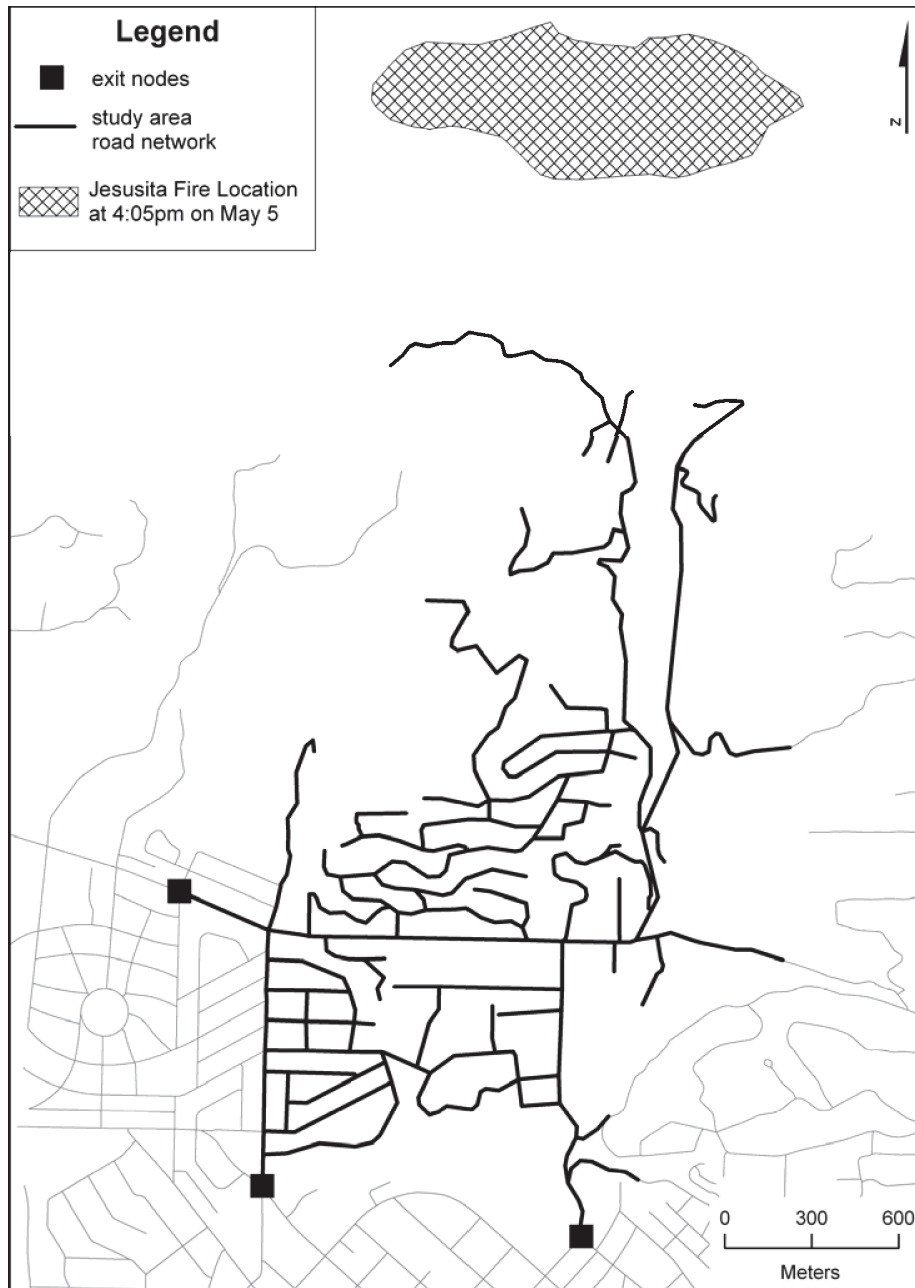
Cognitively Engineered Evacuation Routes

Why do evacuees choose a route that is longer than the shortest distance between their origin and chosen exit? One of the most intuitive answers to this question is that evacuees prefer routes that may get them to their destination more quickly than the shortest distance route. While a majority of the streets in our study area have a posted speed limit of 25 miles per hour, several of the major arterials have speed limits of 35 mph. We hypothesized that evacuees chose routes that have a higher posted speed limit than the shortest distance route. To test this hypothesis, we obtained speed limit data for every street segment in our study area using both GIS data and field observations. We then calculated the average speed limit for each evacuation route and compared it to the average speed limit for each corresponding shortest distance route. On average evacuees select routes with a speed limit that was 0.4mph greater than the shortest distance route. This difference may seem small, but a one-sample t-test reveals that it is statistically significant (p-value <0.01). We can accept the hypothesis that Jesusita fire evacuees chose routes with a higher posted speed limit than the shortest distance route.

Another factor that may influence evacuee route selection is the direction of travel. Evacuees may favor street segments that lead them directly away from the fire rather than street segments that are moving perpendicular or towards the fire. We tested this hypothesis by calculating the azimuth of each street segment in our study area. An azimuth of 0° represents a street segment that points due north while an azimuth of 180° is due south, while azimuths of 270° and 90° are due west and due east, respectively. A map of the earliest recorded Jesusita fire perimeter (Figure 6) shows that fire was north

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Figure 6: Jesusita Fire location on the day the fire began





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(0°) to northeast (45°) of our study area. It follows that evacuees might choose routes that utilize street segments heading due south (180°) to southwest (225°) to move directly away from the fire. The average azimuth of routes chosen by our evacuees is 210.5°, while the average azimuth of the shortest distance routes is 211.3°. A t-test reveals that the difference between these azimuths is not statistically significant ($p\text{-value} > 0.1$) thus we cannot conclude that the direction of street segments influenced the route selection of Jesusita Fire evacuees.

One unique feature of our study area road network is that there are both public and private roads. Public roads are owned and maintained by the City or County of Santa Barbara and are freely accessible to anyone. Private roads are owned and maintained by private landowners, and may feature physical barriers to entry such as locked gates or perceptual barriers to entry such as 'private road' or 'no trespassing' signs. Some of these private roads provide the only connection between homes or subdivisions and the public road network, thus evacuees had no choice but to drive on them. Other private roads pass through private property but connect two or more parts of the public road network. Private roads of this latter type can theoretically be driven on by anyone, provided that there are no physical barriers to entry or egress. Yet, many people might be unaware that these private roads actually connect two public sections of the road network, or might be dissuaded from driving on them by warning signs or other perceptual barriers.

We believe that utilization of connecting private roads may influence whether an evacuee



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takes the shortest distance route between their origin and exit. Two such roads in our study area are Glendessary Lane and Mission Park Drive. Glendessary Lane connects to Mission Canyon Road, a major arterial route through our study area. Multiple signs are posted at the entrance to Glendessary Lane indicating that it is a private road and a dead end, but there are no physical barriers. While it is indeed a private road, Glendessary Lane actually connects to Mission Park Drive, another private road which in turn is connected to a public street, Puesta Del Sol Road. Three Jesusita Fire evacuees chose to drive on Glendessary Lane and Mission Park Drive, and two of these three evacuees chose the shortest distance route from their origin to exit. Perhaps more striking is that four evacuees who did not take their shortest distance route could have if they had chosen to drive on these two private roads. These four evacuees could have traveled a total of 371 meters less if they had used Glendessary Lane and Mission Park Drive. While the sample size for private road utilization is too small to test for statistical significance, we believe that it is important to consider the impact of private road utilization issue when modeling evacuation traffic flow.

2. Network flow

In the previous section, we uncovered several wayfinding strategies that evacuees may have used during the Jesusita Fire. It is clear that while distance remains the primary factor when choosing an evacuation route, the elevation of road network exits, speed limits on street segments, and utilization of private roads all may play a role. Our previous analysis was focused on understanding the evacuation route choice process for an individual or



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household. These results help us develop the Cognitively Engineered Evacuation Routes model (CEER), which can be used to predict evacuation traffic flow at the aggregate level. While many aggregate approaches consider only distance or travel time, our approach is unique in that we account for the individual wayfinding strategies used by Jesusita Fire evacuees:

- i, j index of network nodes
- A set of directed arcs connecting i, j
- d_{ij} distance from i to j
- μ_{ij} traffic flow capacity from i to j
- δ total evacuee traffic flow
- K set of wayfinding strategies
- c_{ij}^k cost of traveling from i to j for evacuees using strategy k
- L set of arc congestion levels
- c_{ij}^l cost of traveling from i to j at congestion level l
- A_{ij}^l breakpoints in the interval $[0, \mu_{ij}]$
- b_i net evacuee traffic flow at node i

Decision Variables:

- x_{ij}^k traffic flow from i to j for evacuees using strategy k
- f_{ij}^l traffic flow from i to j at congestion level l



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The objective of this model (1) is to minimize the total cost for evacuees traveling along the road network, plus the total traffic congestion cost. The conservation of flow constraint (2) ensures that all traffic flow on the network leaves the origin nodes, passes through any intermediate nodes, and arrives at one of the destination nodes. Our next two constraints (3,4) insure that a congestion cost is imposed when flow on an arc exceeds a specific percentage of that arc's total capacity. No negative traffic flow is allowed, nor can traffic flow exceed the total capacity of a given arc (5).

This formulation is similar to many linear cost multicommodity network flow models commonly used in operations research (Kennington 1978). Along this vein, the 'commodities' are the set of wayfinding strategies K in our model, and the cost of traveling along an arc, c_{ij}^k , varies depending upon which wayfinding strategy is used. The addition of a congestion cost c_{ij}^f to the travel cost allows us to model how traffic congestion may cause evacuees to change their wayfinding strategy. This piecewise-linear (Wagner 1975) approach to modeling costs accounts for the decreasing returns (Glover et al. 1992) associated with choosing an evacuation route as congestion becomes heavier. To our knowledge, there are no emergency evacuation modeling approaches that combine multicommodity network flow and piecewise-linear costs. The CEER model represents a novel approach to modeling traffic flow during an emergency evacuation.



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While results from our survey indicated that most evacuees did not change their route while evacuating, most survey respondents also reported that they experienced little traffic congestion. Most people in Mission Canyon had at least 24 hours to evacuate before the Jesusita Fire directly impacted their neighborhood, thus evacuation departures were generally spread out, reducing traffic congestion. Future wildfires could force people to evacuate in a much shorter time period; thus, it is important to account for the congestion that may occur.

We tested the applicability of the CEER model by applying it to the study area of our Jesusita fire survey. The goal of this model is to predict evacuee traffic flow at the aggregate level. The first step is to determine the total amount of evacuee traffic flow in our study area and the origin locations. We used the cadastral shapefile and results of from our Jesusita fire survey to calculate these data. First, we selected all tax parcels from the cadastral shapefile that have their centroid within the boundaries of our study area. We then used the property classification field to determine the amount of flow from each parcel. Parcels classified as single-family residences, condos or rancho estates were assigned one unit of flow, and residential income parcels with 2-4 units were assigned three units of flow.

This preliminary calculation assumes that one vehicle (ie. one flow unit) evacuates from each housing unit in our study area. Our Jesusita Fire survey results indicate that many



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households utilized more than one vehicle when evacuating. Our evacuee flow calculation should be adjusted to reflect this. We asked survey respondents how many people evacuated from their household. Replies to this question indicated that an average of 1.8 vehicles departed from each household, with a minimum of one vehicle and a maximum of six. The simplest way to account for these additional vehicles would be to multiply this average by the amount of flow from each parcel. Alternatively, we could randomly multiply each unit of flow by a value drawn from the empirical distribution of the number of vehicles used by survey respondents. This method allows us to avoid the conceptually difficult assumption that 1.8 vehicles evacuate from each household. Rather, between one and six vehicles depart from each household, with a mean of 1.8.

Finally, we assigned the vehicular flow from each parcel centroid to the closest (Euclidian distance) node on our road network. After this nearest node assignment we have a total flow (δ) of 2638 vehicles evacuating from our study area. For nodes that are neither an evacuation route origin or destination the total flow is set to zero, forcing any traffic flow which enters these nodes to leave them. Each of our three destination nodes can handle the entire flow on our network, allowing the evacuation routes to resolve endogenously.

By using this method of determining evacuee traffic demand we assume that all housing units are occupied, that all residents are home at the time of the evacuation, and that all residents will obey a mandatory evacuation order. We used this approach because it is



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unlikely to underestimate the total evacuee traffic flow from a residential neighborhood. Emergency evacuations are by nature wrought with uncertainty, thus it is critical to have a traffic flow estimation method that can be applied quickly and that will generate an upper bound on the amount of traffic flow to expect.

We used the comparison of Jesusita Fire evacuation routes to shortest distance routes to inform the design of our wayfinding strategies K . While distance remains the most important factor in determining an evacuation route, speed limits and knowledge of private roads may influence the decision of which roads to take. We developed the following general evacuation wayfinding strategies:

k_1 = shortest distance

k_2 = shortest travel time according to posted speed limits

k_3 = shortest distance with limited private road use

k_4 = shortest travel time with limited private road use

We calculated a different arc cost c_{ij}^k for each wayfinding strategy:



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$$c_{ij}^{k_1} = d_{ij} \text{ for all } (i, j) \in A$$

$$c_{ij}^{k_2} = d_{ij} - d_{ij} \times \frac{(\text{speed}_{ij} - 25)}{35} \text{ for all } (i, j) \in A$$

$$c_{ij}^{k_3} = \begin{cases} d_{ij}, & \text{if arc } (i, j) \in A \text{ is a public road} \\ M, & \text{if arc } (i, j) \in A \text{ is a private road} \end{cases}$$

$$c_{ij}^{k_4} = \begin{cases} d_{ij} - d_{ij} \times \frac{(\text{speed}_{ij} - 25)}{35}, & \text{if arc } (i, j) \in A \text{ is a public road} \\ M, & \text{if arc } (i, j) \in A \text{ is a private road} \end{cases}$$

The cost of using an arc for evacuees using wayfinding strategy k_1 is simply the distance of that arc. For strategy k_2 , the arc cost is an adjusted distance which reflects the potential decrease in traveling time when driving on arcs with a 35mph speed limit rather than arcs with a 25mph speed limit. We assigned two different arc costs for evacuees using heuristic k_3 : if the arc is on a public road, the cost is the same as distance, while if the arc represents a private road, the cost is a very large number M . Because the objective of our model is to minimize the total cost, assigning a very high cost to private road arcs will effectively prevent flow on them except for evacuees who must use a private road to leave their origin node. The arc cost for wayfinding strategy k_4 is identical to k_3 except that our cost for public roads is adjusted to account for speed limits as in k_2 .



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The next model parameters we set are the capacity for flow on each arc (μ_{ij}). These capacities are calculated using the following formula, which is based on the Highway Capacity Manual:

$$\mu_{ij} = S_{0_{ij}} \times nlanes_{ij} \times f_{w_{ij}} \times f_{g_{ij}} \times \frac{g_{ij}}{C_{ij}}$$

The basic saturation flow rate for an arc ($S_{0_{ij}}$) is 1800 passenger cars per hour. This value is adjusted based on the number of lanes on an arc ($nlanes_{ij}$), and adjustment factors based on the width of the lane ($f_{w_{ij}}$) and the uphill or downhill grade ($f_{g_{ij}}$). The

final part of this formula ($\frac{g_{ij}}{C_{ij}}$) is the green time ratio, which we use to account for the



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reduction in arc capacity at controlled intersections. For arcs that end at an uncontrolled intersection the value of this ratio is 1, and for arcs that end at a stop sign it is 1/2. There is only one actual traffic signal in our study area, and we determined this ratio observing this signal from 4pm to 5pm on a weekday afternoon and timing the cycle time (C_{ij}) and duration of the green period (g_{ij}).

We choose a set of arc congestion levels L that reflects the traffic conditions a driver may experience during an evacuation:

l_1 = free flowing

l_2 = moderate congestion

l_3 = heavy congestion

The impact of these different levels of congestion is modeled by setting different traffic congestion costs:

$$c_{ij}^{l_1} = 0$$

$$c_{ij}^{l_2} = d_{ij}$$

$$c_{ij}^{l_3} = d_{ij} + d_{ij}$$



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We also set our capacity breakpoints (μ_j^l), which determine the amount of traffic flow on an arc at which the congestion cost will increase. These breakpoints may vary for individual evacuees based on their driving style and knowledge of the road network. We set each of these three values at $\mu_{ij}/3$ for the initial instance of our CEER model, then allowed them to vary stochastically for later solutions to reflect the uncertainty associated with the differences between individual evacuees. This method of modeling congestion is linear, and therefore it may not capture traffic dynamics such as queuing or lane changing behavior. We believe this simpler representation of congestion is a good approximation of a highly complex phenomenon, and has the benefits producing a fast model solution time while accounting for behavioral uncertainty.

D. Results

We solved the CEER model using LPSolve on a Dell Precision T3500 with 12GB of RAM and a quad-core 2.4 Ghz processor. The initial instance of our CEER model was solved to optimality in 57.09 seconds. For this solution, average distance traveled by an evacuee was approximately 1,328 meters and the total distance that all evacuees traveled along private roads was 7,928 meters. After solving the initial instance of our model, we allowed the capacity breakpoints (μ_j^l) to vary stochastically to reflect the uncertainty associated with how evacuees will react to traffic congestion. We randomly sample three



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values from a uniform distribution of capacity breakpoints, with a minimum value of 0.01 μ_{ij} and a maximum value of $0.98 \mu_{ij}$. Together these breakpoints must sum to the total capacity of each arc (μ_{ij}). We solve 1,000 instances of the CEER model, each with a different set of capacity breakpoints. The average distance traveled by an evacuee for all 1,000 stochastic instances of the model is 1,318 meters, and the average total distance that all evacuees traveled along private roads was 8,211 meters. Next we examine two specific stochastic model instances: the minimum total distance and the maximum total distance traveled. These solutions are of special interest as they can be thought of as the 'best-case' and 'worst-case' scenarios. For the minimum total distance solution, the average distance traveled by an evacuee was approximately 1,295 meters and the total distance that all evacuees traveled along private roads was 8,612 meters. These values for the maximum total distance solution were 1,380 and 7,928, respectively. The final stochastic model instance we generated is the maximum distance traveled on private roads. The total distance traveled on private roads is 13,736 meters and the average distance traveled by an evacuee is 1,352 meters. The complete parameters for these results are shown in Figure 7 below. We also created traffic flow maps based on these results (Figure 8), which allow for a more intuitive visual assessment.

In the earlier comparison of Jesusita Fire evacuation routes to the shortest distance routes, we found that evacuees choose exits at a lower elevation than their nearest exit. The potential influence of destination node elevation is not explicitly accounted for in the first version of



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our CEER model, thus we develop a second version that accounts for elevation by limiting the flow capacity of our destination nodes. In the previous section, we observed that the total amount of evacuation traffic flowing to each of our three network exits was more balanced (32%, 38%, 30%) than the amount of flow to each exit for the

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Figure 7: CEER model parameters and results

Model instance	λ_j^{-1} μ_{ij}	λ_j^{-1} μ_{ij}	λ_j^{-1} μ_{ij}	Average distance traveled by an evacuee (m)	Total private road distance (m)
Initial solution	.33 μ_{ij}	.33 μ_{ij}	.33 μ_{ij}	1,328	7,928
Maximum distance	.34	.04 μ_{ij}	.62 μ_{ij}	1,380	7,928
Minimum distance	.79 μ_{ij}	.07 μ_{ij}	.14 μ_{ij}	1,295	8,612
Maximum private road distance	.24 μ_{ij}	.05 μ_{ij}	.71 μ_{ij}	1,352	13,736

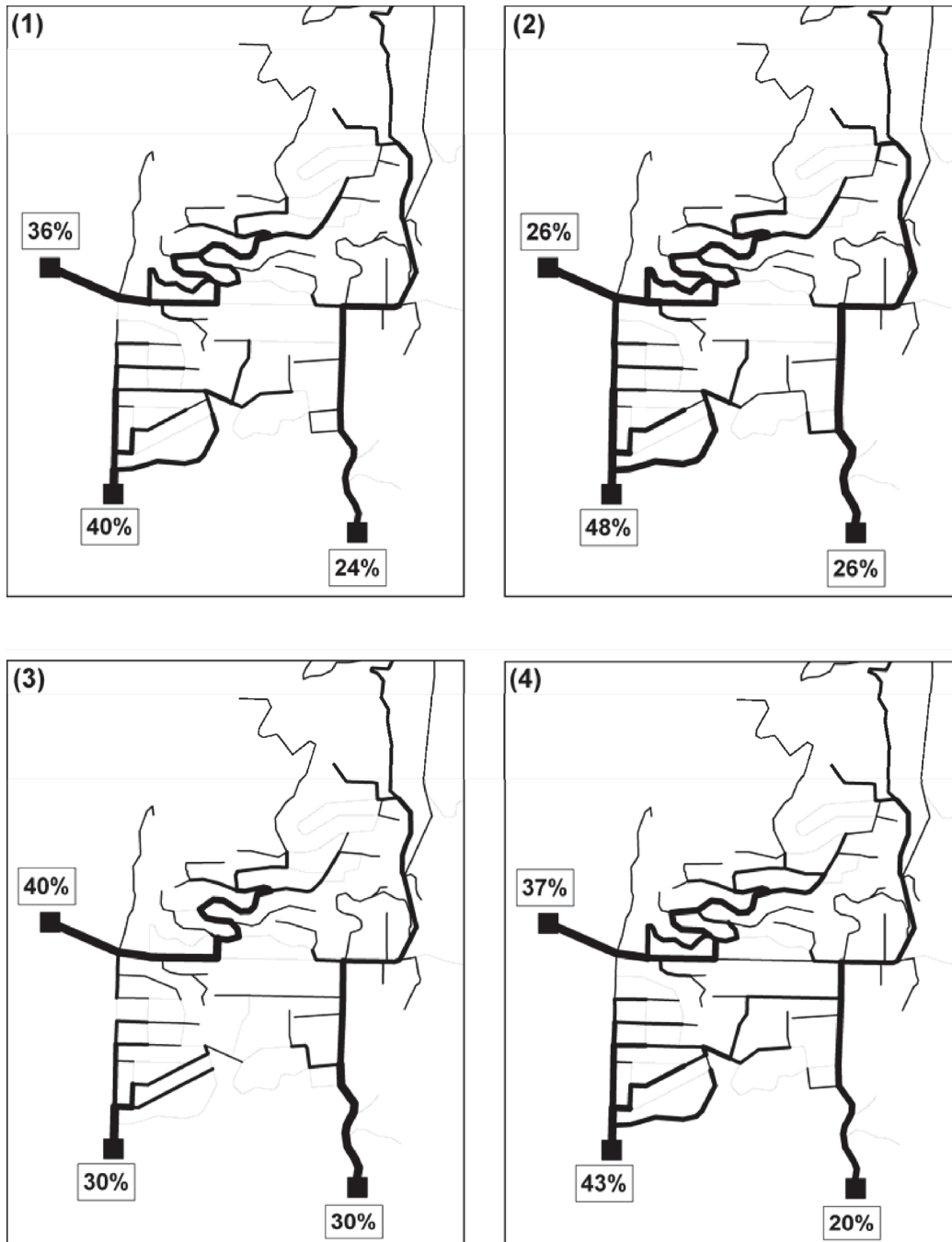
shortest distance to nearest exit routes (39%, 13%, 47%). We used this information to set the amount of flow into our three network destination nodes:

$$b_i = \frac{s}{n_D} + s \times \left(\frac{(\overline{elev_{i,D}} - elev_i)}{\overline{elev_{i,D}}} \right)$$

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Figure 8: Maps showing results of the CEER model. (1) is the initial model instance, (2) is the maximum total distance, (3) is the minimum total distance, (4) is the maximum total distance on private roads. Thicker lines indicate more traffic flow, percentages indicate amount of total flow into each destination node.





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The first term represents an equal allocation of the total traffic flow δ to each of our three destination nodes, then the second term represents an adjustment of this flow demand based on how much the elevation of a given destination node $elev_i$ differs from the mean elevation of all destination nodes ($\overline{elev_{iED}}$). By applying this equation to our study area data we allocated 31%, 39%, and 30% of the total traffic flow to our three network exits, respectively. These values are very similar to the values we observed in the survey results. While limiting the flow capacity of destination nodes may impose unnecessary constraints on the results of our model for our specific study area, we believe that the above methodology may be important for calibrating the CEER model if applied to other road networks. As with the previous version of the CEER model, we solved an initial instance of the capacitated destination version of the model and then solved 1000 model instances with stochastic variation of the capacity breakpoints. The results of these model instances are shown in Figure 9.



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Figure 9: Capacitated destination CEER model parameters and results

Model instance	λ_1	λ_2	λ_3	Average distance traveled by an evacuee (m)	Total private road distance (m)
Initial solution	.33	.33	.33	1,342	7,928
Maximum distance	.34	.04	.62	1,352	7,928
Minimum distance	.79	.07	.14	1,321	7,928
Maximum private road distance	.24	.05	.71	1,344	8,940



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These results and the associated maps have considerably less solution variability than our the first formulation of our model, which allowed destination nodes to have unlimited capacity. We believe that it is important to produce a wide range of model solutions given the dynamic and uncertain nature of emergency evacuations, and therefore do not consider the capacitated destination version of the CEER model for the remainder of this report.

E. Discussion

In discussing the implications of our research, it is useful to refer back to the research questions posed at the beginning of this report:

Do evacuees take the shortest distance route to the nearest exit?

It is clear from our assessment of Jesusita fire evacuation routes that a majority of survey respondents did not take the shortest distance route to the *nearest* exit. When we compared the actual evacuation routes to the shortest distance route to each evacuee's *chosen* exit, the assumption of shortest path routes is reasonably accurate. Based on this finding, understanding how evacuees choose an exit becomes a critical factor for modeling evacuation routes for a given study area.

What characteristics of the environment influence evacuee route choice?

The answer to this question can be split into two parts. Elevation is the characteristic of the environment that influenced the choice of an exit for the Jesusita fire evacuees. We believe that traffic congestion and distance from the fire may have influenced the choice



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of an exit as well, but there was insufficient statistical evidence to show that these other factors were significant. Speed limits are a characteristic of the environment that influenced the choice of roads for Jesusita fire evacuees, and knowledge of private road 'shortcuts' may be an important factor as well. Direction of travel, road gradient and width, and intersection control type are all factors that should be further analyzed in future studies.

Can a model that accounts for environmental perception represent a system of evacuation routes with greater accuracy?

To answer this question is it useful to refer back to Figure 3, which shows the actual Jesusita fire evacuation routes taken by our survey respondents. Comparison of this map to the fourth map produced by our CEER model (Figure 8, bottom right) shows that the modeled traffic flow pattern is similar to the actual flow pattern. When compared to the traffic flow pattern produced when one assumes that all evacuees will take the shortest path route to their nearest exit (Figure 4), we can see that our CEER model, which accounts for environmental perception, is more accurate. These results are specific to our study area and the Jesusita fire, thus additional research is needed to better define the role of environmental perception in evacuation route modeling.

How does behavioral uncertainty impact this system of evacuation routes?

We can see from Figure 8 that a system of evacuation routes can have very different traffic flow patterns depending on the wayfinding strategies and response to congestion of evacuees. Much of the behavioral uncertainty during emergency evacuations is due to



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their infrequent occurrence and difficulties in collecting data. Often the default modeling approach is to assume that people will behave the same way during an evacuation as they do during normal vehicular travel. Other evacuation modeling approaches may assume that people will panic and behave irrationally. We believe the truth lays somewhere in between these two extremes, but this cannot be confirmed without additional empirical data on emergency evacuations.

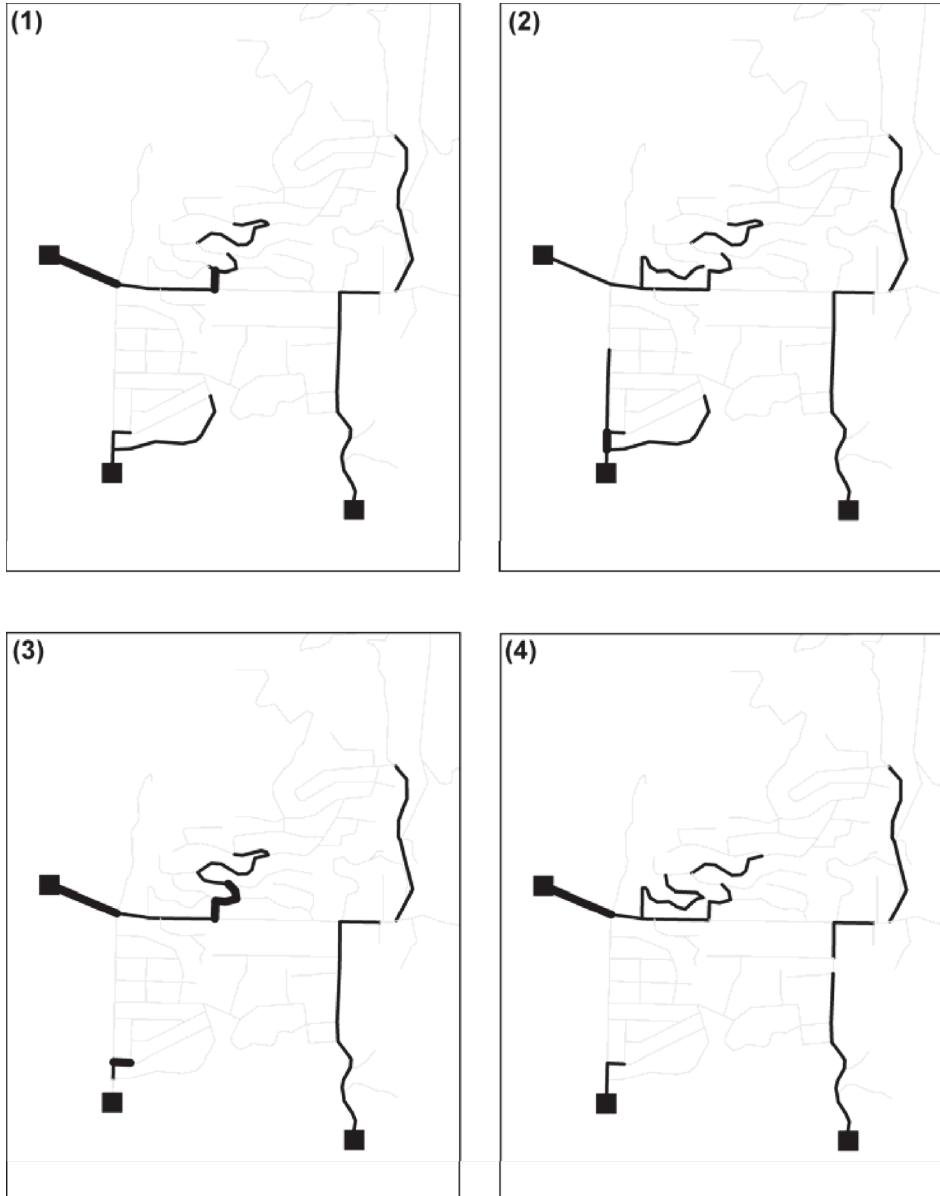
These answers to our initial research questions are valuable for future studies, but additional analysis is needed to help evacuation planners and emergency managers make use of our CEER model results. To address this need, we produce a new set of maps (Figure 28) showing the ratio of traffic flow volume to capacity (v/c) for each arc on our network:

$$\frac{v}{c} = \frac{\sum_{k \in K} x_{ij}^k}{\mu_{ij} \left(\frac{-elev_i}{l_{ED}} \right)}$$

These maps can be used to identify 'hotspots' on the road network, where a high volume of evacuation traffic flow may lead to long queues and bottlenecks. Displaying the results of our CEER model in this manner is useful because certain areas of the network are likely to become congested regardless of the wayfinding strategy and response to congestion of evacuees. A composite map (Figure 11) showing the average volume to capacity ratio across all four of the maps in Figure 10 clearly identifies these 'hotspot' areas.

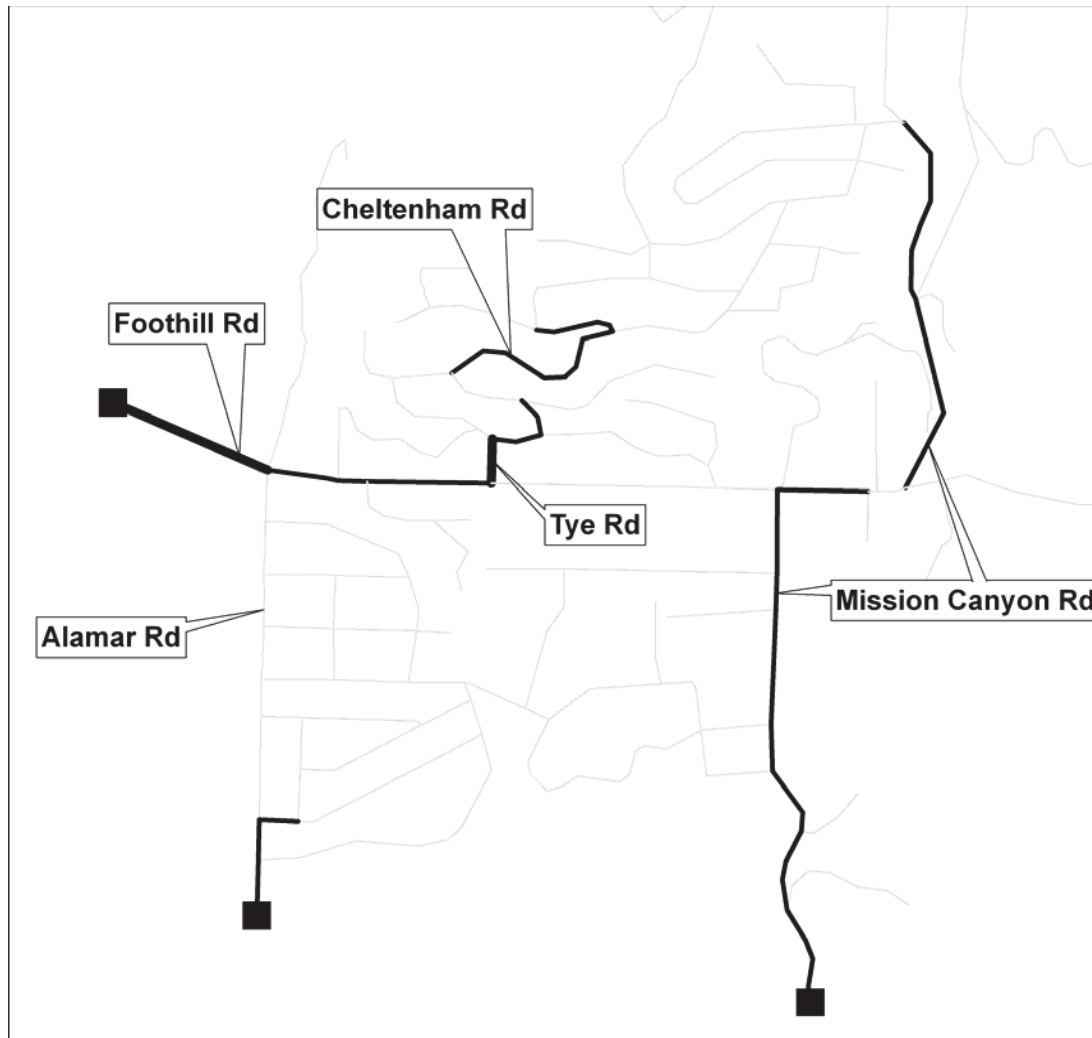
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Figure 10: These maps show the volume to capacity ratio for the four iterations of the CEER model from the previous section. The thickest black lines indicate that volume is greater than 50% of capacity, and thinner black lines show volumes between 25% and 50% of capacity.



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Figure 11: Composite volume to capacity ratio for CEER model results. The thickest black lines indicate that volume is greater than 50% of capacity, and thinner black lines show volumes between 25% and 50% of capacity.



The potential for bottlenecks on Cheltenham Road, Tye Road and upper Mission Canyon Road are of particular concern as these roads are located in steep, heavily vegetated terrain in which a wildfire can spread quickly. The westbound section of Foothill Road is of concern as well, although evacuees have the option of turning left onto Alamar Road to



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reduce congestion on these links. Downstream congestion on Alamar Road and lower

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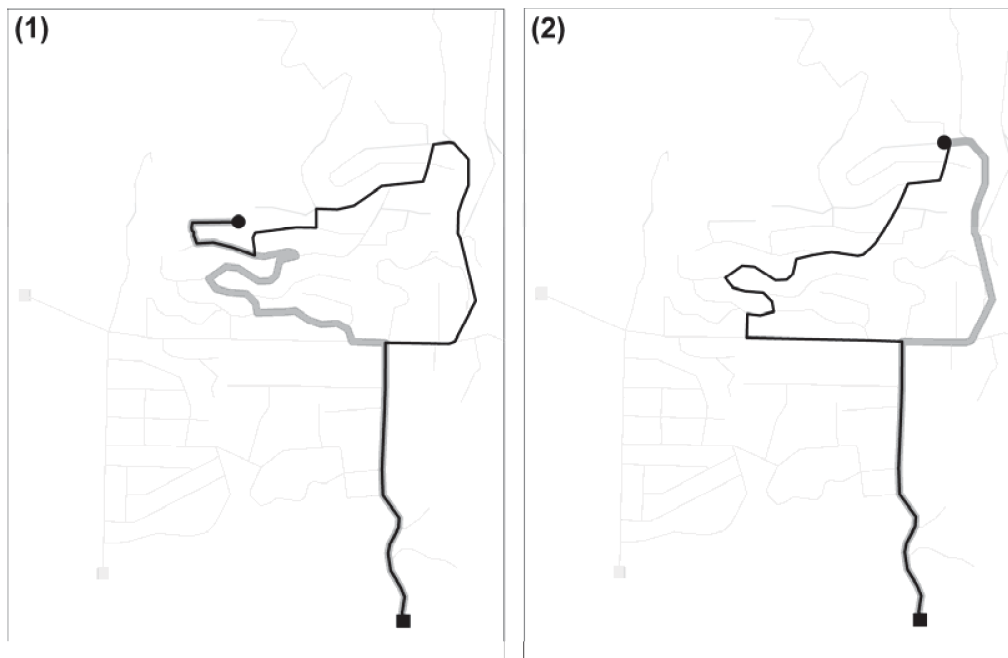
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Mission Canyon Road are of lesser concern because a wildfire is less likely to spread quickly into these areas.

Although a model that incorporates wayfinding can represent a system of evacuation routes with greater accuracy than a model based on simpler behavioral assumptions, it is still difficult to fully account for the unique behaviors of individual evacuees. The CEER model is intended to represent aggregate traffic flow in our study area, thus by design cannot fully represent individual choices and decision-making. In addition, some routes taken by Jesusita fire evacuees simply defy what any researcher might reasonably expect. Figure 12 shows two examples of such routes.

Figure 12: Unexpected routes taken by Jesusita fire evacuees. Black lines show the actual evacuation route and thick grey lines show the shortest distance route. The circle is the route origin node, the black square is the route destination node.





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In the first map, the evacuee chose a route that was 747 meters longer than the shortest distance route between the same origin and destination. Even more surprising is that this evacuee drove uphill and in the direction of the Jesusita fire, which had spread into the northern most sections of our study area at this evacuee's time of departure. One possible explanation is that this evacuee wanted to get a closer look at the fire before leaving the area. In the second map, the evacuee chose a route that was 1,072 meters longer than the shortest distance route. One possible explanation for this choice is that the evacuee wanted to avoid Tunnel Road, which intersects Mission Canyon Road, one of our identified traffic congestion 'hotspots'. These routes represent complex evacuation behavior that would be difficult to account for in any generalized, aggregate traffic model. Future research directions include developing models that can better reflect individual evacuee choice, as well as collecting the additional evacuation data that is needed to make generalized claims about evacuation behavior. Further exploration into evacuation psychology is also needed, perhaps by incorporating more open-ended questions in future surveys or conducting follow-up interviews with survey respondents. The survey comments left by the two evacuees whose routes are mapped above exemplify the complexity of evacuation process:

Comment 1:

" I first received information regarding the fire from high school friends that lost their home in the tea fire. He heard about the fire over his cb band and called me to get out. We saw smoke right behind our homes and got out as it was windy and hot and it seemed likely to spread as the fire



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personnel have no access to water drop equipment in Santa Barbara any longer. Sometimes neighbor helping neighbor is the most effective early warning system. I alerted my 85 year old neighbor who was sleeping and had not heard the warnings yet. Being a good neighbor and clearing your brush and being aware of each other is important when you live in a high risk area. I grew up in this home and this was my lifetime 5th evacuation and the one that came the closest to taking my home with it."

Comment 2:

- " 1. When the winds blow look to the hills.*
- 2. Keep looking.*
- 3. Install a 1 1/2" fire hose line. "*



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TRACK II – Cross Cutting Modeling & Simulation
Modeling the Evacuation Decision**

Modeling the Evacuation Decision

Micah Brachman

1.0 Introduction

Emergency evacuations are essential for protecting people from hazardous events such as wildfires, tsunamis, hurricanes, industrial accidents, and terrorist actions. One way to assess the effectiveness of an evacuation plan is through mathematical models that represent the road topology, population characteristics, and hazard conditions of a specific geographic area. Current emergency evacuation models are often based upon assumptions about spatial behavior that may poorly represent human actions during an actual evacuation. In this paper we address the issue of when and whether a resident may decide to evacuate. Most evacuation modeling is based upon assumptions as to when people will decide to evacuate. The assumptions as to when people will flee have a great impact on the outcome in modeling an evacuation event.

The stay-or-go decision of people living in a mandatory evacuation area is of critical importance to emergency managers. One of the objectives of this part of the research was to develop a better understanding of spatial behavior during an emergency evacuation. Collectively, such behavior may either cause gridlock or may be manageable.



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2.0 Research Design, Data and Methods

On the afternoon May 5th, 2009 a wildfire began in the foothills above Santa Barbara, California. Named the Jesusita Fire after a popular hiking trail in the area of ignition, this fire burned nearly 9,000 acres, destroyed 80 homes, and caused 30 firefighter injuries. An estimated 30,500 people were ordered to evacuate due to the danger posed by this fire, and 29,000 people were warned that they might be ordered to evacuate on short notice. The analysis of the Jesusita Fire evacuation presented in this paper is the outcome of a natural experiment. We rely on observations of variables related to the natural environment, the population at risk, and the wildfire itself in several neighborhoods in Santa Barbara that were impacted by the Jesusita Fire.

Emergency evacuations are infrequent, dynamic processes, and thus it is extremely difficult to control specific variables or be certain that variables are independent. Although this natural experiment does not have the inherent reliability of a controlled study, we attempted to collect data in a way that allows for the contribution from all variables to be measured. Given the paucity of empirical data from emergency evacuations, we believe that both our analysis and the data collected to perform it represent an important addition to the body of scientific knowledge related to this complex process.

2.1 Jesusita Fire Survey

We developed an online survey instrument to assess household behavior during the Jesusita



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fire for an approximately two square mile study area covering the Mission Canyon and Oak Park neighborhoods in Santa Barbara (Figure 1). There were a total of 57 items that can be split out into four general categories: risk perception, information flow, travel behavior, and demographics.

Most risk perception items used a Likert scale, while questions covering information flow and demographics were generally closed-ended with an open-ended ‘other’ response. Travel behavior was measured through simple yes/no questions and other closed-ended questions such as a novel map interface that allows respondents to trace the evacuation route they took. Many critical questions are asked twice using both open-ended and closed-ended formats, allowing for cross-checking validation of answers as well as the possibility of obtaining responses we did not anticipate. The two methods used to recruit survey participants were door hangers placed on the front doorknob or fence and an email list provided by the Mission Canyon Association. We distributed approximately 2,000 door hangers covering 857 houses, 324 condos, and 40 apartment buildings between November 19th and November 24th, 2010. Six hundred current and former residents of Mission Canyon were recruited via email on November 23rd. These potential respondents voluntarily provided an email address to the Mission Canyon Association, but do not necessarily still reside in the neighborhood. The internet-only English language instrument effectively limited participation to Anglophones with Internet access and basic computer skills. There were 264 total responses to the survey.



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2.2 Secondary data

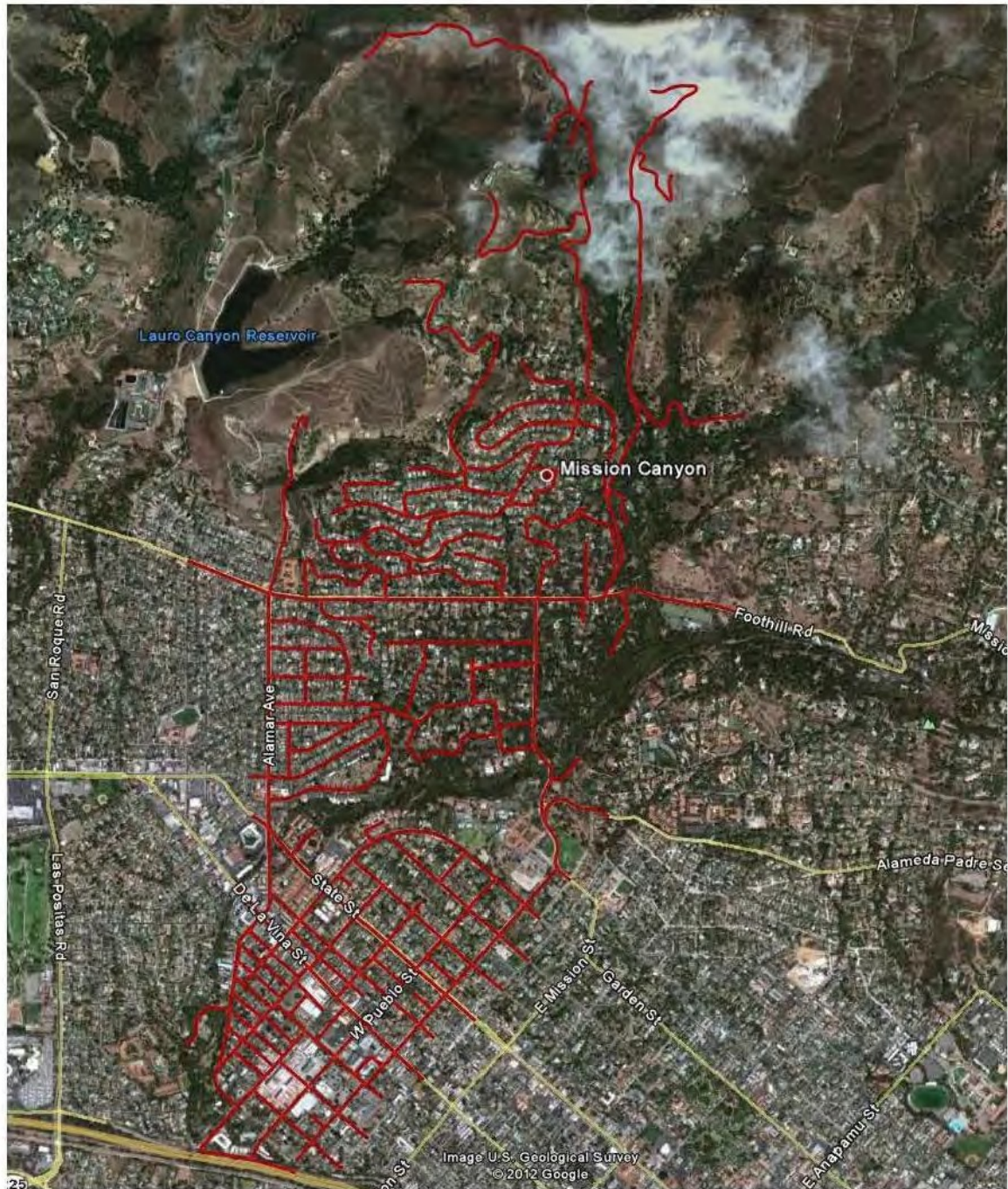
We collected several GIS data layers that allowed us to assess environmental and physical road network characteristics during the Jesusita Fire evacuation. Several fire perimeter polygons representing the location of the Jesusita Fire at different points in time between May 5 and May 7, 2009 were obtained through the County of Santa Barbara online GIS data catalog. These polygons were generated while the Jesusita Fire was burning by mapping personnel from the California Department of Fire and Forestry Protection. To determine elevations in our study area, we acquired the United States Geological Survey 7.5-minute Digital Elevation Model (DEM) covering Santa Barbara. This DEM was produced as part of the National Mapping Program, and has 30 by 30 meter grid cells. We also obtained a shapefile showing private roads in our study area from the Santa Barbara County Department of Planning and Development, and a street layer from the Santa Barbara County GIS Office with numerous data fields including street names, address ranges, and speed limits. In order to estimate the population of our study area we obtained a cadastral dataset from the Santa Barbara County assessor's office. We also downloaded data from three weather stations located near our study area. Access to this historic weather station data was provided by the weather underground website (<http://www.wunderground.com>).

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Figure 1: Red roads show the Jesusita Fire survey study area.





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2.3 Methods

The methods used for this research are statistical analysis and hypothesis testing based upon survival analysis. Primary data and secondary data are used extensively in the application each of these methods. In this paper our focus is on the evacuation decision: Will people choose to evacuate from a wildfire, and if so, when will they depart? We use survival analysis to measure the impact of risk perception, distance from the fire, and environmental conditions on this decision. The results of our survival analysis inform the design of a generalized Rayleigh probability model, which can predict the departure timing of evacuees.

3.0 Modeling the Evacuation Decision

The critical decision faced by an individual when confronted by a fast-moving wildfire in the woodland-urban interface is composed of two interrelated but distinct questions: Will I evacuate? If I decide to evacuate, when shall I go? We believe that many of the same factors affect the answer to each of these questions, thus we use the term *evacuation decision* to encompass both. Despite being an area of active research across diverse disciplines such as psychology, sociology, geography, and engineering, much remains to be learned about the evacuation decision. The infrequency of evacuations as well as the variability of affected populations and the hazard itself makes generalization of research



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findings especially difficult. Our contribution to the body of knowledge on the evacuation decision presented in this paper should thus be considered in the proper context. We study the evacuation decision for a single wildfire event for several neighborhoods in Santa Barbara, CA that are within or near the wildland-urban interface. Despite the specificity of this research project, we hope that our findings will contribute to a better understanding of the factors that affect the evacuation decision for wildfires and other hazards as well.

The basic question we address with this research is: What factors influence the wildfire evacuation decision? We believe that numerous factors influence this decision, many of which are difficult or impossible to observe or measure. It is thus important to narrow this basic research question into specific hypotheses that can be tested using factors we are able to measure. The four research hypotheses we test are:

- 1) People who receive a mandatory evacuation order are more likely to evacuate, and will evacuate earlier than people who do not
- 2) People who believe the fire posed a high risk are more likely to evacuate, and will evacuate earlier than those who believe the fire posed a lesserrisk
- 3) People who are close to the fire are more likely to evacuate, and will evacuate earlier that people who are further away
- 4) Environmental factors such as high temperature and high wind speed increase the likelihood of evacuation at the time of their occurrence.



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The factors considered in these hypotheses are interrelated and may be codependent. For example, it is unlikely that someone would receive an evacuation order unless they were within a certain distance from the fire. We attempt to control for this potential covariance in our analysis to the greatest extent possible, and thus treat these factors as independent variables with an implicit understanding of the limitations of this approach.

This paper is structured as follows: First, we review the literature related to both the evacuation decision and the methods we shall use to address it. Next, we present both the primary and secondary datasets used in our analysis. We then describe the use of survival analysis to determine the significance of various factors in the wildfire evacuation decision, and develop a generalized modeling framework for predicting when evacuees will depart. We conclude by discussing the implications of our results, the limitations of this study, and possible directions for future research.

3.1 Literature Review

Statistical Models of the Evacuation Decision

Statistical models are often used to test research hypothesis related to the evacuation decision and identify new factors that may be significant. A properly specified statistical model needs an underlying conceptual framework, such as representing specific evacuation behaviors as a binary ‘yes/no’ decisions. The most useful output of such models is often an assessment of which variables correlate with the evacuation decision and/or an estimate of



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when people will depart which can be used to represent travel demand in traffic engineering models. The discrete choice model is frequently used to represent such decision making, and can be used to address problems such as choosing an exit from a building during a fire (Ren-Yong and Hai-Jun 2010) or estimating the probability that a household will evacuate during specific time periods before a hurricane makes landfall (Fu and Wilmot 2004). A model of evacuation decision making during a hazardous materials spill in Nanticoke, PA found the timing and content of warning messages that evacuees received were significant factors in their departure timing (Sorensen 1991). Another model of the evacuation decision involving the 2004 Indian Ocean tsunami showed that distance to nearest seashore, education level, and local knowledge were significantly related to household evacuation timing (Charnkol and Tanaboriboon 2006). Research focused on the Three Mile Island nuclear power plant accident found distance from the plant and the actions of friends and neighborhoods to be significant factors in the decision to evacuate or not (Zeigler et al. 1981, Cutter and Barners 1982). A study of people affected by Hurricanes Hugo and Andrew found prior evacuation experience and perception of high risk to be important variables in the decision to evacuate or stay home (Riad et al. 1999). Researchers studying wildfires in parts of Australia found distance from the fire and the number of vehicles owned to be significant household-level predictors of the decision to evacuate (Alsnih et al. 2005), and receipt of voluntary and mandatory evacuation orders has also been positively correlated with the decision to evacuate from a wildfire in the woodland-urban interface (Mozumder et al. 2008).



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Survival Analysis

One alternative to discrete choice models is survival analysis. This statistical method for studying the occurrence and timing of events is well suited to analysis of longitudinal data with censoring and time-dependent covariates, which can be difficult to handle using traditional statistical techniques (Allison 1995). The method has been adapted to analyze time series data in numerous fields, including epidemiology (Hagan et al. 2004), engineering (Christian et al. 1994), economics (Burton et al. 2003), and political science (Berry and Berry 1990). Survival analysis has been used in the general field of transportation, but seldom in studies of emergency evacuations to date. Hensher and Mannering (1994) applied survival analysis to several transportation problems such as how long commuters delay trip departures to avoid traffic congestion and how long travelers may wait before trying a new mode of transportation. Other researchers have used survival analysis to compare the duration of trips for the purposes of shopping, personal business, or free time between men and women (Niemeier and Morita 1996). The scheduling of different travel activities has been addressed through survival analysis as well, accounting for both the duration of the work-to-home commute (Bhat 1996) and the amount of time spent at home (Mannering et al. 1994). One potential output of such analyses is a time-dependent simulation that can forecast travel activities independently of the data used in the initial survival models (Auld et al. 2011). Survival analysis is well suited to evacuation decision data, which is often right-censored (people evacuate before the end of the study



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period) and can have time-dependent factors such as an individual's distance from the hazard. Despite this fit, the only published survival analysis of the evacuation decision that we found during a thorough literature search (Fu and Wilmot 2006) uses a Cox Regression model (Cox 1972) and a piecewise exponential survival model to estimate dynamic travel demand during a hurricane evacuation, accounting for factors such as receipt of an evacuation order and distance from the storm. To our knowledge there is no published survival analysis of wildfire evacuation data, although there is an interesting application of survival analysis to assess the relationship between the age of wildfire fuels and the probabilities of wildfire occurrence (Moritz et al. 2004).

Rayleigh Probability Distribution

Survival analysis and other statistical modeling techniques are very useful for assessing the significance of specific variables on the decisions made by individuals. These methods can also be used to forecast the behavior of individual based on the values of these variables. One drawback to the use of these models for forecasting is that they produce estimates of the decision outcome for each individual that are specific to the event or process being studied. This makes generalization of these forecasts difficult, especially for events such as emergency evacuations, which vary significantly depending on the characteristics of both the hazard and the population at risk. The Rayleigh probability distribution has been used to model wind velocity (Corotis et al. 1978), predict ocean waves (Ochi 1978), and has been applied to numerous other natural processes.



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Transportation applications using this distribution include modeling how airline traffic is effected by weather and other uncertainties (Jinwhan et al. 2012) and improving vehicle fuel efficiency using adaptive cruise control systems (Khayyam et al. 2011). Tweedie et al. (1986) used the Rayleigh probability distribution to model evacuee departure times for a nuclear power plant evacuation. Many evacuation researchers have since adopted this approach to model evacuation travel demand for other hazards such as hurricanes (Duanmu et al. 2011) and tsunamis (Mas et al. 2012). It is important to select evacuation travel demand models that can accurately replicate traffic conditions during actual evacuations in an area of study (Yazici and Ozbay 2008). One advantage of using a pre-specified probability distribution to model travel demand rather than an event- specific statistical model is it may be possible to move towards a generalized forecasting model of evacuation travel demand.



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3.2 Data used in the evacuation decision

Our primary data is from a survey of Santa Barbara residents we conducted following the May 2009 Jesusita wildfire. The complete survey can be found in the appendix section of this report. The secondary data we utilize include GIS data layers downloaded from the Santa Barbara County GIS website (<http://www.countyofsb.org/gis/>) and weather data downloaded from three weather stations near our study area.

Primary Data

Several survey questions were used to establish that respondents were in Santa Barbara and living in our study area during the Jesusita fire. The survey question below was asked of all respondents who met the previous criteria:

Question 7. Did you evacuate during the Jesusita Fire?

(Yes, No, Don't Recall)

Only respondents that responded yes or no were considered for further analysis. These data were transformed into a binary variable (*evac*), with 1 = Yes and 0 = No. We asked all respondents who indicated that they evacuated during the Jesusita Fire to provide the time and date of their evacuation. The interface we used to collect these data allowed respondents to select a one-hour time period from midnight on May 5th until 11pm on May 11th. The official start time of the Jesusita Fire was 1pm on May 5 and nearly all mandatory evacuation orders were lifted by 10am on May 10. All of our survey response fall into this



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time period, with the exception of 10 respondents who gave an evacuation time that was before the fire started. We assumed that these respondents may have made an error when indicating their time period of evacuation, thus we excluded them from our analysis. The last evacuation time given by a survey respondent was 3pm on Saturday May 9th, thus we have 99 total one-hour time intervals between when the fire started and when the last respondent evacuated. Each respondent who answered yes to the evacuation question is thus assigned a value from 1 to 99 indicating the 1-hour time period in which they evacuated.

Many factors may influence the decision to evacuate. For the purpose of hypothesis testing it is convenient to split these factors into several general categories. Notification is one category of factors that may influence the decision to evacuate, and includes variables such as whether an individual was told to evacuate and how they received information about the evacuation and the hazard. Variables that measure distance from the hazard form another important category, as well as variables that assess the risk perception of affected people. We use data from our survey to develop variables in each of these categories. The complete survey can be found in the appendix section of this paper.

We also asked additional questions related to demographics, housing tenure, and previous evacuation experience. Demographics questions include sex and age, housing tenure questions asked how long respondents had lived in Santa Barbara and whether they rented



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or owned, and our evacuation experience question asked whether respondents had ever evacuated from a fire or other hazard prior to the Jesusita Fire. These factors are not included in our research hypotheses as it is difficult to predict how they will influence the decision to evacuate if at all. We include these variables to test for any emergent, unexpected relationships that could be further assessed in future research.

Secondary Data

The GIS data layers we downloaded include basic study area features such as road topology, tax parcels, and census block groups as well as fire-specific variables such as polygon layers that show the extent of the Jesusita Fire and the boundaries of mandatory evacuation zones at several time periods. We also downloaded data for several weather and environmental variables from three weather stations located near our study area. By matching these secondary data to the locations given by survey respondents, we can generate several additional notification and distance variables.

4.0 Methods

4.1 Geolocation of Survey Respondents

Survey respondents must first be assigned a location before GIS variables can be calculated. Based on advice received from the UCSB Human Subjects Institutional Review Board, it was determined that the greatest location precision we could ask respondents was the city block they lived on. We believe that it is more intuitive for people to identify their location by street name than block number, thus we used ArcGIS to split each street in our study



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area into segments that correspond to the length of a block. In our survey we asked respondents to indicate their location by clicking the street segment they lived on using an interactive GoogleMaps interface, and also asked that they type in the name of the street they lived on in a text box. We began with an initial set of 234 survey responses, which includes all respondents who indicated that they either did or did not evacuate during the Jesusita Fire and typed in the name of the street on which they live. Of these 234 respondents, 151 clicked on a street segment using the GoogleMaps interface. Many respondents indicated difficulties using the GoogleMaps interface in the comments section of our survey, which may explain the discrepancy between the number of responses to the text-based and map-based location questions.

The first method we used to geolocate respondents was to simply match the street name they entered in the text box to the street name of the segment they clicked on the map. We corrected text box entries to account for misspellings, abbreviations (e.g. Dr/Drive), and commonly used alternate street names (e.g. Highway 192/Foothill Road) and were able to assign 134 respondents to street segments using this method. Six respondents who did not click a street segment on the map provided an exact address (house number and street) in the text box. The location of these respondents was generalized to the street segment level. We removed nine responses from our original dataset that could not be matched to any street segment in the study area. These respondents did not click a street on the map, and either entered a street name in the text box that was not in our



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study area or provided only a numeric house number but no street. In this initial round of geolocations we matched 140 out of the 225 valid survey responses to a street segment in our study area.

The remaining 85 survey respondents entered a street from our study area in the text box but did not click a street segment on the map. It is important to assign these respondents spatiotemporal variables thus we develop a method to geolocate them that accounts for the lack of geographic precision inherent in their survey response. For each of these respondents we matched the street name they entered to a random street segment of the same name in our study area. This method certainly introduces a degree of uncertainty regarding the accuracy of assignment of our spatiotemporal variables, but we believe this uncertainty is mediated by several factors. Many streets in our study area are less than four blocks in length, thus a randomly assigned location that is three blocks away from the respondent's true location still provides an acceptable approximate location within our study area. Uncertainty is inherent to most spatiotemporal data, and the fire perimeter and evacuation zone polygons that we use to generate variables for our survey respondents are not an exception. We believe that the uncertainty associated with this pseudo-random geolocation method is mitigated by maintaining an acceptable standard of location precision, and should not ultimately bias our results due to the uncertainty inherent in all geographic data.

To generate our GIS variables we first calculated the midpoint of each street segment



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assigned to a survey respondent. These street segment midpoints are used to represent the place of residence of each survey respondent. We downloaded polygon layers showing the boundaries of mandatory evacuation zones at 22 specific points in time, thus we can determine if the place of residence of each respondent was located in a mandatory evacuation zone. We use these data to generate a binary variable (*mangis*).

For evacuees who were in a mandatory zone at or before their time of evacuation are assigned *mangis* = 1, for those who were not *mangis* = 0. For non-evacuees *mangis* = 1 if their house was in a mandatory evacuation zone at any time period from $t = 1$ to $t = 99$, and 0 if not. The second GIS variable we calculate is the distance from the fire for each respondent from $t = 1$ to the time of their evacuation (*fdist*). Respondents who did not evacuate have a distance from the fire from $t = 1$ to $t = 99$. We first downloaded polygon layers showing the boundaries of the Jesusita fire at 10 specific points in time. We then calculate the cartesian distance from each street segment midpoint to nearest point on each fire perimeter polygon at these 10 points in time. To generate hourly distance measurements for each respondent, we interpolated between observed fire time periods (

fdist') using the formula below:

$$fdist_{t+1} = fdist'_t + \frac{fdist'_{t+n} - fdist'_t}{n}$$



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This linear interpolation gives a rough, inexact measure given the non-linear nature of fire spread, but we believe this method is preferable to assuming a static fire location over time.

We also used the survey respondent locations to assign weather variables. We calculated the Euclidian distance from each street segment midpoint to each of the three weather stations, and assigned each midpoint to its closest weather station. Two of these weather stations are located on the western boundary of our study area near the intersection of Foothill Road and Alamar Avenue, and the other is located further south, approximately 300 meters away from the eastern boundary. These data are unique compared to our other in that we have non-interpolated measurements for each survey respondent at each time period leading up to their evacuation (or from $T=1$ to $T=99$ for non-evacuees).

Observations were recorded at approximately 10 minute intervals for two of the weather stations and at 5 minute intervals for the third, so the data needed aggregation to match the 1-hour evacuation intervals from our survey. For four of our weather variables, air temperature (*temp*), wind direction (*winddir*), wind speed (*windspd*), and humidity (*hum*) we simply took the average of all observations at each weather station within each one hour time period. For our fifth weather variable, maximum wind speed (*windgust*) we took the maximum value observed at each weather station during each time period.

Our final set of location-based variables are used to indicate the unique geographic areas in which survey respondents were located (Figure 2). Our first geographic area (*zone1*)



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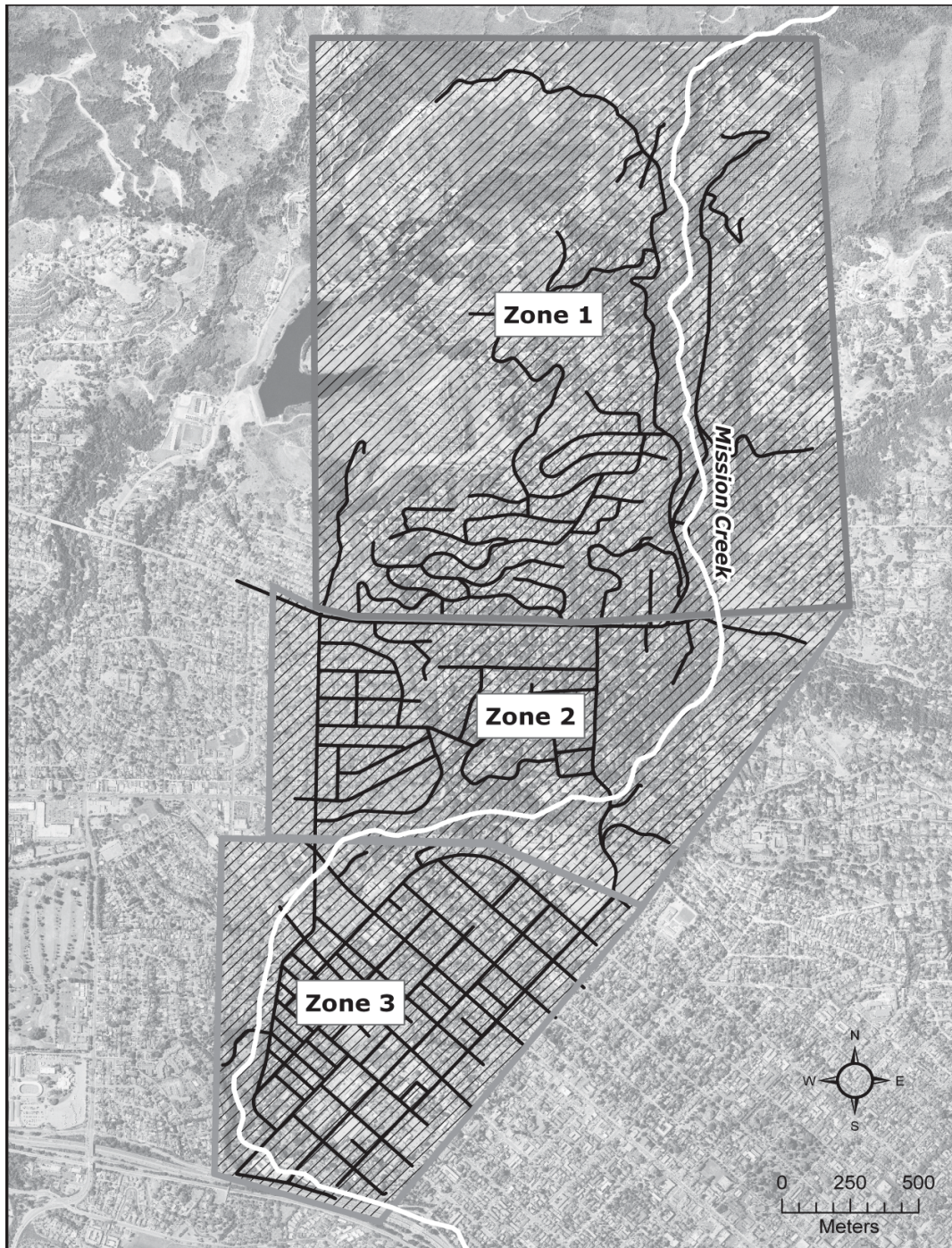
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encompasses the part of our study area north of Foothill Road (i.e. Highway 192). This area is the location of Mission Canyon and is unique for its steep, mountainous terrain and the limited egress options out of the neighborhood during evacuations. The second area (*zone2*) between Foothill Road and Mission Creek is significantly flatter and has many more egress point. Our third geography zone (*zone3*) is south of Mission Creek and covers an area that is generally considered safe from all but the most extreme wildfires. These variables are simply coded as one or zero depending on the location of the respondent.

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Figure 2: Geographic zones in the Jesusita Fire study area.





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4.2 Survivor Function Comparison

Survival analysis is a way to model the time it takes for events to occur. One of the most prevalent uses of this methodology is to examine time until death for recipients of different medical treatments, hence the term ‘survival’. The event we are concerned with is evacuation from a wildfire, thus ‘survival’ in this analysis should be thought of as ‘time to evacuation.’ Everyone who evacuated from the wildfire is considered to be a ‘survivor’, which makes sense intuitively as evacuation is a typical response when people are faced with exposure to a natural hazard that may result in injury or death.

The first step in our survival analysis of the Jesusita Fire evacuation is to generate a survivor function. Let T represent the time to evacuation, a random variable with a cumulative distribution function $P(t) = \Pr(T \leq t)$ and a probability density function $p(t) = dP(t)/dt$. The survivor function $S(t)$ is the probability that a survey respondent evacuated after time t , where t can be any time period from the start of the fire until all mandatory evacuation orders were lifted. This is simply the complement of the distribution function $1 - P(t)$. Survey responses for people who did not evacuate are considered to be right censored since observation of these respondents is terminated at $t = 99$. All evacuations occurred at or before $t = 99$, and all non-evacuees are censored at $t = 99$, thus our survival data set can be described as single right censored. We used the Kaplan-Meier method to estimate the survival function for our data. For each observed event time $t = 1, 2, 3, \dots, 99$ we



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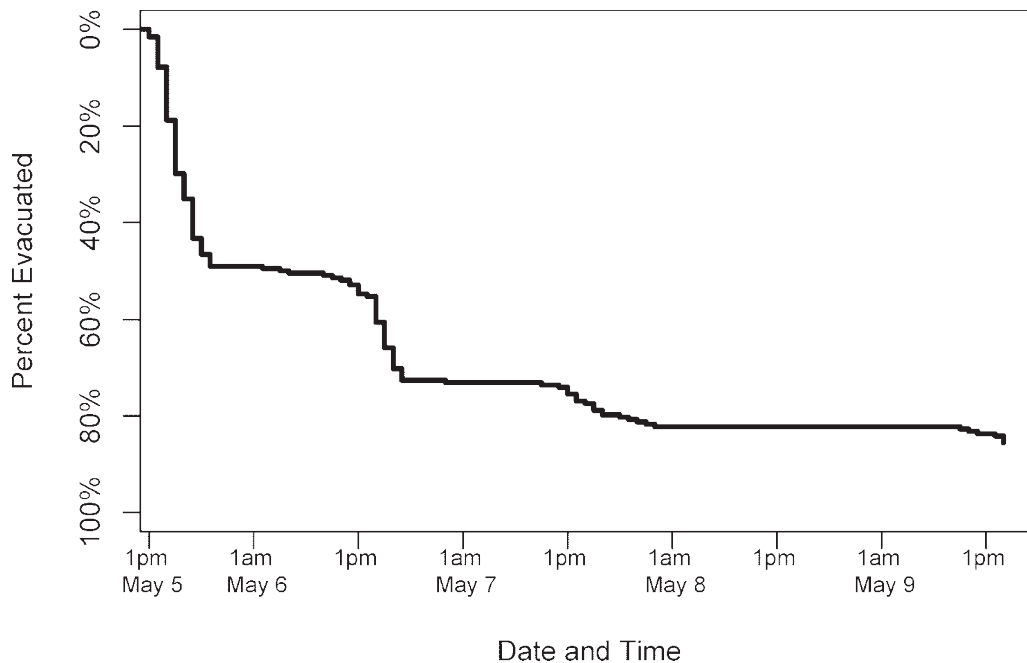
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simply divide the number of evacuees by the total number of responses (208). For our non-evacuees the Kaplan-Meier estimate is undefined.

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We believe it is more intuitive to think of an evacuation survival function in terms of the percentage of people who have evacuated over time, thus we simply subtract each Kaplan-Meier estimate from one and multiply by 100 to calculate this percentage at each time period. The survival curve produced by the Jesusita Fire evacuation survivor function is shown in Figure 3 below.

Figure 3: Jesusita Fire Evacuation Survival Curve



There are several distinct time periods at which a majority of the evacuations occurred. They are May 5th from the start of the fire at 1pm until 9pm, May 6th from noon until 6pm, and May 7th from 1pm until 5pm. At the end of our study period at 3pm on the 9th of May, 30 (or 14.4%) of a total 208 survey respondents had not evacuated. The presence



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of these distinct evacuation clusters is not surprising as a majority of wildfire events in Southern California are driven by Santa Ana winds which generally begin in the afternoon and continue until twilight. This environmental factor is closely linked to the speed at which the fire spreads, and is taken into account by emergency managers when deciding to issue an evacuation warning or mandatory evacuation order. Many Southern California residents living in the wildland-urban interface understand that Santa Ana winds contribute to rapid spread of wildfires thus may have a heightened sense of danger when these conditions exist. Examination of the Jesusita fire evacuation survivor function can provide preliminary clues as to which factors may influence the timing of the decision to evacuate.

One method for preliminary testing of our research hypotheses is to determine whether there is a statistical difference in the time to evacuation (i.e. survival times) for different groups of evacuees. We can formulate the hypothesis test as follows:

$$H_0: h_1(t) = h_2(t) = \dots = h_n(t) \text{ for all } t$$

$$H_A: h_i(t) < h_j(t) \text{ for all least one pair } i, j \text{ and time } t_0$$

Let:

t_i = times when people evacuated

d_{ik} = the number of evacuations from group k at time t_i

Y_{ik} = the number of people in group k that had not yet evacuated at time t_i These

$$d_i = \sum_{j=1}^n d_{ij}$$

$$Y_i = \sum_{j=1}^n Y_{ij}$$



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We compute the vector Z , where the k^{th} element is

$$Z_k = \sum_{i=1}^D a_{ik} d_{ik} \frac{d}{Y_i} Y_i$$

and also compute the covariance matrix \hat{A} and the test statistic $X^2 = Z' \hat{A}^{-1} Z$.

Under the null hypothesis, X^2 follows a χ^2 distribution with n degrees of freedom,

thus if $X^2 > \chi^2_{1-\alpha, df}$ we reject H_0 .

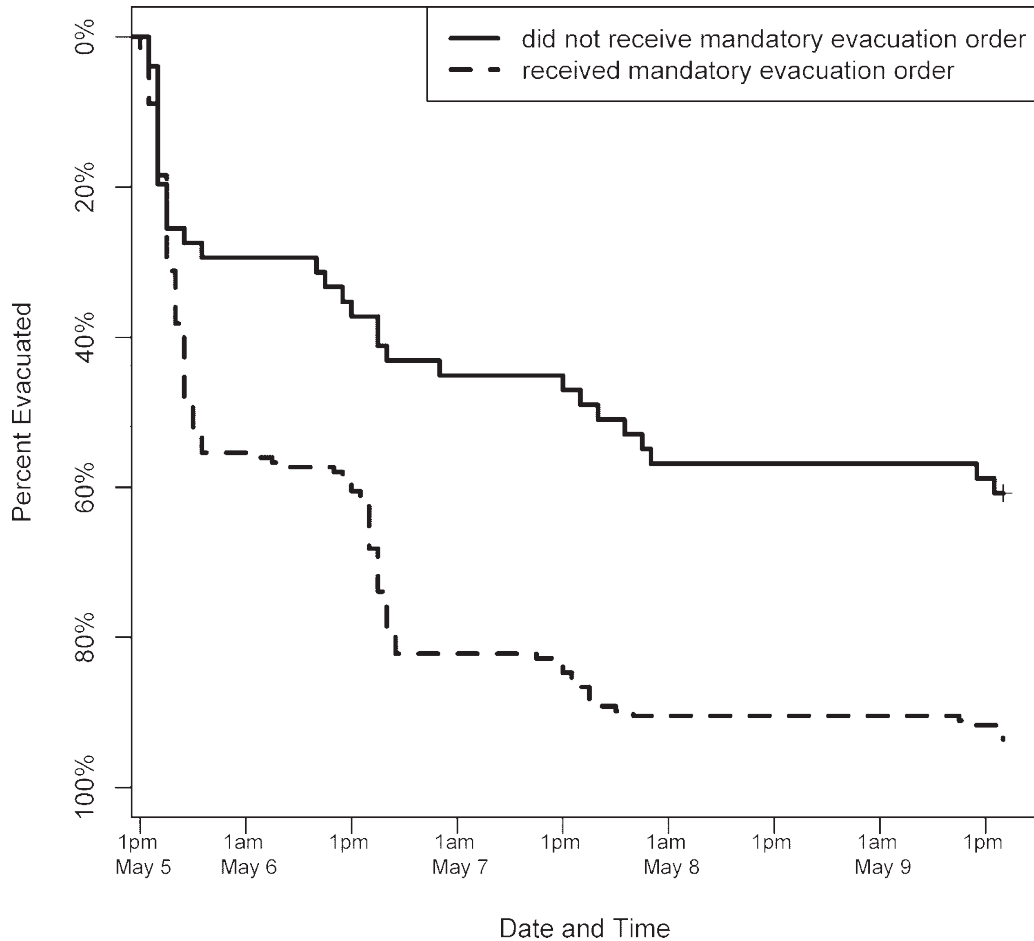
The first groups we compare are those who reported receiving a mandatory evacuation order and those who did not. We find significant support (p-value < 0.001) that there is a difference in evacuation times for these two groups. We can plot survival curves for each of these groups, which allow us to visually assess how these evacuation times differ. As seen in Figure 4 the survival curves for these two groups are similar for the first few hours of the evacuation but then diverge at approximately 5pm on May 5th. This initial similarity can be attributed in part to people evacuating soon after seeing flames and smoke in the foothills, before they actually received an official evacuation order. The similarity may also be explained by the phone tree system set up in Mission Canyon where residents warn each other of a wildfire outbreak, but which may not be considered a “mandatory evacuation order” per se. The later divergence of the survival functions for these two groups lends support to the hypothesis that people who receive a mandatory evacuation order evacuated earlier than those who did not.

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Figure 4: Mandatory Evacuation Order Survival Curves



At the end of our study period a greater percentage of people who received a mandatory evacuation order had evacuated than those who did not, supporting the second part of our hypothesis, which states that receipt of a mandatory evacuation order increases the likelihood of evacuation.

Second we compared two groups of evacuees based on their perception of the risk posed by the fire. These groups are defined using the responses to five risk perception



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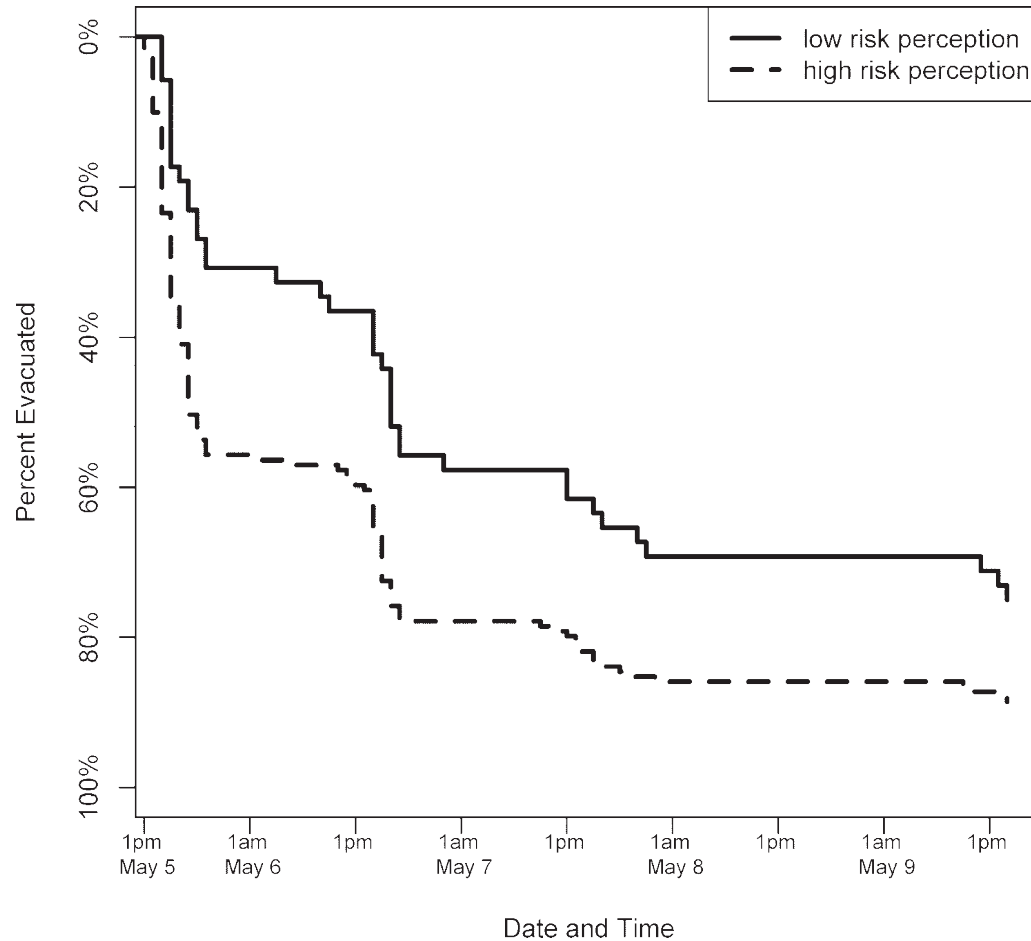
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questions. We first calculated the mean response value to the five questions for each evacuee. Respondents with mean values that fall above our neutral risk score of zero generally agreed that the Jesusita Fire posed a high risk, thus were assigned to the high-risk group. Respondents with mean values that fall below our neutral risk score were assigned to the low risk group. Again we found significant support ($p\text{-value} < 0.01$) that there is a difference in evacuation times for these two groups. The survival curves for these two groups (Figure 5) show divergence throughout the entire evacuation time period, with a higher percentage of respondents who perceived that the Jesusita Fire posed a high risk deciding to evacuate. This comparison supports the hypothesis that people who perceived a high risk evacuated earlier and were more likely to evacuate.

The last groups of survey respondents we compared are those who reported being one-quarter mile or closer to the Jesusita Fire and those who reported being further away than one-quarter mile. These groups are split at one-quarter mile because that was the median answer to this question among all survey respondents. There is significant support ($p\text{-value} < 0.001$) for a difference in evacuation times for these two groups.

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Figure 5: Risk Perception Survival Curves



The divergence in survival functions of these groups (Figure 6) shows support for the hypothesis that people who are close to the fire are more likely to evacuate, and will evacuate earlier than people who are further away. It is important to note that the question we asked was “Estimate how close the fire was to your place of residence at its closest point”, not “Estimate how close the fire was to your place of residence when you evacuated.” Despite this temporal discrepancy, we believe that this question still



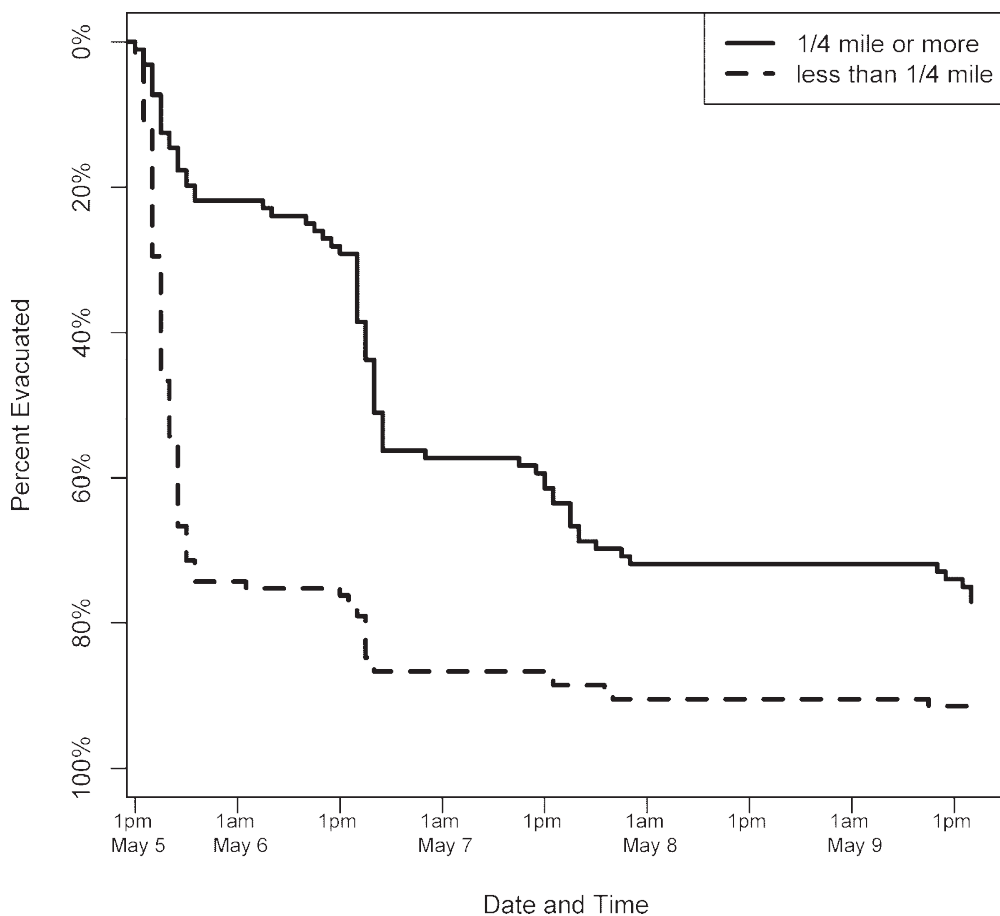
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may capture the effect that distance from the fire had on the decision to evacuate. While it is likely that the fire had not yet reached its closest point to a given respondent's residence at the time that they evacuated, it is also likely that they perceived that the fire would get close based on wind direction, smoke, ash, and other environmental clues. Fire distance can be thought of as a more indirect, proxy measure that may interact with perception of danger or other variables to influence the decision to evacuate.

Figure 6: Fire Distance Survival Curves





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4.3 Environmental Time Series

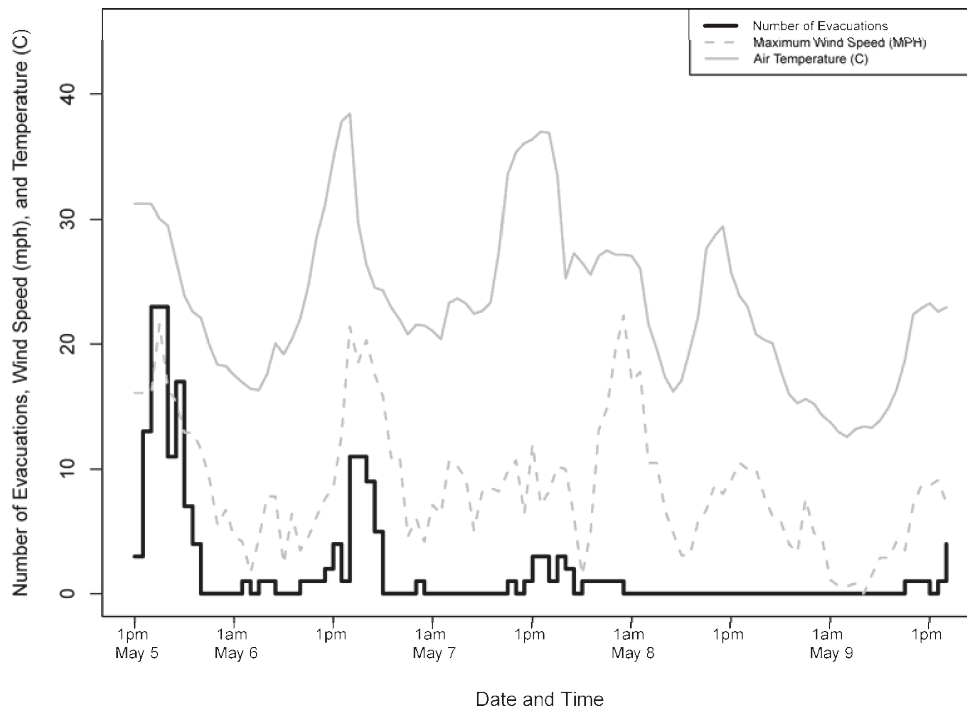
We used a graphical method for preliminary testing of the influence of environmental cues such as air temperature and wind speed on the evacuation decision. Unlike the variables we tested by comparing survival curves, we can measure the change in these environmental factors at very short time intervals. This temporal variation and the fact that most evacuees likely experienced similar environmental conditions at a given time makes it difficult to define different groups based on these factors. We developed a simple plot (Figure 7) showing the number of evacuations during each time 1-hour time period along with the average air temperature and maximum wind speed at the time period. This plot shows similar diurnal cycles for all three measurements. Temperature, maximum wind speed, and the number of evacuations reach their lowest value at night, and reach their peaks in the early to mid-afternoon. This pattern should come as no surprise to one who is familiar with the Southern California wildfire season and the Santa Ana winds that usually preclude it. This plot provides visual support for the hypothesis that environmental factors such as high temperature and high wind speed increase the likelihood of evacuation at the time of their occurrence.

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Figure 7: The number of evacuations in each time period plotted with wind and temperature data





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4.4 Cox Regression Models

To further assess the influence of these variables on the decision to evacuate we developed two Cox Regression Models. The Cox Regression is one of the most widely used survival analysis modeling techniques, and the most commonly used Cox regression is the proportional hazards model, which uses a hazards function to represent the distribution of survival times. The hazards function $h(t)$, which for our purposes can be thought of as the instantaneous risk of evacuation at time t conditional on not having yet evacuated, is defined as follows:

$$h(t) = \lim_{\Delta t \rightarrow 0} \frac{\Pr[t \leq T < t + \Delta t | T \geq t]}{\Delta t}$$

$$= \frac{f(t)}{S(t)}$$

One unique feature of the Cox Proportional Hazards model is that it does not require choice of a particular probability distribution to represent survival times. We can leave the baseline hazards function $\alpha(t) = \log h_0(t)$ unspecified, allowing us to assess which factors influence the decision to evacuate even if the actual evacuation survival distribution is unknown. We do know the survival time distribution for the Jesusita Fire evacuation, but this distribution appears to be non-parametric and thus would be difficult to fit using the commonly used Gompertz or Weibull distribution. While the baseline hazard can take any form, the covariates enter the model linearly thus the model is considered semi-parametric. The general form of the Cox Proportional Hazards model



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is:

$$\log h_i(t) = \alpha + \beta_1 x_{i1} + \beta_2 x_{i2} + \dots + \beta_k x_{ik}$$

This model can be estimated using the partial likelihood method, which allows for the estimation of β coefficients without having to make an arbitrary assumption about the form of the baseline hazard function. One assumption that is inherent in this model is that the hazards are proportional. This implies that the hazard of evacuation for any individual is a fixed proportion of the hazard for any other individual, thus the ratio of hazards is constant over time. This model formulation allows us to implicitly account for any unmeasured time-dependent covariates, and thus more accurately assess the influence of our measured variables on the evacuation decision over time.

The focus of our Cox Proportional Hazards Evacuation Planning model is on factors that may help emergency managers and other decision makers plan for a faster, more orderly evacuation from a future wildfire event. The factors we test using this model are based on *a priori* knowledge about the population at risk. These static factors that may influence the evacuation decision fall into several general categories:

- 4.1 Information access
- 4.2 Demographics
- 4.3 Geographic location
- 4.4 Risk perception
- 4.5 Previous evacuation experience



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Of course these factors are not truly static in the sense that many of them can change for an individual over time. Rather they are static in the sense that emergency managers can have knowledge of these factors well before a wildfire occurs, and they are unlikely to change at the same time scale as the wildfire itself. In generating the data for our model we simply have one row for each survey respondent that answered each survey question under consideration ($n = 200$). We first formulated this model using 22 variables from our primary and secondary data sets that fit into the categories defined above. We then finalized the planning model using backward elimination, by which we start with all candidate variables and delete any that are not statistically significant at a p-value < 0.1 . The variables included in the final planning model are shown in the formulation below.

$$\log h_i(t) = \alpha + \beta_1 mand_i + \beta_2 personal_i + \beta_3 neighbors_i + \beta_4 residence_i + \beta_5 prevevac_i + \beta_6 tsb_i + \beta_7 zone3_i$$

All variables are significant at p-value < 0.05 (Figure 8). Receipt of a mandatory evacuation order (*mand*) is positively correlated with the decision to evacuate, as is perception that the fire posed a high risk to a respondent's personal safety (*personal*) or place of residence (*residence*). Previous evacuation from a wildfire or other event (*prevevac*) is also positively correlated with the decision to evacuate. This relationship may be explained in part by the large number of long-term residents of Mission Canyon who responded to our survey, which is the part of our study area most frequently threatened by wildfires. One geographic zone indicator variable (*zone3*) is negatively correlated with the decision to evacuate, which makes sense given that this zone was the furthest from the fire and was only partially under a mandatory evacuation order.



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Figure 8: Planning Model Results

Variable	Coefficient	Standard Error	P-value
mand	0.59485	0.25686	0.020564
personal	0.29278	0.12090	0.015451
neighbors	-0.41083	0.15458	0.007867
residence	0.37689	0.11749	0.001337
prevac	0.62329	0.16527	0.000162
tsb	-0.20645	0.07499	0.005903
zone3	-0.74788	0.30207	0.013293
Likelihood ratio test= 95.53 on 7 df, p=0			
Wald test = 80.44 on 7 df, p=1.121e-14			
Score test = 87.3 on 7 df, p=4.441e-16			

Perception that the fire posed a high risk to neighbors (*neighbors*) is negatively correlated with the decision to evacuate. This finding may be counterintuitive for researchers who believe that the people around them heavily influence an individual's decision making. There are many possible explanations for this counterintuitive finding. One is that an individual decides whether to evacuate or not well in advance of the occurrence of a wildfire, thus is not influenced by any effect the fire may be having on people nearby. Another more nuanced explanation lies in the fuzzy definition of 'neighbor', which can be interpreted as 'the people next door', 'the people down the street', or the 'people who live in the same neighborhood as me'. Given the irregularity with which fire may affect individual homes and/or property in a neighborhood, it is possible that while survey respondents recognized that other people in the neighborhood were at high risk, personally they felt safe. The number of years the respondent has lived in Santa Barbara



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(*tsb*) is also negatively correlated with the decision to evacuate.

This finding can also be interpreted in a number of ways, but may lend support to the notion that people make up their minds whether to evacuate or not well in advance of the actual event. Long term residents of our study area may have experienced wildfires before, and thus created defensible space or purchased personal firefighting equipment such as hoses and sprinklers in preparation to ‘stay and defend’ their home.

As mentioned earlier, the central assumption of the Cox Proportional Hazards model is that the hazard for any individual is a fixed proportion of the hazard for any other individual. Checking for violations of this assumption is important for assessing how well the fitted model describes our data. One way to check for violations of proportionality is to calculate the Schoenfeld residuals for each covariate and plot them against time. The Schoenfeld residual is the covariate value for each individual that evacuated minus its expected value. The expected value at t_i is an average of the covariate weighted by the likelihood of failure for each individual in the risk set at t_i :

$$S_{residual} = x_{ik} - \frac{\sum_{j \in R(t_i)} x_{jk} p_j}{\sum_{j \in R(t_i)} p_j}$$



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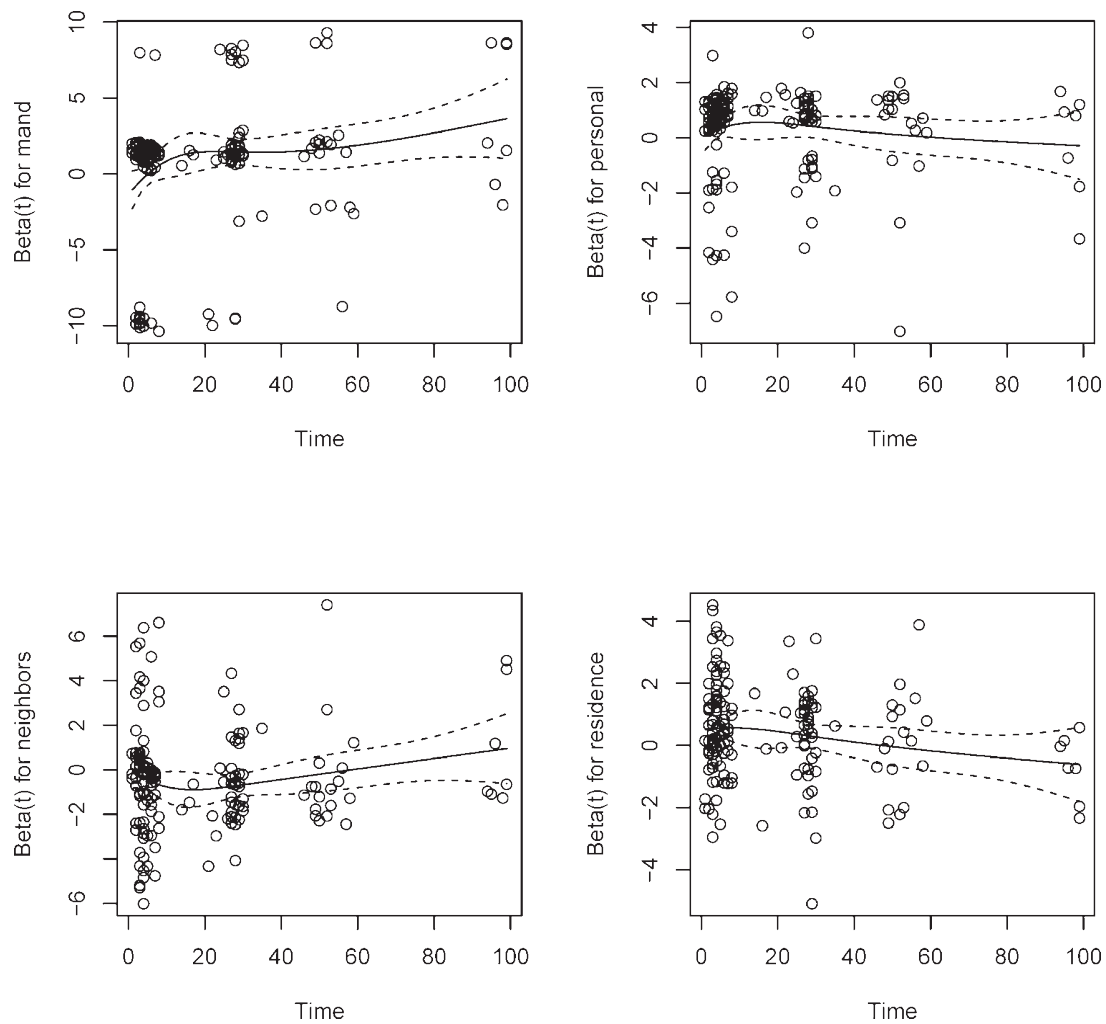
The plot for each covariate should show residuals to be randomly distributed throughout time, and the line fitted to these residuals should be horizontal. The plots in Figure 9 show clustering of residuals around the earlier time intervals of our study period, which is not surprising given that most of our observed evacuations occurred then. In the plot of residuals for our mandatory evacuation order variable (*mand*) the fitted line deviates from horizontal and we see additional clustering of residual values beyond the early time intervals. We thus consider the hazard for this variable to be non- proportional. In the second set of plots (Figure 10), variable *prevevac* and variable *zone3* both show departures from the horizontal fitted line and clustering of residuals that indicate non-proportionality. Although the slope of the fitted line for variable *tsb* varies considerably, its overall trend is approximately horizontal and the residuals are well scattered. One way to account for non-proportional hazards is to include interactions between the offending covariates and time in the Cox regression model.

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Figure 9: Schoenfeld Residuals (1)

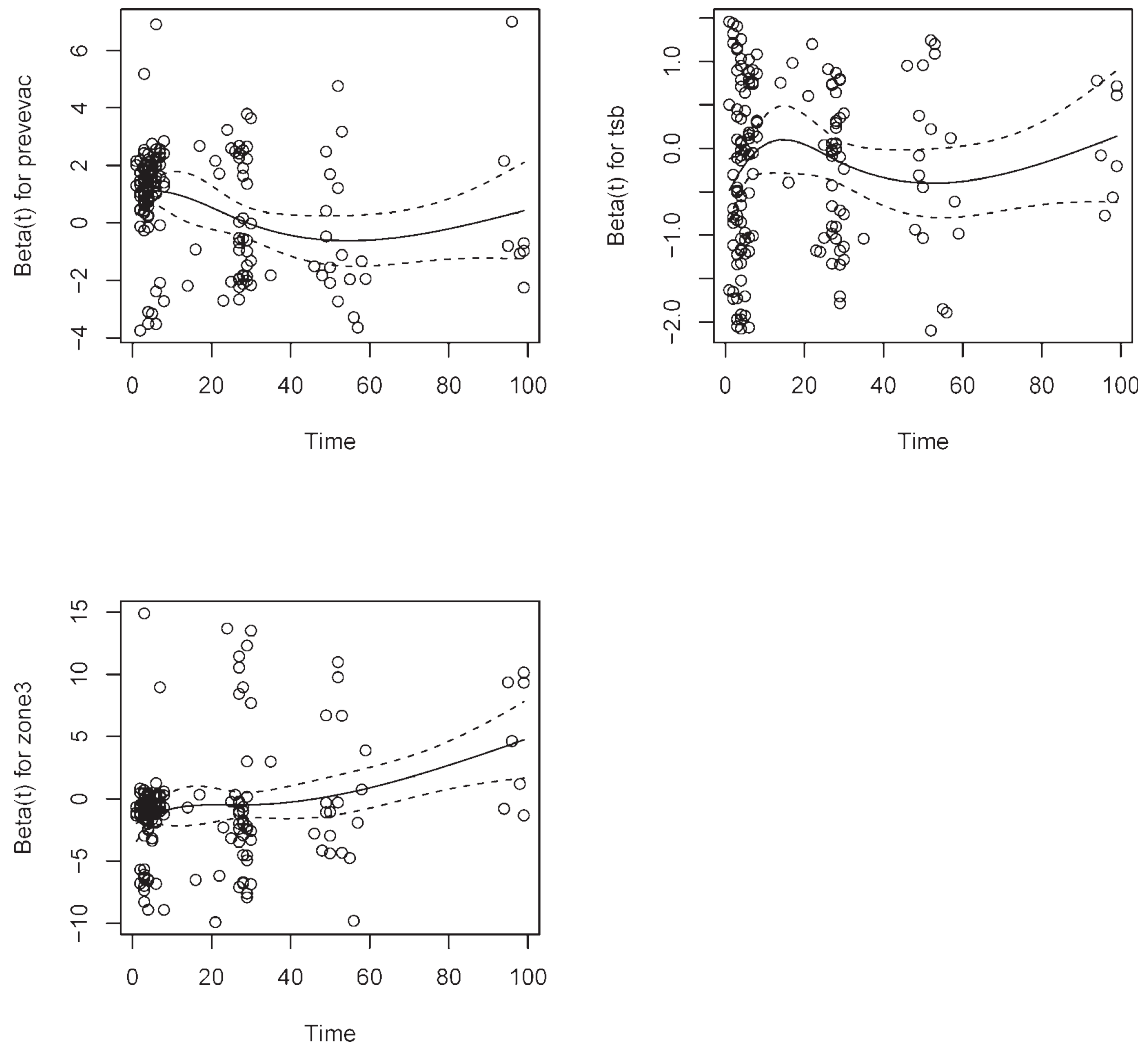


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Figure 10: Schoenfeld Residuals (2)



We can then examine the coefficient of these interaction terms to assess if the hazard of the covariance does indeed change over time and determine how this may impact the ability of our model to fit the data. For instance:



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$$\log h_i(t) = \alpha + \beta_1 t + (\beta_2 + \beta_3 t) \text{mand}_i + \beta_4 \text{personal}_i + \beta_5 \text{neighbors}_i + \beta_6 \text{residence}_i + (\beta_7 + \beta_8 t) \text{prevevac}_i + \beta_9 \text{tsb}_i + (\beta_{10} + \beta_{11} t) \text{zone3}_i$$

The interaction variables (for *mand*, *prevevac*, and *zone3*, respectively) are all highly significant (p-value < 0.01) and each has a negative coefficient indicating a declining effect over time. The signs for the coefficients of the original *mand* and *prevevac* variables are positive, thus one way this trend could be interpreted is that people who decided not to evacuate stuck with this decision despite receipt of a mandatory evacuation order or a previous evacuation experience. The original coefficient sign for *zone3* is negative, thus the corresponding interaction term may reflect the increased number of people evacuating from zone 3 as the fire moved closer and threatened this part of our study area. Although these three variables appear to violate the assumption of proportional hazards, the reason for these violations makes sense in the context of the process we are trying to model. The coefficient estimates for original non-interacted terms can be considered to represent the average effect over the entire study period, thus we maintain the original formulation of our planning model.

A secondary assumption made in the Cox Proportional Hazards Model is that the parametric part of the model is linear in form. We can test for nonlinearity by plotting the Martingale residuals against each non-dichotomous covariate. The solid line that we fit to these data should exhibit little or no deviation from the horizontal dashed line if the parametric part of the model is indeed linear. We can see in Figure 11 that this is the case,



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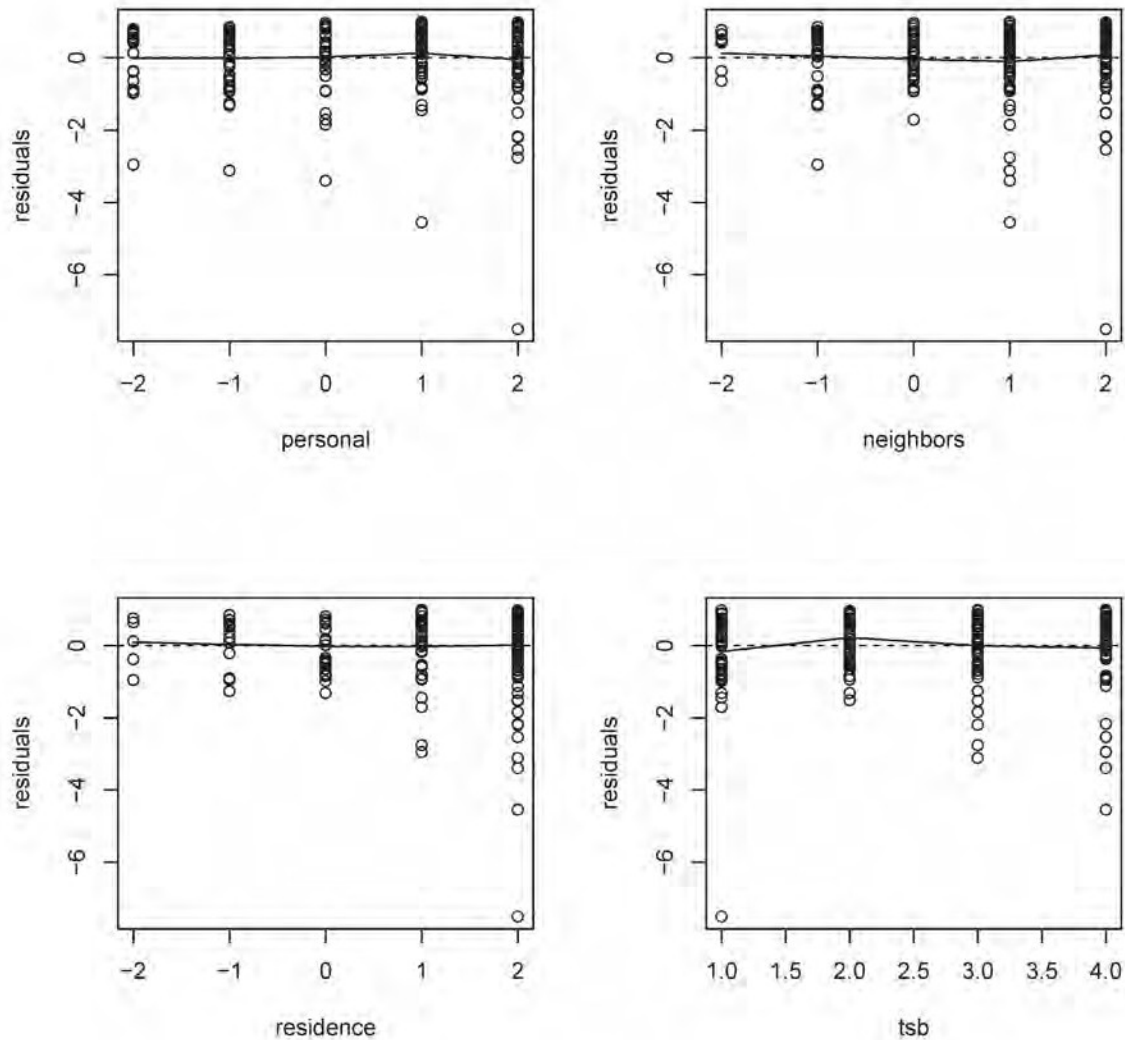
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thus we can be confident that the functional form of our planning model is linear and thus correctly specified.

Of course the most intuitive test of model fit is how well the model generated survival curve matches our empirical data. As seen in Figure 12, the evacuation time distribution produced by our planning model fitted values appears to approximate our empirical evacuation time distribution well. The planning model overestimates the number of evacuees during the evening of May 6th, which may be attributed to the fact that a small but significant number of survey respondents decided to remain in their homes beyond this point in time despite receiving a mandatory evacuation order and being well aware of the high risk posed by the fire to their personal safety and their property. Despite this divergence the empirical data is very close to being within the 95% confidence interval of our modeled data for this section of the curve, thus the planning model can be considered to be a good representation of our Jesusita Fire evacuation time series.

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Figure 11: Planning Model Martingale Residuals

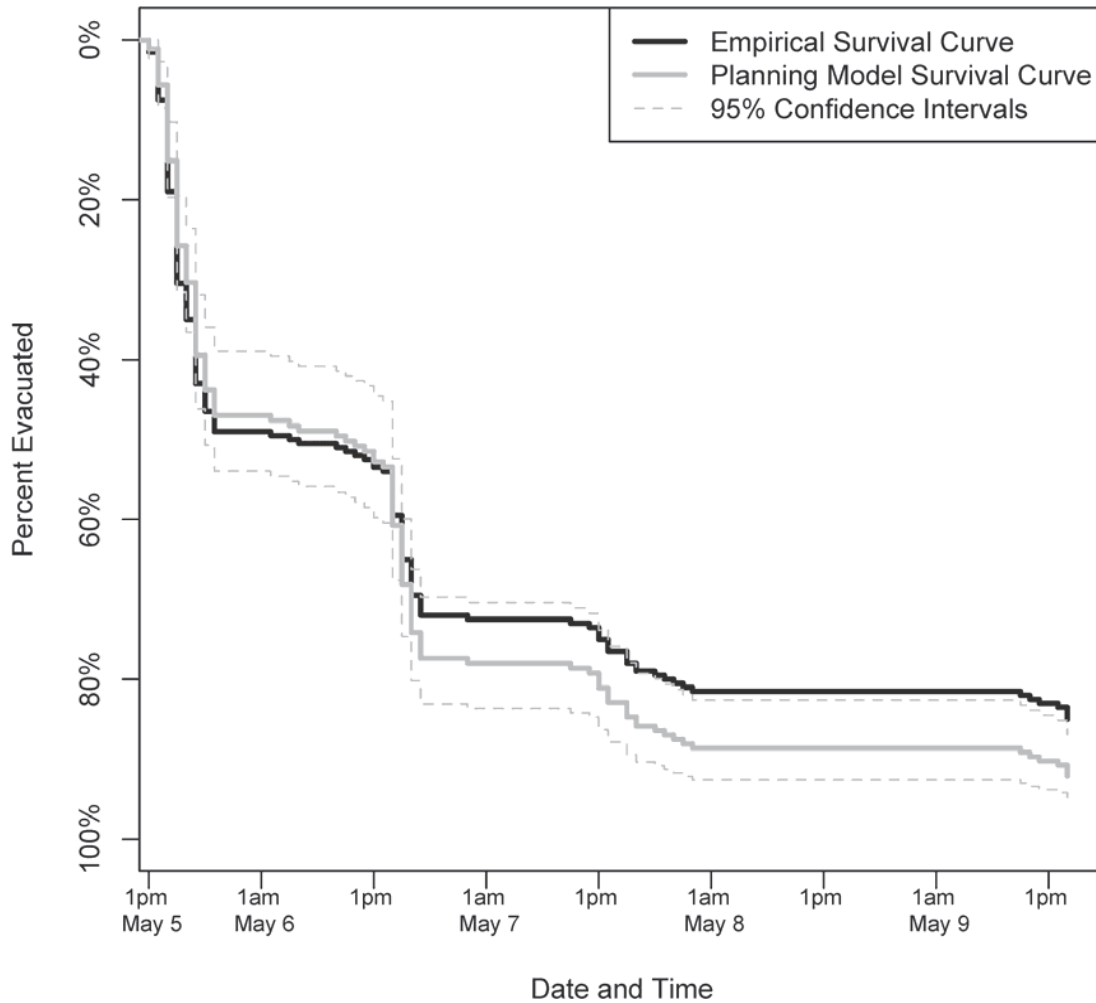


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Figure 12: Planning Model Survival Curve



The second Cox model we developed is focused on evacuation operations. Evacuation operations refers to actions taken by emergency managers, police officers, and other personnel who are responsible for managing the logistics of an emergency evacuation after the onset of a hazardous event. We use this model to assess dynamic, time-dependent factors that may influence the evacuation decision with the goal of helping emergency



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managers respond to changing conditions on the ground after the start of a wildfire. Unlike our planning model these factors are difficult or impossible to measure before a wildfire starts, and can change at rates similar to those at which the fire changes. These dynamic factors include:

- 4.6 Distance from fire
- 4.7 Location in mandatory or voluntary evacuation zone
- 4.8 Wildfire impact on homes and property
- 4.9 Weather

This model incorporates time-dependent variables, so it requires a different data structure than our planning model. We have one row for each survey respondent at each 1-hour period of time from the start of the fire until they evacuated. Respondents who did not evacuate have 99 rows, the number of hours covering the entire study period. This model is first formulated using 19 variables from our survey and GIS data that fit into the categories defined above. The general form of this model is very similar to the Cox Proportional Hazards model, with slight adjustments needed to account for both time dependent and non-time dependent variables:

$$\log h_i(t) = \alpha + \beta_1 x_{i1} + \beta_2 x_{i2} + \dots + \beta_k x_{ik}$$

We finalized this operations model using backward elimination and deleted any variables that are not statistically significant at a p-value < 0.1. The final form of the operations model is shown below:

$$\log h_i(t) = \alpha + \beta_1 temp_i(t) + \beta_2 windspd_i(t) + \beta_3 d1_i + \beta_4 d2_i + \beta_5 zone2_i$$



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Each of the variables in our operations model is significant at $p\text{-value} < 0.01$ and is positively correlated with the decision to evacuate (Figure 13). This positive correlation makes intuitive sense for environmental factors such as air temperature (*temp*) and wind

Figure 13: Operations Model Results

Variable	Coefficient	Standard Error	P-value
temp	0.13442	0.03724	0.000306
windspd	0.28973	0.04340	0.000000
d1	0.87636	0.32590	0.007166
d2	0.70748	0.21855	0.001207
zone2	0.94503	0.20144	0.000002
Likelihood ratio test= 92.26 on 5 df, $p=0$			
Wald test = 74.1 on 5 df, $p=1.432e-14$			
Score (logrank) test = 88.26 on 5 df, $p=0$			

speed (*windspd*) which are often indicative of increased wildfire severity and faster fire spread. The positive correlation of a geographic zone indicator variable (*zone2*) also makes sense given that this zone was the next closest to the fire after Mission Canyon (i.e. *zone1*) and was under a mandatory evacuation order. The destruction of a respondent's home (*d1*) by the Jesusita fire is also positively correlated with the decision to evacuate, as is damage to a respondent's home (*d2*). While these variables are static and thus we cannot know exactly when their place of residence was impacted, we believe this variable may serve as a proxy measure of the overall impact of the fire on the built environment.



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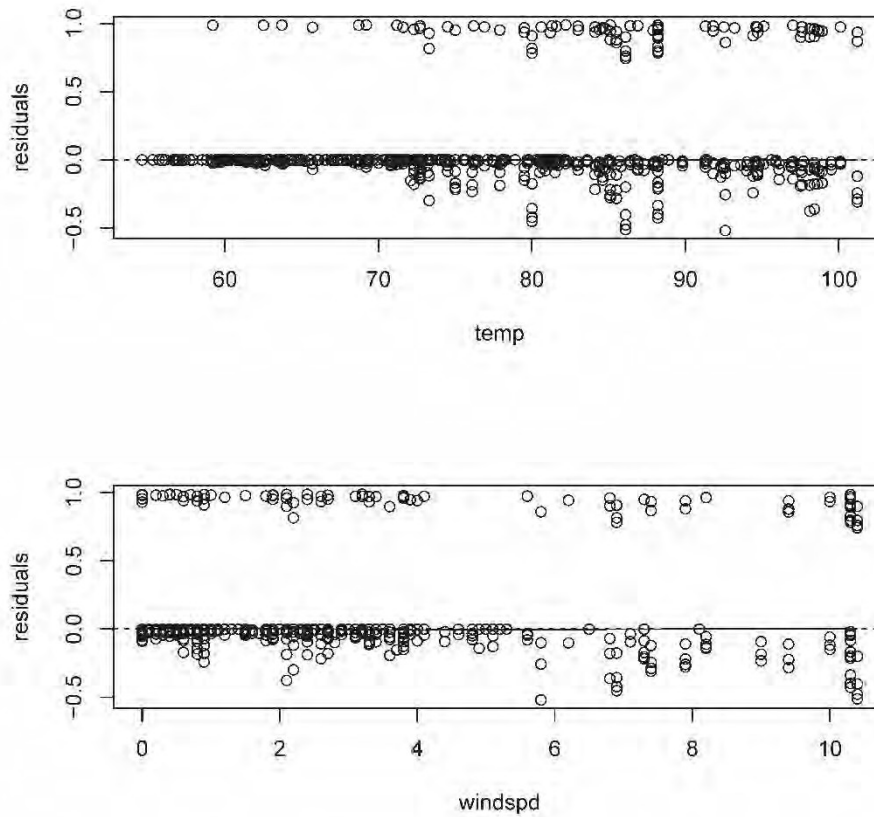
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Despite the similarity in form of the operations model to the planning model, the operations model is not a proportional hazards model. The time-dependent covariates in the operations model will change at different rates for different individuals, thus the ratios of their hazards cannot remain constant. We can ignore the test for proportional hazards and proceed directly to the test for non-linearity to assess the fit of the model. In the plot of Martingale residuals against our two non-dichotomous covariates *temp* and *windspd*, (Figure 14) the solid line that we fit to the data shows no deviation from the horizontal dashed line. We can therefore be confident that the functional form of our operations model is linear and correctly specified.

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Figure 14: Operations Model Martingale Residuals





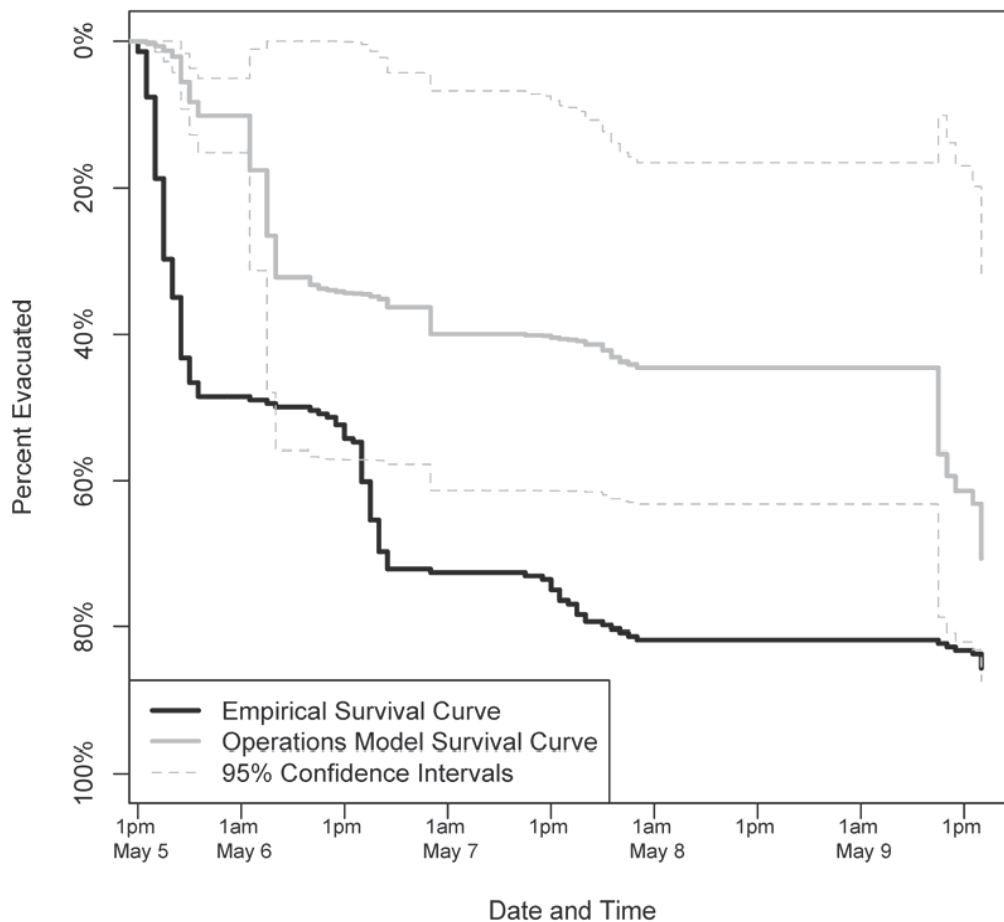
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The final and most important check for the fit of our operations model was to plot the modeled survival curve against our empirical evacuation data. As seen in Figure 15, our operations model significantly under predicts the number of evacuees for most of our study time period. A great majority of our empirical survival curve falls outside the 95% confidence intervals for our modeled data. This means that our operations model can be considered to be a poor fit for our empirical evacuation data.

Figure 15: Operations Model Survival Curve





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One possible reason for this poor fit is the large number of records in our dataset at where evacuation does not occur. The data structure required for this type of model has one row for each time period t from the start of the fire until the time at which an evacuee departed. Survey respondents who did not evacuate have 99 rows. Of the 6,504 total observations at which evacuation is possible there are only 178 at which an evacuation actually occurs ($evac = 1$). Thus even though some of the factors may in fact correlate with the evacuation decision over time, there may simply be too few non-zero response variables to establish a good model fit. One possible method for dealing with this issue would be to exclude the time periods from the dataset where no one evacuates, or to introduce time-lagged variables into the model formulation. This is beyond the scope of our current analysis but could prove useful for future modeling efforts.

Despite the poor fit of our operations model we believe that the covariates considered do play some role in the decision to evacuate. Two ordinary least squares regressions of the form

$$y_i = \beta_0 + \beta_1 x_1 + \epsilon_i$$

confirm the likelihood of this relationship. In our first regression model the number of evacuations per hour is the dependent variable and the average air temperature average is the independent variable. We find that air temperature accounted for 16% of the variance in the number of evacuations per hour ($R^2 = 0.16$) and is highly significant (p-value <



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0.001). The second regression also has evacuations per hour as the dependent variable, with average wind speed at each hour as the independent variable. Average wind speed accounted for 46% of the variance in the number of evacuations per hour ($R^2 = 0.46$, p value < 0.001). The relationship, if any, between the decision to evacuate and our two 'fire impact' variables $d1$ and $d2$ is less clear. Not surprisingly, every respondent whose house was damaged or destroyed by the fire decided to evacuate. Due to the design of the survey questions we cannot know the time at which these respondent's homes were damaged or destroyed for comparison to the time at which they evacuated. Given the results of our survival curve comparison we believe these variables may be important, but should be measured differently for future modeling efforts.

4.5 Rayleigh Probability Model

We used the results of our survival analysis to inform the design of our Rayleigh Probability Model. While survival analysis is useful for assessing the influence specific variables may have on the evacuation decision, we prefer to use a model based on the Rayleigh Probability Distribution to actually forecast evacuation travel demand because it may be easier to generalize for additional wildfire evacuation datasets. In our earlier comparison of survival curves we determined that receipt of a mandatory evacuation order, perception of the risk posed by the fire, and distance from the fire at its closest point are variables that influence the evacuation decision. Our Cox proportional hazards planning model confirms the significance of these variables, but also indicates that having previous evacuation experience and the amount of time one has lived in Santa Barbara may be



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influential as well. Although the overall fit of our operations model to the empirical data is poor, our post-analysis reveals that the environmental factors of wind speed and air temperature are positively correlated with the number of evacuations in a one-hour time period. These factors are considered in the formulation of our Rayleigh Probability Model for evacuation travel demand. Let,

$$\begin{aligned}
 &\pi_3, \text{ if the fire has burned homes} \\
 f_1 &= 2, \text{ if the fire poses a significant threat to homes} \\
 &\quad 1, \text{ if the fire poses a minimal threat to homes} \\
 &\pi_3, \text{ if wind speed and air temperature are extreme} \\
 f_2 &= 12, \text{ if wind speed and air temperature are above average} \\
 &\quad 1, \text{ if wind speed and air temperature are at or below average} \\
 &\pi_3, \text{ if all residents have been ordered to evacuate} \\
 f_3 &= 2, \text{ if some residents have been ordered to evacuate} \\
 &\quad 1, \text{ no evacuation order issued} \\
 f_{bar} &= \frac{(f_1 + f_2 + f_3)}{3}
 \end{aligned}$$

Rayleigh Probability Model:

$$P_{evac} = \exp - T^{\wedge f_{bar}} / 50$$



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The three factors that influence the probability of evacuation P_{evac} are analogous to the significant variables from our survival analysis. The first factor f_1 is intended to capture the effect of distance from the fire on the evacuation decision. We believe that quantifying distance using the impact on homes as a proxy for an actual distance measurement may be more intuitive for the emergency managers and traffic engineers that may use our model. In addition, accurate distance measurements can be difficult to obtain in lieu of the smoke generated by a wildfires and the steep, mountainous terrain on which they often occur.

Similarly, our second factor f_2 allows for an estimation-based measurement for environmental factors which can vary locally but whose overall effect is usually quite obvious. The third factor f_3 refers to the number of residents of a wildfire-prone neighborhood or subdivision who have been notified that an emergency evacuation order is in effect. In our formulation T is a vector of sixteen elements that are simply the whole numbers 1,2,3... 16. These numbers represent the sixteen half-hour time steps that occur in an 8-hr time period, the length of time of a typical shift for police officers and other personnel often responsible for managing traffic during an emergency evacuation. It is important to note that the significant factors from our survival analysis related to the perception of danger, previous evacuation experience, and the length of residency in Santa Barbara are not included in our Rayleigh Probability Model. These variables are difficult to measure without the use of a comprehensive survey and may vary significantly for different portions of a neighborhood. We believe they should be left out of the model in the interest of generalizability.



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5.0 Results

We tested the applicability of the Rayleigh Probability Model for evacuation travel demand using both our primary and secondary datasets related to the Jesusita Fire. This model can only represent travel demand during a single eight hour time period. Using our survey data we calculated the number of evacuations per hour from the start of the fire (May 5th at 1pm) until 9pm on May 5th. The empirical evacuation time distribution that we used to test model fit is shown in Figure 16.

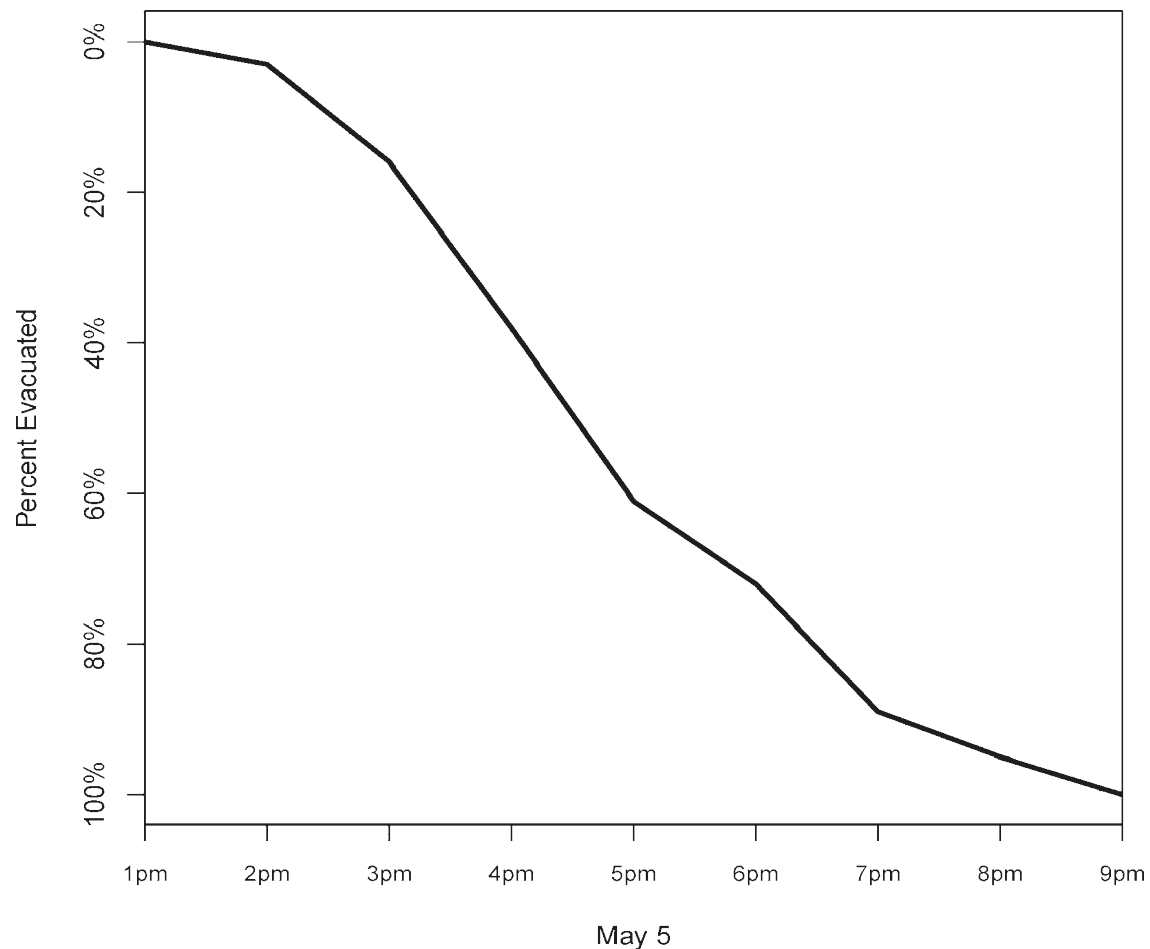
Figure 16: 8hr Empirical Evacuation Time Distribution



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We determine the appropriate value for f_2 by comparing weather conditions for our eight hour study period to both the conditions over the five day time period of the Jesusita Fire evacuation and the normal conditions experienced during early May in our study area. The mean wind speed for our eight-hour time period was approximately 3mph, while the value for our entire five-day time period was approximately 2.3mph. The corresponding values for air temperature are 77.0° F and 76.0° F, respectively. These values are similar, but



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when compared to the values for average weather conditions in our study area in early May¹ (61.3° F, 1.7mph), we see a considerable difference. Based on these differences we determined that wind speed and air temperatures were above average but fell well short of the extremes for the five day Jesusita Fire evacuation time period (101.2°F, 10.4mph). This lead us to assign $f_2 = 2$.

One way to determine the appropriate value of f_3 is to calculate the percentage of evacuees from our eight-hour time period who reported receiving a mandatory evacuation order. Of our one hundred evacuees from this time period, eighty-five reported receiving mandatory evacuation order (85%). In addition, all evacuees located in geographic zone one (n=83) were under a mandatory evacuation order by 5:45pm on May 5th, while e vacuees from zone two (n =17) were not officially ordered to evacuate until May 6th². The appropriate value for f_3 is 2, indicating that some residents have been ordered to evacuate.

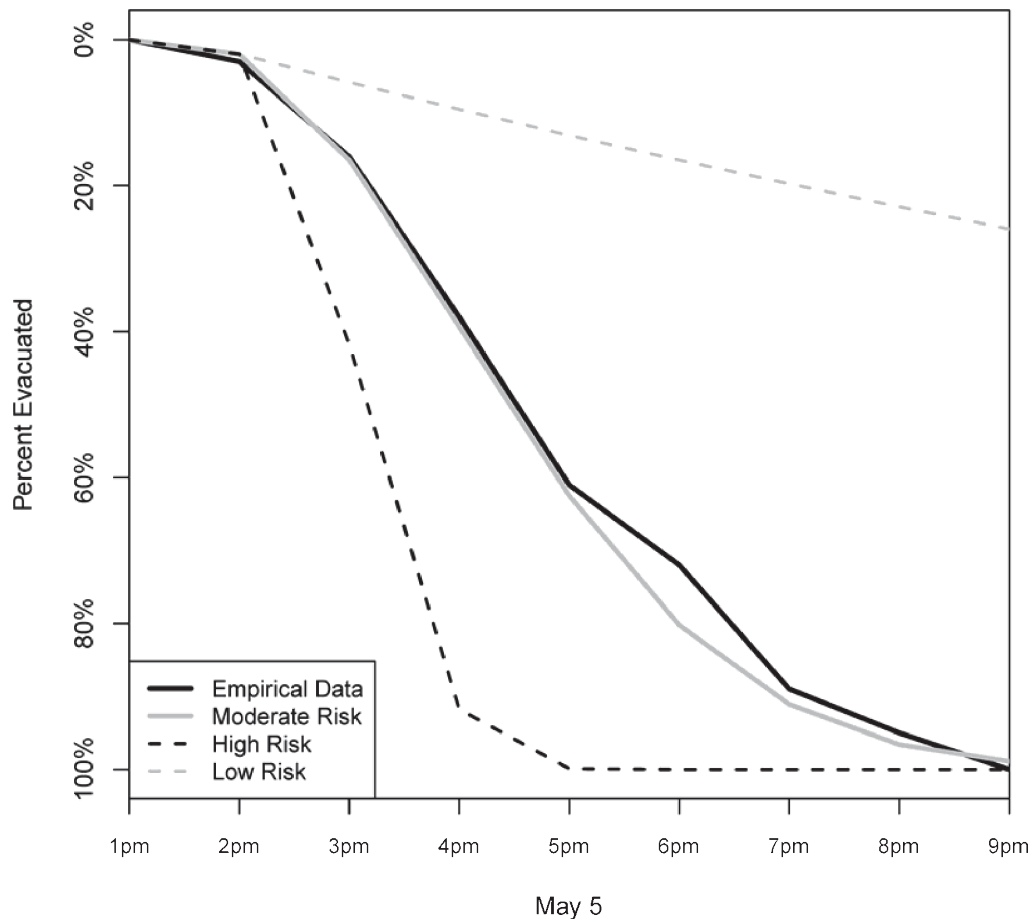
¹ We downloaded the seven-day averages from May 5th - May 12th for 2007 through 2012 from the same weather stations used to download data for our weather variables. These values are simply the mean of the seven-day average for all years.

² The timing of these mandatory evacuation orders was obtained from the official press releases from the Santa Barbara County Emergency Operations Center.

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The value for f_{bar} using the variables defined above is 2. Overall, this average can be thought of as indicative of a 'moderately risky' wildfire event, with homes being threatened, substantial but not extreme wildfire weather conditions, and a segment of the population of interest officially ordered to evacuate. The results of our Rayleigh Probability Model can be seen in Figure 17.

Figure 17: Rayleigh Probability Model Results





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The evacuation probability curve generated for our 'moderate risk' wildfire event is an excellent match for our empirical data. We generated two additional curves with our model that correspond to a 'high risk' wildfire event ($f_{bar} = 3$) and a 'low risk' wildfire event ($f_{bar} = 1$). It should be noted that these additional curves are purely hypothetical and have not been compared to any empirical evacuation distributions.

6.0 Discussion

The evacuation decision encompasses two critical questions: will people evacuate, and if they choose to evacuate, when will they depart? The success of an emergency evacuation is heavily dependent on having accurate answers to these questions. Survival analysis can be used to model the both of these evacuation decision questions simultaneously, but has been used infrequently in the fields of hazards and emergency management. We believe that survival analysis is an intuitive and powerful method for modeling the evacuation decision and should be used more often by researchers.

The findings of our survival analysis suggest that receipt of an evacuation order, distance from the fire, and risk perception are important factors for people faced with the evacuation decision. While impact of these factors has been well documented in past emergency evacuation research, comparing the survival curves for different groups of people allows for simple visualizations of how each factor effects the evacuation decision over time. The Cox Regression framework allows us to determine the relative influence of multiple



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factors while implicitly controlling for any unmeasured variables. Measuring every variable is nearly impossible for events as complex as an emergency evacuation, thus the Cox Regression is particularly useful.

One drawback to survival analysis as well as many other statistical modeling techniques is that they require large, detailed datasets that can be difficult to obtain. A Rayleigh Probability Model utilizing simple, easily estimated data can be used to forecast the rate of evacuations over an 8-hour time window. The Rayleigh function is very similar to the S-curve function, which is widely used to forecast evacuation departure timing for hurricanes and other hazards. To our knowledge, no research has shown that the S-curve or Rayleigh function can be used to forecast evacuation departure timing for a wildfire. Models of this type may be preferable to event and place-specific statistical analysis because they are more easily applied and tested for other emergency evacuation datasets.

One of the major limitations of the current formulation of our Rayleigh Probability Model is that it does not account for people who did not evacuate. One could infer that non-evacuees are of little interest when trying to manage the logistics of an emergency evacuation. Yet because California firefighters must protect people who choose to stay in homes that are threatened by a wildfire, there is both an in-flow and out-flow of traffic during an evacuation that must be managed. Understanding who is likely *not* to evacuate and why a critical question left is largely untouched by our research.



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Besides the aforementioned study of non-evacuees, there are several other directions for future research. The Rayleigh Probability Model should be tested on additional emergency evacuation datasets to determine if it is indeed suitable as the basis of a general framework for forecasting evacuation travel demand. Currently there is a paucity of empirical data on emergency evacuations, thus additional survey research should be undertaken to develop new datasets. Finally, new methods of collecting data on emergency evacuations should be employed. Approximately two-thirds of our survey respondents reported using a cell phone immediately before or during their evacuation, thus the increasingly advanced capabilities of mobile technologies could be harnessed to generate data that builds a better understanding of the evacuation process.



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Appendix

The complete Jesusita Fire survey as seen by online respondents can be seen below.

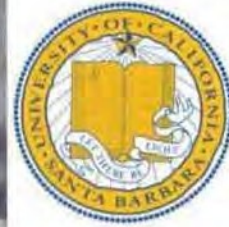


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Modeling the Evacuation Decision

<https://survey.ucsb.edu/fire/>



Background Information

The Jesusita Fire began on Tuesday, May 5th 2009 and was declared 100% under control on May 18th, 2009. It is estimated that nearly 30,000 Santa Barbara residents evacuated due to the threat posed by this fire. The intent of this survey is to ensure that people have the ability to safely evacuate should another event such as the Jesusita Fire occur. Please answer all questions accurately to the best of your ability, and don't forget to enter a valid email address at the end of the survey to qualify for the free iPod drawing. All data collected in this survey will remain confidential and anonymous, and will be used only for academic research.

Thank you for your help and good luck in the iPod drawing!

Were you in Santa Barbara during the Jesusita Fire?

- ☐ Yes
- ☐ No
- ☐ Don't recall

Next





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Modeling the Evacuation Decision



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Modeling the Evacuation Decision

<https://survey.ucsb.edu/scripts-7i/perseus6.pl>

Were you living at your current address during the Jesusita Fire?

- ☐ Yes
- ☐ No
- ☐ Don't recall

Next



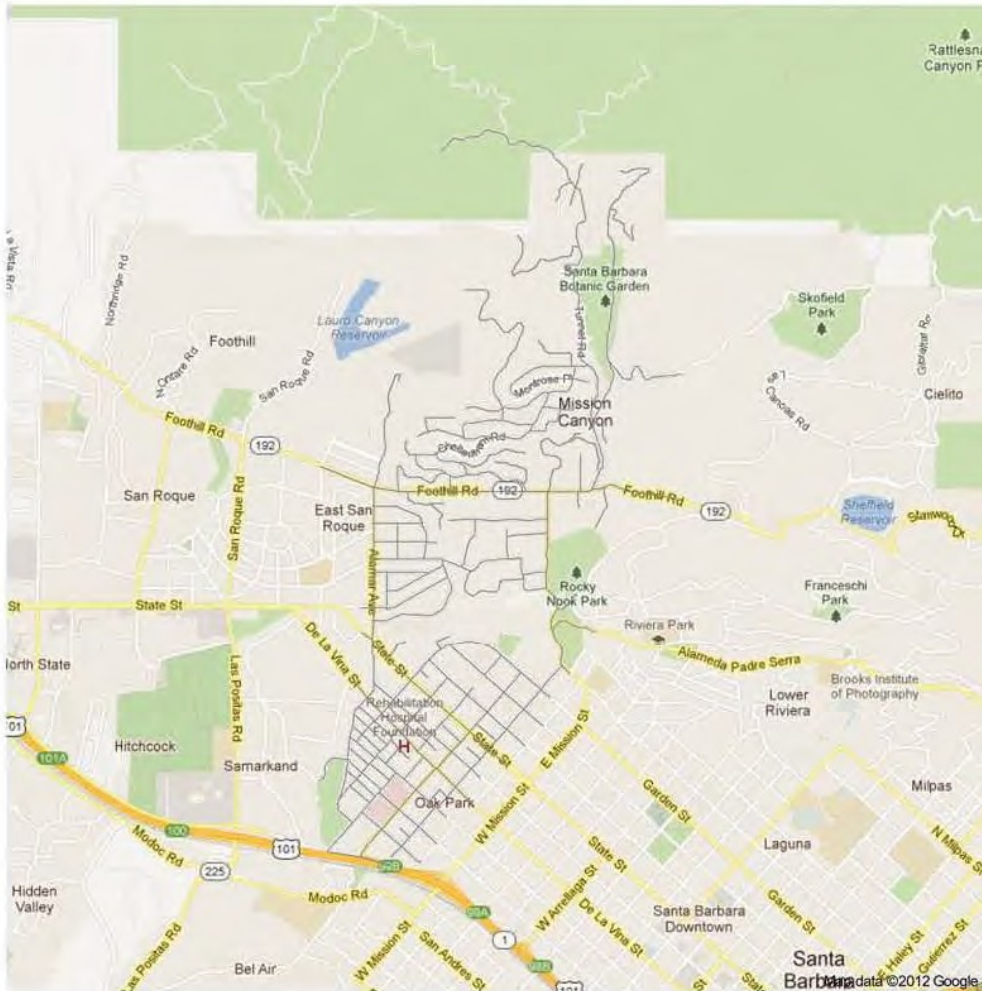
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TRACK II – Cross Cutting Modeling & Simulation

Modeling the Evacuation Decision

<https://survey.ucsb.edu/scripts-7i/perseus6.pl>

Please click on the map to select the street you live on. When the street is selected it will be highlighted in red. It can be unselected by clicking a second time. If your street does not appear on this map, check the N/A box below the map and click next.



☐ N/A

Next



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Please enter the name of the street you live on:

Street





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<https://survey.ucsb.edu/scripts-7i/perseus6.pl>

Did you receive a **voluntary** evacuation order during the Jesusita Fire?

- ☐ Yes
- ☐ No
- ☐ Don't recall

Next





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Modeling the Evacuation Decision

<https://survey.ucsb.edu/scripts-7i/perseus6.pl>

How were you first notified?

- ☐ Reverse 911 call
- ☐ A policeman, firefighter, or other official (CHP, etc) knocked on my door
- ☐ A policeman, firefighter, or other official (CHP, etc) drove past my house with a loudspeaker
- ☐ Radio
- ☐ Television
- ☐ Internet
- ☐ Through the people I live with
- ☐ Through a neighbor
- ☐ Through a friend and/or family member I do not live with
- ☐ Other (please explain)
- ☐ Don't recall

Next





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Modeling the Evacuation Decision

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Did you receive a **mandatory** evacuation order during the Jesusita Fire?

- ☐ Yes
- ☐ No
- ☐ Don't recall

Next





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- ☐ A policeman, firefighter, or other official (CHP, etc) drove past my house with a loudspeaker
- ☐ Radio
- ☐ Television
- ☐ Internet
- ☐ Through the people I live with
- ☐ Through a neighbor
- ☐ Through a friend and/or family member I do not live with
- ☐ Other (please explain)
- ☐ Don't recall

Next





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Did you evacuate during the Jesusita Fire?

- ☐ Yes
- ☐ No

Next





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<https://survey.ucsb.edu/scripts-7i/perseus6.pl>

Jesusita Fire Timeline: May 2009



Please use the time line above to help determine the date and time you evacuated.

I evacuated on

Date

(Click here to choose)

Time

(Click here to choose)

Next





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<https://survey.ucsb.edu/scripts-7i/perseus6.pl>

How well do you remember the time and date you evacuated?

Perfectly Very well Moderately Well Not very well Not at all

Why did you evacuate? (check all that apply)

- ☐ Received mandatory evacuation order
- ☐ Received voluntary evacuation order
- ☐ Felt unsafe and decided to leave
- ☐ The people I live with evacuated
- ☐ My neighbor(s) evacuated
- ☐ Friends or family members I do not live with evacuated
- ☐ Other (please explain)

Did everyone you live with evacuate?

- ☐ Yes
- ☐ No
- ☐ Not applicable

Next





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Modeling the Evacuation Decision

<https://survey.ucsb.edu/scripts-7i/perseus6.pl>

What mode of transportation did you use to evacuate?

- ☐ Drove my car or truck
- ☐ Motorcycle
- ☐ Received a ride from someone else from my place of residence
- ☐ Public transportation
- ☐ Bicycle
- ☐ Walked
- ☐ Other (please explain)

Did other people you live with evacuate separately from you?

- ☐ Yes
- ☐ No
- ☐ Not applicable





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<https://survey.ucsb.edu/scripts-7i/perseus6.pl>

How long after you decided to evacuate did you actually depart?

- ☐ Less than 15 minutes
- ☐ 15 -30 minutes
- ☐ 30 - 45 minutes
- ☐ 45 minutes - 1 hour
- ☐ 1 - 2 hours
- ☐ More than 2 hours
- ☐ Don't recall

How far from your house did you travel to reach your evacuation destination?

- ☐ Less than 1 mile
- ☐ 1-5 miles
- ☐ 5 - 10 miles
- ☐ 10 -15 miles
- ☐ 15 - 20 miles
- ☐ 20 miles or more
- ☐ Don't recall

Next





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<https://survey.ucsb.edu/scripts-7i/perseus6.pl>

How long did it take to reach your evacuation destination?

- ☐ Less than 15 minutes
- ☐ 15 -30 minutes
- ☐ 30 - 45 minutes
- ☐ 45 minutes - 1 hour
- ☐ 1 - 2 hours
- ☐ More than 2 hours
- ☐ Don't recall

How would you describe the traffic conditions you experienced while you were evacuating?

- ☐ Gridlock
- ☐ Heavily congested
- ☐ Moderately congested
- ☐ Lightly congested
- ☐ Free flowing
- ☐ Don't recall

Next



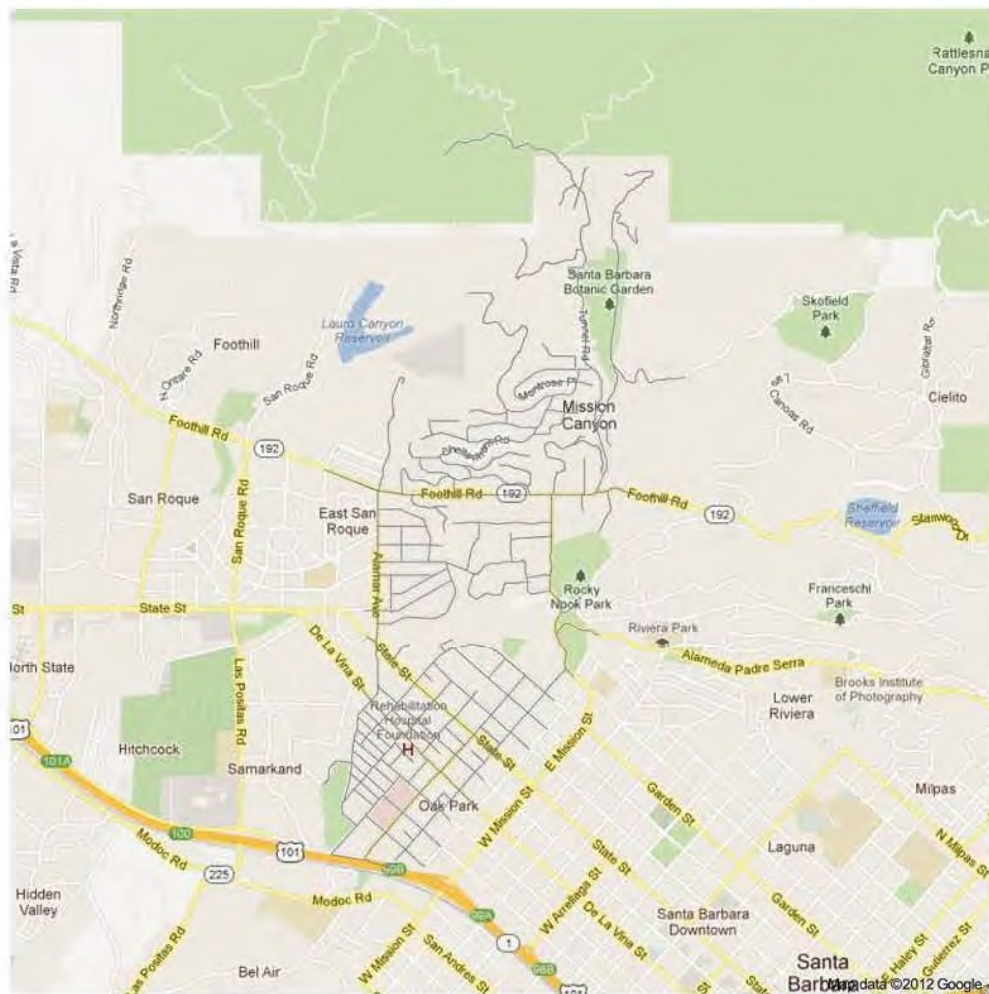
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Modeling the Evacuation Decision

<https://survey.ucsb.edu/scripts-7i/perseus6.pl>

Please click on the map to select the streets you drove on while evacuating from the Jesusita Fire. When a street is selected it will be highlighted in red. It can be unselected by clicking a second time. When you are finished click the submit button. If you did not drive on any of the streets on this map while evacuating, check the N/A box below the map and click next.



☐ N/A



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Please describe your evacuation route (turn-by-turn if possible):

Next





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How well do you remember the evacuation route you took?

Perfectly Very well Moderately Well Not very well Not at all

☐ ☐ ☐ ☐ ☐

Did you consider multiple routes?

- ☐ Yes
- ☐ No
- ☐ Do not recall

Did you change your route while you were evacuating?

- ☐ Yes
- ☐ No
- ☐ Do not recall

Do you have a cell phone?

- ☐ Yes
- ☐ No

Next





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Did you use your cell phone immediately before or during the evacuation?

- ☐ Yes
- ☐ No

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How? *(check all that apply)*

- ☐ Made phone calls
- ☐ Sent text messages
- ☐ Took pictures
- ☐ Connected to the Internet
- ☐ Looked at maps or got directions
- ☐ Other

How was your cell phone reception immediately before or during the evacuation?

Perfect Very good Moderate Not very good No reception at all

Next





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Do you have an in-car navigation system?

- ☐ Yes
- ☐ No
- ☐ Don't know

Next





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<https://survey.ucsb.edu/scripts-7i/perseus6.pl>

Do you have a GPS (other than an in-car or cell phone system)?

- ☐ Yes
- ☐ No
- ☐ Don't recall

Next





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<https://survey.ucsb.edu/scripts-7i/perseus6.pl>

Do you use Google Maps, MapQuest, or other internet mapping websites?

- ☐ Yes
- ☐ No
- ☐ Don't recall

Next





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What was your primary source of information about the Jesusita Fire?

- ☐ Television
- ☐ Radio
- ☐ Internet
- ☐ The people you live with
- ☐ Neighbors
- ☐ Friends and/or family members you do not live with
- ☐ Other

Next





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What other sources did you use to obtain information about the Jesusita Fire?

- ☐ Television
- ☐ Radio
- ☐ Internet
- ☐ The people you live with
- ☐ Neighbors
- ☐ Friends and/or family members you do not live with
- ☐ Other

Next





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<https://survey.ucsb.edu/scripts-7i/perseus6.pl>

Indicate to what extent you agree or disagree with the following statements:

"I received valuable information about the Jesusita fire...

	Strongly Agree	Agree	Do not agree or disagree	Disagree	Strongly Disagree	N/A
... from television."	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>
... from radio."	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>
... from the internet."	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>
... from the people I live with."	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>
... from my neighbor(s)."	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>
... from my friends and family that I do not live."	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>

Indicate to what extent you agree or disagree with the following statement:

"I am confident in the ability of firefighters to protect people during wildfires."

Strongly Agree	Agree	Do not agree or disagree	Disagree	Strongly Disagree
<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>

Next





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<https://survey.ucsb.edu/scripts-7i/perseus6.pl>

Indicate to what extent you agree or disagree with the following statements:

The Jesusita fire posed a high risk to...

	Strongly Agree	Agree	Do not agree or disagree	Disagree	Strongly Disagree	N/A
... my personal safety."	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>
... the safety of the other people I live with."	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>
... the safety of my neighbors."	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>
... the safety of friends and family I do not live with."	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>
... my place of residence."	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>

Next





First Responder Support Systems & Technologies (FiRST) Testbed

TRACK II – Cross Cutting Modeling & Simulation

Modeling the Evacuation Decision

<https://survey.ucsb.edu/scripts-7i/perseus6.pl>

Was your place of residence or surrounding property burned by the Jesusita Fire? (*check all that apply*)

- ☐ My place of residence was destroyed
- ☐ My place of residence was damaged
- ☐ My garage or other outbuilding was destroyed
- ☐ My garage or other outbuilding was damaged
- ☐ Most of my surrounding property was burned
- ☐ Some of my surrounding property was burned
- ☐ A little of my surrounding property was burned
- ☐ My place of residence and surrounding property were not burned
- ☐ Don't recall

Next





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<https://survey.ucsb.edu/scripts-7i/perseus6.pl>

Estimate how close the fire was to your place of residence at its closest point:

- ☐ My place of residence was damaged or destroyed
- ☐ Less than 1/4 mile
- ☐ 1/4 mile
- ☐ 1/2 mile
- ☐ 3/4 mile
- ☐ 1 mile or more

Next





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<https://survey.ucsb.edu/scripts-7i/perseus6.pl>

Have you ever evacuated from a fire or other disaster before?

Yes No Don't recall

☐ ☐ ☐

Indicate to what extent you agree or disagree with the following statements:

"My decision to evacuate or not-evacuate during the Jesusita fire was the right decision for me and I would make the same decision again in a similar situation."

Strongly Agree Agree Do not agree or disagree Disagree Strongly Disagree Not applicable

☐ ☐ ☐ ☐ ☐ ☐

"The experience of previous fires in the Santa Barbara area made me more likely to evacuate during the Jesusita fire."

Strongly Agree Agree Do not agree or disagree Disagree Strongly Disagree Not applicable

☐ ☐ ☐ ☐ ☐ ☐

Next





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Modeling the Evacuation Decision

<https://survey.ucsb.edu/scripts-7i/perseus6.pl>

What is your age?

- ☐ Under 18
- ☐ 18 - 24
- ☐ 25 - 29
- ☐ 30 - 39
- ☐ 40 - 49
- ☐ 50 - 59
- ☐ 60 - 69
- ☐ 70 - 79
- ☐ 80 and over

What is your gender?

- ☐ Male
- ☐ Female

What is your ethnicity? *(check all that apply)*

- ☐ African-American
- ☐ American Indian
- ☐ Asian
- ☐ Hispanic or Latino
- ☐ White
- ☐ Other

Next





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How long have you lived in Santa Barbara?

Years:
Months:

How long have you lived at your current place of residence?

Years:
Months:

Do you rent or own your place of residence (house, apartment, condo)?

- ☐ Rent
- ☐ Own
- ☐ Other (please explain)

How many other people do you live with?

Family members:
Non-family members:





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Modeling the Evacuation Decision

<https://survey.ucsb.edu/scripts-7i/perseus6.pl>

Please use this space if you would like share any other information about the Jesusita Fire, the evacuation, or the resources available for residents

Please enter an email address if you'd like to be entered to win a free iPod

Submit Survey



Planning for a disaster: A review of the literature with a focus on transportation related issues



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Planning for a disaster: a review of the literature with a focus on transportation related issues

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Report Outline

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Preface

The spectrum of possible emergency events ranges from natural events like floods, pandemics and earthquakes to human activity-based disasters like terrorism, train accidents, and nuclear power plant failures. Because disasters do not happen very often, most people become complacent about risks, such as floods and earthquakes. But when one does happen, like hurricane Katrina hitting New Orleans, it is easy to tell when a system response is inadequate. The value of advanced planning and modeling can help to reduce the likelihood of inadequate response to an emergency. It is the responsibility of public agencies to be prepared to deal with such disasters.

Although this report for the most part does not focus on specific types of disasters it is important to understand that there are major risks to the population of California across a wide spectrum of specific types of events. Some events could be particularly disastrous. For example, a study concluded that a terrorist strike on a chlorine tank car along a major railroad route in the Washington, D.C. area could produce a toxic cloud 4 miles by 41 miles and kill and injure up to 100,000 people (Jay Boris, Naval Research Lab). The risk in a number of cities in California is equally great. Even accidents involving bulk shipments of chlorine are dangerous. In 2005 a train accident near Graniteville, S.C. involving a chlorine tank car killed 8 and hospitalized 240 people due to a toxic cloud. Although the probability of such an event has been lowered as some cities have switched to using bleach and other more stable forms of chlorine or other methods of disinfection for water and sewage treatment, this risk is a major issue in the United States. Another example of risk is flooding in California's Central Valley. The system of levees in the Central Valley is considered old and inadequate. In a recent report to the California Department of Water Resources (Independent Review Panel Report (2007)), it is stated that the "the outlook for the future under business-as-usual is grim." The reasons for this prognosis are based upon the current state of the levee system, a better understanding of possible seismic events, the prospect of large and more frequent storms based upon climate change, and the growth of communities and infrastructure within the flood plain. The fact is that major roads and highways may be cut off by floodwaters, reducing the capabilities of emergency response for large areas of the Central Valley.

Even frequent and well planned for events such as wildfires can present transportation challenges. The May 5, 2009 Jesusita Fire constituted a grave threat to the city of Santa Barbara, necessitating the evacuation of nearly 30,000 residents. By most accounts, the threat posed by this hazard was handled well: firefighting resources were allocated efficiently, citizen evacuations went smoothly, and loss of property and life was minimized. Yet during the Jesusita Fire, mandatory evacuation zone boundaries were drawn to specifically exclude nursing homes, hospitals, and other facilities with large evacuation assistance needs. While people remained in these facilities, most major arterial routes in Santa Barbara were extremely congested due to evacuation traffic. Had the winds shifted and these facilities been threatened, could emergency response personnel have moved in and successfully evacuated these vulnerable populations?

Federal agencies such as the Department of Homeland Security (DHS), the Federal Emergency Management Agency (FEMA), and State agencies such as California's Office of Emergency Services have a primary goal to ensure safety, plan to respond in the event of a disaster as well as promote plans and regulations that will decrease risk, increase safety, and reduce possible damages. In a recent report (State of California: Emergency Plan (Draft, Nov. 2008)) all state agencies, including Caltrans are assigned functions associated with responding to an emergency. Agencies such as Caltrans must be prepared for their roles in disaster/incident response. To do this requires a great deal of advanced planning and analysis, for the risks of not planning and responding too late with too little are great and the benefits of making the appropriate response in a timely manner are considerable.

The goal in planning for major emergencies is to plan for the extraordinary. It is important to develop advanced plans whenever possible as well as support research into model development and data collection that can support real time event tracking and mitigation. It is also important to make the best use of limited resources by maximizing the benefits provided to an area undergoing a disaster, whether that be in providing supplies, inspecting damaged infrastructure, or guiding people in an evacuation. The best response to an emergency is based upon advanced planning and research, frequent emergency drills, and maintaining appropriate levels of resources that may be needed in an emergency. This report presents a review of the literature

associated with techniques that have been developed to support disaster planning, response, management and mitigation as well as discuss how some of these techniques can be used specifically for transportation analysis and planning.

Preface Notes: Data or material in preface references the following reports or papers

The data on chlorine based toxic cloud deaths was calculated by Dr. Jay Boris of the Naval Research Laboratory in Washington, D.C. He testified that a worst-case scenario for that city could result in up to a hundred thousand fatalities. An independent Homeland Security Council report on possible scenarios estimated that a ruptured chlorine gas tank car could kill as many as 17,500 people and injure an additional 10,000.

Independent Review Panel Report (2007) “A California Challenge – Flooding in the Central Valley,” Department of Water Resources, State of California, Oct 15, 2007.

State of California Emergency Plan, Office of Emergency Services, Nov. 20, 2008. (Draft)

1. Introduction

Mitigating the impacts of a disaster, like a wildfire, flood or earthquake, rests on doing a number of things right. One can think of all of the elements in disaster planning and operations as links in a chain, in which any link can prove to be crucial and compromise the other elements. To mitigate the impacts of a potential disaster requires considerable forethought, training, and resources. Recent events like 9-11, Hurricane Katrina, and the Oakland Hills fire have demonstrated that many problems can arise requiring quick decisions, crucial information, and plans that can be successfully implemented. In this report, our objective is to review the scientific literature on emergency disaster preparedness, ranging from advanced planning and resource allocation to real-time operations during a disaster. The major objective of this review is to focus on specific tools and modeling approaches that an agency, such as Caltrans, should consider developing or using in emergency management operations.

It is important to recognize that many governmental agencies, like the California Emergency Management Agency (CalEMA), and private organizations like the American Red Cross already play a significant role in disaster planning and mitigation. For example, in California each county is required to set up contingency plans for a wide variety of possible disasters. It is also fundamentally clear that in many circumstances, current systems respond with the necessary capabilities in a timely fashion and gain high marks in subsequent public review. Further, planning drills and mock emergencies also help to focus on critical issues of communication, coordination, and training. Also, modeling tools are being developed which may make it easier to make critical decisions in terms of which roads to close and how to best help an area evacuate.

Past success in dealing with emergencies should not make anyone complacent, as there is still room for improvement in both planning and operations response. For example, there still exist problems of communication between agencies based upon equipment protocols, and the capability to transmit timely event data often doesn't exist. To highlight this issue, one only needs to look at a recent article in the *Santa Barbara Sound* that focused on the lack of timely information available to the public associated with the July, 2008 Gap wildfire. Fire maps that were posted on public kiosks were often several days out of date. Traffic information about road

closures was often misleading, leading to more congestion than necessary. Perhaps the most egregious issue raised in the article is that the City of Santa Barbara cable TV channel posted road closure and other fire information about the 2007 Zaca Fire but not the Gap fire of 2008 while the Gap fire was in progress! As a further example of the possible lack of preparation on the part of emergency services in California, it was found in a recent audit by the City of Los Angeles Controller that the city lacks an overall strategic plan to respond to an emergency such as “an earthquake, fire or other calamity” (LA Times; July 15, 2008). The internal audit identified that 16 of the city’s emergency preparedness plans have not been updated for at least three years, and that one of the fire department plans had not been updated since 1992.

Preparedness should begin with a list of needs to be addressed in the event of an emergency. For each need, specific methods should be outlined in terms of how this need is to be met during the emergency. Do resources exist to meet the emergency demand and how much time will it take in order to respond? What techniques will be available to monitor the event and determine exactly where such resources should be allocated? When the demand for a resource outstrips supply, is there an approved priority defined approach to allocate this scarce resource optimally? Managers of state and county agencies need to ensure that their departments have developed contingency plans so that after an emergency has happened, the agencies are noted for their effective response.

Key factors in any emergency include understanding which infrastructure elements are still functional to support emergency response and possible evacuation, the ability to communicate to those involved as to the actions they need to take, the capability to collect and share real time data about the event among agencies, the capability to respond with support teams and resources, and the restoration of immobilized services as quickly as possible. For a transportation agency or public works department, this entails having enough personnel trained and available to inspect infrastructure, support special communication and transportation needs, and develop and implement an evacuation or emergency response plan.

The major focus of this report is on modeling techniques than can aid in emergency management operations. When there exist a multitude of issues and competing needs for resources, models

can be a significant aid to decision makers before, during, and after an emergency. The basic premise is that many problems are difficult to address without good models and appropriate data. Using such tools and data may help smooth operations and avert tragedy.

This report has been developed as a part of the First Responders System Testbed (FiRST) project at the University of California, Santa Barbara. The FiRST project investigates the integration of transportation and communication modeling and simulation to improve understanding of emergency preparedness and response. The report is organized as follows: We begin by defining key terminology commonly used in the academic literature on emergency management. The next section is a detailed examination of emergency evacuation modeling at multiple scales, with special focus on contraflow lane reversal. Disaster preparedness in California is then examined via analysis of state and county emergency plans, followed by several model formulations that may help planners locate emergency warning systems and shelters optimally. Next we cover emergency response, with a specific focus on models that help allocate personnel and resources where they are needed most. One technique that can greatly aid emergency responders is the pre-positioning of resources in preparation for a disaster, thus we cover this topic in detail as well. We examine the issue of infrastructure fragility, and then conclude with a series of recommendations.

2. Defining terms

This section is devoted to defining the terminology that is used within the field of disaster management. Throughout this section we use issues associated with Hurricane Katrina to underscore specific points. We begin with the term **disaster**. In the most general sense, a disaster occurs when a natural or human-caused event exceeds the capabilities of our respond to it, resulting in an adverse outcome. One of the better definitions of disaster found in the academic literature is “an event, concentrated in time and space, in which a community experiences severe danger and disruption of its essential functions, accompanied by widespread human, material or environmental losses, which often exceed the ability of the community to cope without external assistance (Smith 2004).” It is further possible to subdivide disasters into natural and human, with the former referring to a physical earth process beyond human control

and the later referring to an event caused directly by human actions. This distinction is not absolute, as exemplified by the extensive flooding of New Orleans by Hurricane Katrina that resulted from a natural storm surge overtopping man-made levees.

Underlying any disaster is a **hazard**, which is any natural or technological threat to people or things they value (Cutter 2001). In the case of Katrina, the major hazard was the hurricane itself with storm surge, high winds, and inadequate levee systems as sub-hazards. **Risk** is nearly universally defined as the product of the probability of a hazard occurring and the vulnerability of the people affected by this hazard (Mitigating natural disasters: phenomena, effects and options. A manual for policy and planner, 1991). For example, the people of New Orleans faced a high risk of being adversely affected by Katrina due to the increasing probabilities that it would hit the city (Hurricane Katrina Probabilities Report Number 15 & Hurricane Katrina Probabilities Report Number 21, National Hurricane Center) and the dual vulnerabilities of living in a floodplain and not having the means or desire to evacuate to higher ground.

Vulnerability is defined as the potential for loss, with **physical vulnerability** encompassing the interactions between nature and society and **social vulnerability** composed of the demographic and economic characteristics of different population groups. Put simply, physical vulnerability is the likelihood of exposure to a given hazard while social vulnerability is the likelihood of adverse outcomes (Cutter 1996). These two types of vulnerability are not mutually exclusive and depend heavily on the underlying geography of a place. For example, the physical geography of the New Orleans city site lies at the root of vulnerability, which is a city occupying a very low area that relies on a levee system and pumps for protection.

There are several important geographic parameters for any hazard that help determine physical vulnerability. These can also be thought of as “environmental parameters for human response” (Burton, Kates et al. 1993), as they also largely determine how people may respond when faced with a hazard and thus are a component of social vulnerability as well. **Magnitude** can be generalized as a measurement of the energy released by a given hazard. For example, Katrina had sustained winds of 110 knots when it first made landfall on the gulf coast, thus was classified

as a Category 3 hurricane according to the Saffir-Simpson Hurricane Scale (Knabb 2006). Other familiar measures of magnitude include the Richter scale for earthquakes, the Fujita scale for tornados, and could include the surge height of a tsunami or speed of movement of a wildfire front. **Frequency** is how often an event of this magnitude occurs. Katrina was a Category 5 storm shortly before landfall, and the frequency of the formation of a Category 5 hurricane forming in the Atlantic basin is on average once every three years (Atlantic Tracks File, 1851-2007, National Hurricane Center). Over 80 tsunamis have hit the California coast since 1850, thus the frequency of such an event is approximately once every 2 years (The Tsunami Threat to California, CA Seismic Safety Commission). **Duration** is how long the event persists. As an example, Katrina produced hurricane force winds in New Orleans for less than 24 hours, but the subsequent floodwaters inundated the city for weeks afterward. The Gap Fire in the Santa Ynez Mountains near Santa Barbara began on July 1, 2008 and was declared fully contained on July 28th (InciWeb, Gap Wildland Fire). **Areal extent** is space covered by event, which ranges from relatively small such as the 9,443 acres burned by the Gap Fire to very large in the case of Katrina, with hurricane force winds at one point extending 90 nautical miles from the storm's center. (Knabb 2006) **Speed of onset** is length of time between initial event appearance and its peak. Katrina was classified as a tropical storm five days before reached its peak category 5 strength, thus giving this event a much slower speed of onset than a tsunami (a few hours at most) or an earthquake (instantaneous). **Spatial dispersion** is the pattern of distribution over the space in which the event can occur. Hurricane wind speed and earthquake intensity decrease with distance from the event center, while a wildfire front may jump large areas or change direction in an unpredictable fashion. **Temporal spacing** is the sequence of events. A simple timeline for the events in New Orleans surrounding Katrina could be *storm surge, levee breaches, flooding*, while a timeline for an earthquake could be *ground shaking, building collapse, structure fire, aftershock*. Time periods are also an important component of temporal spacing, particularly when planning evacuations or search and rescue operations.

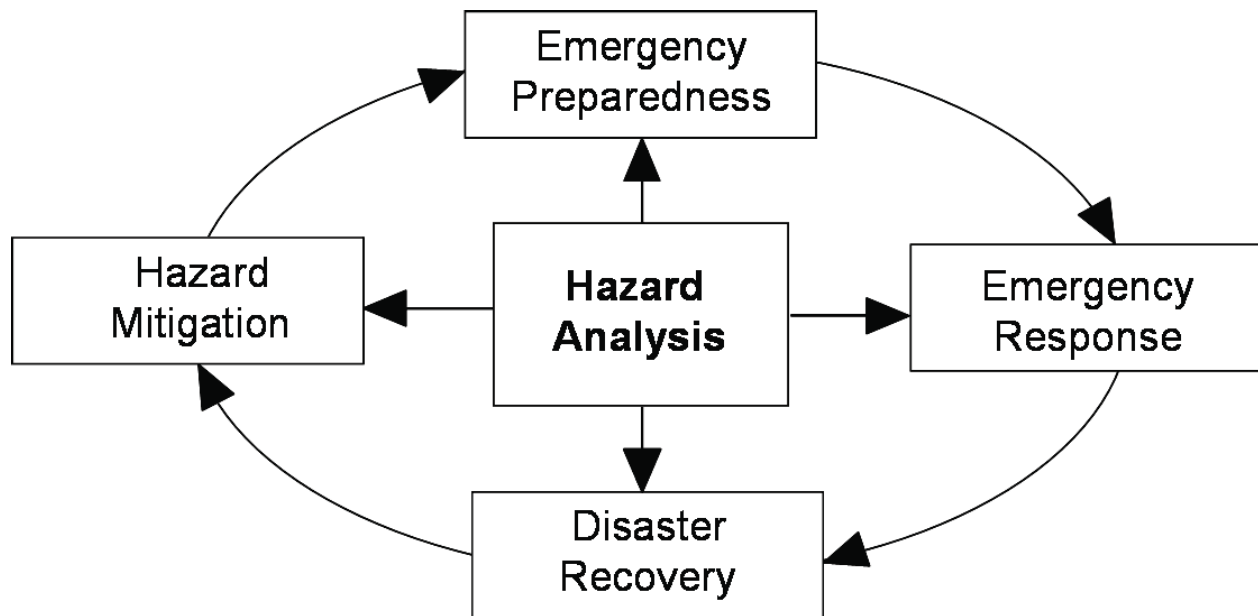
Understanding the unique history of **social vulnerability** in New Orleans is essential to forming a complete picture of the Katrina disaster. Land value in the city is greatest on the highest ground, not surprising given the geographic advantage of being the last to flood and the

first to dry out. African-Americans have always inhabited the lowest lying land, with Jim Crow laws and redlining practices perpetuating slavery's legacy of racial segregation (Colten 2002). When floods strike, the poorest citizens suffer most, perpetuating the cycle of poverty and vulnerability. The geographic variation in social vulnerability requires different mitigation, response, and recovery actions – the one-size-fits-all approach is ineffective (Cutter, Emrich et al. 2006). Living in the most flood prone areas is only one component of the social vulnerability of New Orleans' marginalized populations. With poverty comes limited access to resources, with the inability to secure private transportation playing a significant role in the Katrina tragedy. Mistrust of authority grows out of inequality, leading to a significant communication gaps between government and impoverished citizens. One method that allows emergency management officials to focus disaster mitigation efforts is to identify 'hotspots' of vulnerability. For example, Rashed and Weeks (2003) use a Geographic Information System (GIS) to identify census tracts in Los Angeles County that are vulnerable under historic earthquake scenarios. In each scenario, vulnerability is calculated as a function of both the physical geography and socioeconomic population characteristics of affected places. This spatial multicriteria analysis is combined with fuzzy logic to produce a methodology that takes into account the inherent uncertainty in measuring vulnerability, providing a more robust analysis of susceptibility to earthquakes in Los Angeles.

The four **stages of emergency management** commonly used in the United States are mitigation, preparedness, response, and recovery (Waugh and Hy 1990). **Mitigation** actions reduce the long-term risk of vulnerable populations, including but not limited to zoning decisions, building and safety codes, insurance, and hazard mapping. In assessing the extensive building damage caused by Katrina, the FEMA Mitigation Assessment Team concluded that the lack of a building code not only contributed to residential damage but also to essential facilities including hurricane evacuation shelters, police and fire stations, hospitals, and Emergency Operations Centers (FEMA 2006). Inhabitants of areas along the wildland/urban interface are generally advised to create defensible space on their property to prevent a wildfire from spreading from natural fuels to man-made structures. **Preparedness** activities build operational capability for disaster response and include emergency operations planning, personnel training, and emergency warning systems and communication networks. One of the

few positive outcomes of Hurricane Katrina was the successful development and execution of a contraflow evacuation plan which involved switching the direction of travel of one the I-10 freeway segments to accommodate heavy traffic flow in one direction. This procedure is examined in detail in a later section of this report, but it is important to note that during the Katrina evacuation nearly all persons with access to private transportation were able to escape the city well before hurricane landfall and in less time than anticipated by planners (Wolshon, Catarella-Michel et al. 2006). **Prepositioning** of emergency supplies and locating emergency warning systems are two preparedness activities of particular relevance in California, both of which are further discussed in greater detail. Actions taken in the immediate time periods before, during, or after a disaster fall under **response**, encompassing warnings, evacuations, sheltering, and search and rescue. Preparedness largely determines response capabilities, which were severely limited during Katrina by the inadequate allocation of vehicles and emergency shelters. New Orleans city buses picked up residents and transported them to the Superdome, which was only stocked with enough provisions to feed 15,000 people for 3 days. 30,000 evacuees crowded into the Superdome, which lost electrical power and was completely surrounded by water. 500 school buses that could have been utilized to evacuate vulnerable residents were flooded and immobilized, and the national guard barracks and the high water rescue vehicles they contained were flooded as well, forcing guardsmen to concentrate on saving themselves (Smith 2005). A mutual aid agreement allows emergency responders in California to solicit assistance from other agencies, whose help is often critical to appropriate response to large hazards (Akella 2008). **Recovery** activities are focused on restoring vital systems that expedite the return to normal life, such as setting up temporary housing, clearing debris, and rebuilding or repairing damaged infrastructure. The Army Corps of Engineers unit based in New Orleans was concerned about the levees, yet had no external monitoring equipment for them and had to rely on media reports to find out if they were functioning. Since roads and canals were inaccessible, the Army Corps had to rely on helicopters for the levee repairs necessary to hold the water at bay. It took over a month for the combination of levee repair and pumping to finally dry out the city (Penry-Davey and Chinn 2005). A study of recovery from the 1994 Northridge earthquake found that socially vulnerable populations such as the poor, elderly, and ethnic minorities often rely heavily on non-governmental organizations (NGOs) to met disaster relief

needs (Bolin 1998). The four stages of emergency response are distinct but clearly interrelated, as the following conceptual model from Lindell and Perry (2004) shows.



The final key term that we will define in this section is **interoperability**. Soon after Katrina made landfall, electricity, land lines, cellular networks, and local media outlets failed, leaving emergency officials completely unaware of the extent of damage and the massive flooding that had begun in the city's ninth ward. This massive infrastructure failure contributed to the inability of public safety responders to communicate, but the use of different communication technologies operating on separate frequencies by the multitude of agencies responsible for emergency response looms much larger. Communications interoperability allows personnel from various emergency management agencies to talk seamlessly over one radio and data system across a wide geographic area such as a metropolitan region or state. While achieving interoperability has been a long-standing goal of law enforcement, fire and rescue agencies, funding, governance, and cooperation remain major obstacles to implementation (Mountjoy 2005).

3. Evacuation

Modeling the complex spatial interactions between people and their environment that occur during an evacuation is an important step in developing a successful emergency plan. Despite recent advances in technological capabilities and modeling techniques, coordinating the movement of large numbers of frightened people through a confined space in a short amount of time presents a daunting challenge for researchers. This problem is inherently geographic in nature: spatial and temporal scales are what define the complexity of the evacuation process and dictate the appropriate modeling technique. Spatial scale is important in accounting for the location and characteristics of populations that must evacuate, the layout of the transportation network, and the area affected by a hazard when formulating an evacuation plan. Temporal scale is crucial as well, as event speed of onset largely dictates the start and end times of an evacuation. This scale-based approach has its roots in two classic problems, a large-scale evacuation due to a nuclear power plant accident and the small-scale evacuation of a building. Building evacuation is of great importance even in transportation as techniques developed first for building evacuation now form the basis for most evacuation models in transportation. Disastrous fires such as the 1977 Beverly Hills Supper Club (Southgate, Kentucky), which killed 165 people forced building engineers and fire departments to determine appropriate safe routes from buildings, establish maximum occupancy standards for rooms and change materials to retard the spread of fire. Although the scale of a building is different from a neighborhood or town many of the same issues underlying safe evacuation are present.

Before discussing the nuclear accident and building evacuation problems, it is important to define what is meant by a model. In the simplest construct, a **model** is a simplified version of a real world process, system, phenomenon, or entity. For our purposes this model must include one or more mathematical equations, thus allowing for a solution through enumeration, an algorithm or a heuristic technique. Often models are solved many times with varying input parameters, thus producing a host of solutions to give researchers a better idea of how certain inputs can affect model results. Introducing an element of randomness in a model can produce a

stochastic simulation, which accounts for uncertainty within the underlying process. When geography is explicitly accounted for in such a model it generally will fall into the classification of spatial optimization or spatial statistics.

Back to the question at hand: how best to model evacuations due to a nuclear power plant accident or building fire? Since these problems are fundamentally different in scale, the best approaches for modeling them are different as well. To get the most accurate representation of how people may behave when leaving a building, each person should be individually represented in the model. This technique is known as agent-based modeling or microsimulation, and is best suited to problems of limited size due to the computational complexity of representing individual people and their interactions. Microsimulation can also refer to the modeling of individual vehicles on a transportation network, but the essential small-scale characteristic of such an approach remains. At the other end of the spectrum is the large-scale evacuation required in the event of an accident at a nuclear power plant. Here the goal is to move thousands of people away from the accident site as quickly as possible, thus the inherent size of the problem makes microsimulation less feasible. Macro-scale models group population into larger units, which can then be moved through the transportation network under different starting conditions producing a generalized evacuation plan. The benefit of such an approach is that it can simplify the complex interactions of large groups and thus be solved quickly, which is essential to real-time modeling for decision support. One downside is that the further away one moves from the reality of individuals as independent actors, the greater the likelihood of individuals or groups of people being unaccounted for in the model. Between these two approaches is the meso-scale model, which is neither microscopic nor macroscopic but rather borrows elements from each. A meso-scale model will not represent people individually but may aggregate them into relatively small population units, unlike the macro-scale model, which seeks the largest feasible unit. The spatial extent of meso-modeling can be at the neighborhood or community level, or the entire area affected, e.g. hazardous material cloud or a plume of radioactive material.

Choosing the appropriate modeling scale to use is an important question that extends beyond the narrow scope of evacuations. One way to aid in making the choice of scale is to group potential hazard responses into a typology of disaster management decisions (Wallace 1985). Using this

framework, a micro-scale model is considered best suited to an operational decision such as a neighborhood evacuation occurring at a small spatial and temporal scale. A strategic disaster management decision is made at a large temporal and spatial scale, thus a disaster preparedness tactic such as resource pre-positioning is best modeled at the macro-scale. Tactical operations incorporate both operational and strategic decision making processes, while meso-scale models are often used for location-routing problems at a medium temporal scale such as providing EMS coverage. Now that these different modeling scales have been defined, we will examine how researchers have used them to model evacuations in response to hazards.

Quantitative modeling is an important compliment to the various qualitative studies of emergency evacuation. The partial meltdown at the Three-Mile Island Nuclear facility in 1979 spurred survey-based research on the geography of evacuee behavior, examining route preferences and travel distance (Zeigler, Brunn et al. 1981) and the spatial distribution of social vulnerability (Cutter and Barnes 1982). Many evacuation modeling approaches are based on the groundbreaking research of Dial (1971), who developed a method to account for the fact that drivers will often choose routes that are not the shortest distance to their destinations. This approach better reflects the dynamic and unpredictable flow of traffic during an evacuation. Other researchers have built on this framework and introduced an element of random route assignment that represents driver behavioral decisions under conditions of distance and network topology uncertainty (Daganzo and Sheffi 1977). Estimation of network clearance time emerges as the central focus of evacuation modeling, thus most of the current research has its roots in a modeling approach that can calculate clearance times given variability in network characteristics, intersection control and design, and evacuation strategies. One of the first examples of this is NETVACI, which uses the mathematical relationships between flow, speed, density, queuing, and other traffic measures to estimate clearance time on a node/arc network representation (Sheffi et al. 1982). Applications of this model to simulate evacuations around several nuclear facilities demonstrated that it could efficiently handle relatively large networks, an important consideration even with the development of faster and more capable computers.

An early example of a decision support system designed to craft an evacuation plan is the Transportation Evacuation Decision Support System (TEDSS), which allows planners to

estimate network clearance times for various evacuation scenarios for nuclear power plants (Hobeika, et al. 1994). Another important component of an evacuation plan is where to house evacuees. Yamada (1996) solved two network transportation problems, a shortest path problem and minimum cost network flow problem, with the goal of allocating residents to places of refuge during a simulated evacuation in Yokosuka City, Japan. Results show that the classical shortest path (Dijkstra 1959) solution results in a more uniform evacuation plan and shortest average distance, while the minimum cost solution will split evacuee flows forcing some residents to go to a place of refuge that is not their closest. One interesting theoretical outcome of this research occurs when evacuees are instructed to go to a location further away than the nearest shelter: the greater the disparity between shortest path and maximum network flow solutions, the greater the potential problem of non-compliance by evacuated populations, resulting in an event which will take longer to clear and where a few shelters are likely to be overwhelmed.

Many early models of building evacuation use a network flow formulation similar to those discussed above. Chalmet and Francis (1982) present some of the first research to address problems such as bottlenecks that may occur during the emergency evacuation of buildings. They present a simple model that can efficiently allocate evacuees to exits, thus helping prevent bottlenecks from occurring. For a given building, let:

- k total number of people to be evacuated
- n total number of exit routes
- j index of exit routes
- x_j people using exit route j
- $t_j(x_j)$ time for x_j people to clear exit route j

We can then allocate people to exit routes to minimize the time that it takes the last person to get out of the building using the following formulation:

Minimize $Z = \max t_j : x_j, j = 1, \dots, n$

subject to :

$$1) \sum_j x_j = k$$

$$2) x_1, \dots, x_n \geq 0$$

This model seeks to minimize the maximum amount of time it takes a given group of people to evacuate using a given exit, while ensuring that the entire building is evacuated. The two major assumptions of this model are that each evacuee has access to every exit route, and that the time to clear an exit route relies only on the number of people using it. Comparison of the estimated clearing time of an eleven story building generated by a related but more complex model to empirical measurement of an actual evacuation showed that the model was overly optimistic, largely due to the inability to account for queuing and inefficient evacuee movement through stairwells. This model weakness is due to a linear equation structure that assumes all flows along arcs between origin and destination nodes are constant. This is the very feature that is faced when evacuating an area, where the speed of traffic decreases as the density or number of vehicles per lane mile increase.

A way to account for this weakness is to introduce nonlinear side constraints to the model which allow dynamic evacuee movement to be accounted for (Choi et al. 1988). Models of this type can often be solved expeditiously for small scale building evacuations, but otherwise offer little advantage when compared with agent-based microsimulation. EXIT89 is an early example of a high-rise building microsimulation model which allows stochastic variation in individual evacuee behavior, queuing, and evacuation speed to be represented, thus producing a result more closely in line with actual emergency conditions (Fahy 1995). The ability to model individuals can be incorporated into a Geographic Information System (GIS) to create valuable tools for emergency planners.

Most evacuation based decision support systems are based upon a model integrated with a Geographical Information System (GIS). These computer programs use the topology and feature attribute capabilities of GIS in conjunction with location decisions and simulation runs produced

by models to assist in the decision processes of emergency planners. One of the first systems designed specifically for emergency evacuations is CEMPS, the Configurable Emergency Management and Planning System (Pidd et al. 1996 and de Silva and Eglese 2000). In this system, the GIS is used first to map the terrain and identify the population to be evacuated. These data are stored in a database, which is accessed by a discrete microsimulation model that is used to assess various routing schemes for moving the evacuated population to designated safe areas. The major limitations of most of this earlier work are due to the inability of the microsimulation model to account for dynamic route selection due to congestion, traffic effects such as ‘scrunching’, and the behavior of emergency vehicles. Many of these issues have been addressed by subsequent microsimulation research, greatly improving realistic representation of traffic conditions during evacuations.

One novel approach of representing traffic dynamics is to adopt methods commonly used in physics (Helbing 2001). Using models analogous to micro-scale (particle-base), meso-scale (gas-kinetic), and macro-scale (fluid-dynamic) approaches, physicists have concluded that it is possible to simulate complex traffic interactions and develop natural laws that explain driver behaviors under a multitude of traffic conditions. Of particular interest is a model that incorporates both macro-scale and micro-scale approaches that is well suited to the traffic jams and bottlenecks that may occur during an evacuation.

Rapid housing development and population growth in fire prone areas is of particular concern to California evacuation planners. Most evacuations at the wildland-urban interface occur at the neighborhood level, thus are well scaled to commercial microsimulation software. (Cova and Johnson 2002) developed a modeling approach that incorporates a custom evacuation scenario generator, GIS, and an off-the-shelf microsimulation package to estimate the time it would take each household to evacuate under a multitude of conditions. Using individual household evacuation times allows planners to assess the spatial variability of vulnerability to a hazard and provides a much greater level of detail compared to traditional evacuation measures such as network clearing time. This enables plans that are tailored to the specific needs of a community and thus have a greater probability of successful execution.

Timing of evacuations is another important problem that must be addressed by emergency managers, especially when a large population must be relocated on short notice. Inefficient scheduling can lead to traffic gridlock, impeding the evacuation procedure and increasing evacuee risk of being affected by a hazard. Issues of temporal scale were examined in a microsimulation of a large-scale evacuation of San Marcos, Texas, where researchers found that staged evacuations are more efficient than an all-at-once evacuation for densely populated areas with a grid street network (Chen and Zhan 2006). Recent research in modeling of the process of passenger loading and unloading of planes identified that the fastest method of loading and unloading occurred when people are staged, but also separated (e.g. every third row). Thus, it may be possible to show in simulation that staging with separation may aid in evacuation as well.

Many evacuation modeling approaches rely on the delimitation of an emergency planning zone (EPZ). Cova and Church (1997) point out that defining an EPZ in advance is problematic for fast moving hazards where the population that will need to evacuate is unknown in advance. Because of this they developed a critical cluster model (CCM) to identify neighborhoods that may face transportation difficulties if forced to evacuate. As previously noted, most evacuation modeling addresses either macro-scale events like a hurricane or micro-scale events such as a building fire. The Cova and Church model is among the first to address neighborhood, or meso-scale, evacuation vulnerabilities. The first step in finding a vulnerable neighborhood, or critical cluster, is develop a network representing flow capacities along with attaching estimates of the population needing to evacuate at each node of the network. The next step is to apply the CCM to find clusters of contiguous nodes that have the highest average population per exit lane. This problem is closely related to the graph partitioning problem, and can be defined using the following notation:

- N set of all nodes
 N_1 contiguous partition of nodes containing i^*
 N_2 nodes connected to N_1
 i index of nodes
 j index of nodes connected to i
 a_i weight of node i (population)
 c_{ij} cost of arc ij (lanes)
 s maximum size (in nodes) of N_1
 i^* index of root node $\in N_1$
 x_i 1, if node i is in N_1
 $\lambda 0$, otherwise
 y_{ij} 1, if node i is in N_1 and node j is in N_2
 $\lambda 0$, otherwise

Using this notation, we can formulate the model as:

$$\text{Maximize } Z = \frac{\sum_i a_i x_i}{\sum_i \sum_j c_{ij} y_{ij}}$$

subject to :

- 1) $x_i - x_j \leq y_{ij} \quad \forall i, j \text{ and } i, j \in N$
- 2) $\sum_i x_i \leq s$
- 3) $x_{i^*} = 1$
- 4) $x_i, y_{ij} \in \{0,1\} \quad \forall i, j \in N$

This model maximizes the total population relative to the capacity of the exit lanes, defined as those links connecting selected cluster nodes and nodes directly outside the cluster. The CC model was applied to data of the Santa Barbara area and each node was assigned an evacuation vulnerability value (associated with the worst case cluster in which that node was a member) resulting in an evacuation vulnerability map of Santa Barbara. The results of this application

clearly showed that evacuation difficulty varied from area to area. Transportation planners already recognized some of the more vulnerable areas, but other areas that were identified were a surprise to many.

Church and Sexton (2002) use a different methodology to research evacuation vulnerability at the micro-scale. The Mission Canyon neighborhood in Santa Barbara was previously identified as a critical cluster due to a sizeable population base reliant on a limited number of routes for evacuation. This neighborhood also lies in the urban-wildland interface and is especially vulnerable to wildfires propelled by sundowner winds moving down canyon with great speed. Previous work had estimated evacuation time for such areas by comparing the total vehicle demand to the number of lanes leaving the neighborhood. This research tests the assumptions of this macro-scale approach by modeling different evacuation scenarios using micro-scale traffic simulation. Running multiple simulations allowing the number of vehicles, number of exit routes, road capacity, and level of traffic control to vary, Church and Sexton found that major evacuation problems might occur without a significant coordinated traffic control effort and extensive resident education. Several interesting problems arise from this microsimulation, including the inability of the software to model vehicles that back out of driveways. During times of high fire risk, emergency officials recommend that people back into the driveway (so they are facing the street) to speed up evacuations, but this recommendation is rarely followed. Another interesting problem is that drivers are given dynamic feedback during the microsimulation, thus mimicking the effect of a special radio channel broadcasting real time information on crowding along specific evacuation routes. This assumption speeds up the simulated evacuations, but may not reflect the actions of drivers (turning on the radio) or local broadcast or information gathering capabilities. Overall, they find that while macro-scale evaluation provides similar evacuation time estimates as microsimulation, neither approach can fully account for driver behavior or the behavior of what might happen during an accident or blocked exit (e.g. people abandoning their vehicles on the street causing a relatively permanent roadblock).

One assumption that is frequently made in evacuation modeling is that drivers will behave rationally. Among these assumed behaviors are that evacuees will understand the instructions given them by officials coordinating the evacuation, follow these instructions exactly and obey all posted speed limits and traffic laws. While it is often necessary to make assumptions in order to limit the size and complexity of models, the fear and panic that often occurs when people are threatened should not be overlooked as it may severely affect their decision making. Pel and Bliemer (2008) help account for this uncertainty by introducing a model that explicitly incorporates driver behavior when assessing both voluntary and mandatory evacuation plans. Their three-stage model includes travel demand, travel choice, and network loading components, with the travel choice module capable of modeling the behavioral responses of the evacuees towards evacuation instructions such that they can be followed fully, followed in part, or rejected completely. Models such as these represent an important advance for researchers who seek to produce the most accurate representation of an evacuation situation possible.

Another problem faced by emergency managers is compliance with a mandatory evacuation order. Dow and Cutter (2002) report that only 65% of South Carolinians ordered to evacuate in response to Hurricane Floyd actually did so, thus greatly compounding the problem of keeping people safe from the storm. A related problem is ‘shadow evacuation’, which occurs when people decide to evacuate despite not receiving any official instructions to do so. This may contribute to traffic delays and emergency resource shortages, impeding the safety of those who are directly threatened by the hazard. Research based in Long Island, NY concluded that evacuation planning areas should be expanded in response to the high likelihood of shadow evacuation in the event of a nuclear accident (Johnson 1985). While this approach may help traffic planners design better evacuation models, it does not address the underlying causes of a shadow evacuation. Environmental cues, such as high winds and smoke during a wildfire, can prompt people to evacuate even if they are not directly threatened. A more troubling cause of shadow evacuations is mistrust of information or the authorities who provide it (Lindell and Perry 2004), a problem that may be addressed by providing the most accurate hazard information as quickly as possible to people in an effected area. Although shadow evacuations have been modeled using microsimulation (Cova 2008), further research on this problem through mathematical modeling techniques may be of great benefit to evacuation planners.

The successful evacuation of New Orleans prior to the arrival of Katrina was made possible through the use of contraflow. Contraflow involves reversing the direction of traffic for a set of lanes along a route, so the capacity of a route to handle traffic in a desired direction is enhanced. The success of using contraflow is highlighted in the following statement by Kathleen Blanco (Former Governor of Louisiana):

“Before Katrina came, I developed a new evacuation plan that includes contra-flow, where both sides of the interstates are used for outbound traffic. I am proud that we rapidly moved over 1.2 million people - some 92% of the population - to safety without gridlock or undue delay prior to Katrina.”

Contraflow lane reversal is a valuable option in emergency evacuations by increasing the outbound traffic capacity of a given road or freeway. The first large scale implementation of contraflow occurred in Georgia and South Carolina for Hurricane Floyd evacuations in 1999, and a majority of hurricane threatened states have now adopted contraflow plans (Urbina and Wolshon 2003). As the quote above illustrates, contraflow can be very effective in efficiently moving a substantial proportion of the population in areas threatened by large-scale disasters. Yet the tragic aftermath of Hurricane Katrina shows that it is not a ‘magic bullet’ solution for evacuation planning, especially in places like New Orleans with large populations without access to private transportation. While the vast majority of contraflow evacuation plans are hurricane-specific, many characteristics could be generalized and implemented for other large-scale disasters.

The state of Florida revised its contraflow evacuation plan in response to the busy 2004 hurricane season. With 4 major hurricanes prompting the evacuation of nearly 10 million people, the Florida Division of Emergency Management and the Florida Department of Transportation determined that an improved contraflow plan was necessary given the probability of its implementation for future hurricane evacuations. Some essential components of the updated plan are daylight only contraflow implementation, pre-positioning of traffic coordination

and emergency response vehicles along the contraflow route, and clear delineations of agency roles and means of communication. Specific routing recommendations include assigning the same number of lanes for contraflow exit points as the contraflow route itself has and keeping highway shoulders open for disabled vehicles and emergency responder use. (Contraflow Plan for the Florida Intrastate Highway System, 2005)

Empirical assessment of contraflow evacuation plans utilized during hurricane events shows substantial improvements in vehicle capacity yet also clearly illustrates drawbacks. During the 2000 Hurricane Floyd evacuation, the South Carolina Department of Transportation (SCDOT) measured a 67% increase in the number of vehicles evacuated per hour with four outbound freeway traffic lanes when compared to the standard two inbound, two outbound configuration. Safety, accessibility and cost emerge as the most pressing problems during a contraflow operation. Freeways are generally not designed to handle opposing flow, thus confusing signage, inadequate collision barriers and limited exit ramp accessibility can lead to accidents and breakdowns that may further traffic delays. Contraflow plans can reduce or eliminate inbound traffic, limiting the ability of emergency service personnel to assist those left behind. Manpower requirements can be substantial, with more than 70 personnel needed for an 18 interchange contraflow plan in North Carolina (Wolshon 2001). These empirical results provide a basis for modeling and simulation-based research, which can address the challenges of contraflow evacuations in a controlled setting.

Microsimulation of contraflow for hurricane evacuation of New Orleans showed how suboptimal entry point design and location could limit the number of evacuees able to leave the city (Theodoulou and Wolshon 2004). A North Carolina coastal evacuation simulation showed extensive queue formation at contraflow termination points, highlighting the need for further research on optimal access points and interchange functionality (Williams, et al. 2007) Another challenge in modeling contraflow is the increased size of network flow problems that must account for each individual lane rather than representing roads as a single arc. Tuydes and Ziliaskopoulos (2006) use a tabu search heuristic to address the computational complexity of modeling a contraflow evacuation on a large urban network. Although most research has been directed towards hurricane evacuation, contraflow can be incorporated into traffic management

models for other large-scale disasters. Research comparing different evacuation strategies for downtown Minneapolis, Minnesota also shows that access to a contraflow corridor is a critical determinant of overall effectiveness. By increasing capacity of key entrance ramps, evacuation time was substantially reduced for an evacuation simulation that included more than 50,000 spectators at a major sports venue. (Kwon and Pitt 2005)

Lane-based traffic routing can improve traffic flow during an evacuation by eliminating congestion at critical intersections. When Los Alamos, New Mexico was evacuated in response to the 2000 Cerro Grande wildfire, a lane-based routing plan helped 11,000 residents escape this isolated mountain community using the one available exit in under 4 hours (Mynard, et al. 2003). The essence of a lane-based plan is that it restricts lane changes and directs traffic to make turns at intersections in order to avoid cross traffic. Cova and Johnson (2003) use a lane-based routing model to simulate traffic during an evacuation of downtown Salt Lake City, generating a 40% improvement in network clearing time when compared to no routing plan.

A new and promising approach to contraflow modeling is taken by (Meng, Ling et al. 2008). The optimal contraflow lane configuration problem (OCLCP) and the optimal contraflow lane-scheduling problem (OCLSP) are addressed by combining the linear programming and microsimulation methods. First, the linear program is used to determine a feasible lane-reversal plan that minimizes total travel time in the central business district of Singapore. This plan becomes an input to a microsimulation model developed with PARAMICS software that mimics the response of drivers to these lane reversals. This methodology allows researchers to systematically evaluate each contraflow plan by providing instant data on traffic flow rates and queuing via the microsimulation software.

Although contraflow under emergency evacuation conditions is not implemented as part of their routing plan, it could be incorporated under a similar modeling framework. This unification of traffic routing methods has the potential to further improve network clearing times for mass evacuations, especially if used to address the access point and queuing problems of contraflow operations. There remains a central question that has not been answered by any of the above

models: What evacuation routes will drivers actually choose? Route choice behavior is largely based on the assumptions of rational driver behavior under perfect information, both of which are questionable in emergency evacuation situations given a large-scale disaster. Chiu and Mirchandani (2008) propose a dynamic feedback information routing system, in which evacuation routes are updated according to the current traffic conditions. Such a system could be implemented using existing traffic monitoring and mass communication technologies, and can significantly improve evacuation effectiveness through real-time management.

Spatial and temporal scales are crucial geographic factors in determining the evacuation modeling approach best suited to a given hazard. Individual (micro), aggregate (macro), and intermediate (meso) spatial scale models all have specific strengths and weaknesses which should be carefully considered based on both the capabilities of researchers and the needs of agencies. Timing is critical: a contraflow evacuation plan requiring 5 hours of lead time for placement of signage and personnel is of little use in the face of a levee that breaks without warning. With careful consideration of these factors, modeling can prove invaluable to the formulation of a successful evacuation strategy. The contraflow operations in New Orleans prior to Hurricane Katrina and lane-based routing of evacuees from the Los Alamos, New Mexico Cerro Grande Wildfire provide two examples that demonstrate the benefits in modeling evacuations.

4. Disaster Preparedness

Counties and state organizations are tasked with the development of disaster plans, involving a coordination of agencies and nongovernmental organizations. Such planning documents often list possible emergencies (from chemical spills to flooding), areas of vulnerability (from high fire risk areas to nuclear power plant evacuation zones), and plans for addressing such emergencies. Typically, counties plan drills that are used to train and test for the ability to respond to an emergency. They often are based upon an emergency scenario, bringing a wide variety of emergency personnel in handling a mock disaster drill. These drills are used to identify weaknesses in plans, strengthen ties of communication and promote a focus on coordination and team building.

The role of Caltrans as defined in a November 20, 2008 draft of the State of California Emergency Plan presents several logistical issues of particular interest to researchers affiliated with the First Responders System Testbed project. The first Caltrans responsibility of interest is the classification of state property suitable for use as temporary emergency housing. Selecting suitable sites can be thought of as a function of accessibility via the existing transportation network, proximity to populations in need of temporary shelter, and cost effectiveness in the transportation and support services necessary to meet the needs of affected people. Another Caltrans role is the support of fire-fighting efforts through traffic control via lane-closures or special OES requests such as movement of emergency supplies. Closure of a lane for emergency-only use or allocation of HOV lanes may provide the extra traffic capacity necessary for fire personnel to respond quickly to a dangerous wildfire, and likewise enable the efficient and timely transport of emergency supplies to places of need. Caltrans responsibilities for dealing with hazardous materials and radiological substances also present opportunities for research. Restoring contaminated highways and other state transportation facilities is essential to maintaining efficient and safe traffic flow. Traffic routing with differing network capacities under emergency conditions and allocation of assets before an emergency event occurs emerge as pervasive themes that can be addressed through various modeling techniques to improve Caltrans disaster preparedness.

Responsibility for emergency management in California counties falls under the auspices of each county office of emergency services (OES). A brief survey of county OES websites shows wide discrepancies in the quality, quantity, organization, and accessibility of various types of emergency information that is provided to the public. For example, the San Luis Obispo County Office of Emergency Services website (<http://www.slocounty.ca.gov/OES/>) is well organized, with a direct link to the general county emergency operations plan, dam and levee failure evacuation plans and maps of potential inundation areas, and Diablo Canyon Nuclear Power Plant emergency planning information including potential evacuation routes. In contrast, emergency management information for Alameda County, site of the disastrous Oakland Hills wildfire of 1991, is scattered throughout various county agency websites including county sheriff and county emergency medical services. While these websites contain specifically targeted information, including how day care centers should prepare for an earthquake and special considerations for evacuating medically fragile persons, the lack of a single disaster information

clearinghouse appears to be a glaring deficiency. Also missing from any of these web resources is a map showing evacuation routes. This omission may be due to scale discrepancies between the size of the county itself and the areas that may be evacuated or the variable nature of the routes that may be implemented depending on the geographic characteristics of a specific disaster. Whatever the cause of the omission, a simple map directing people to their optimal evacuation route could be extremely valuable to overall preparedness. Added to this is the fact that the web site is probably updated occasionally, rather than being designed to give up to date information during a disaster. This is not a particular criticism of the Alameda county web site but a general criticism of most web sites.

Unfortunately, there still are noticeable problems in coordination for large area disasters. Despite performing mock drills at an airport or some other type of disaster, there has been too little focus on the sum of all emergency capabilities in responding to a major disaster. This issue was recently discussed by Haji and Lewis (2006) in their study of disaster preparedness of hospitals in Los Angeles County. It should be first noted that a hospital by itself is not designed or operated to handle a large-scale emergency. Hospitals normally operate within given bounds of patient flow and emergency demand. Government programs such as Medicare and private insurance companies reimburse hospitals based upon realistic estimates of costs. Beds not occupied by patients add to a hospitals cost of operations, but do not add to revenue. Insurance companies reimburse for patient care and not for maintaining unused facilities. Since hospitals do plan for fluctuating levels in patient care, this means that bed occupancy is not always at 100%. But just how large should a hospital be, or regionally, how large should the combined capacity of hospitals be in order to handle an emergency event? Given that hospitals by themselves are encouraged to operate at a size which matches average demand plus some surge capacity, it would not be surprising to see that many hospitals are at capacity a certain percentage of the time. When that happens they have little flexibility in handling a large surge based upon an emergency. The economics of hospital operations today has probably pushed the operating envelop toward being at 100% capacity a minimum percentage of the time. One can argue that if a hospital never reaches 100% bed occupancy, then it is too large and is not as efficient as it needs to be in the current operating and reimbursement environment. What this means is that hospitals are not rewarded in maintaining surge capacity for the unlikely event of an emergency.

Haji and Lewis surveyed a sample of hospitals in Los Angeles County in order to assess emergency preparedness. Their survey involved 45 hospitals (each interviewed by telephone as well as being the object of a personal visit). This sample represented more than 50% of the existing hospitals in LA County. Their findings are not surprising in light of the economics of hospital reimbursement discussed above. First, only 29% of the hospitals in the survey had a surge capacity that exceeded 20 beds. It was stated that all hospitals maintained an emergency medical supply of at least 3 days, but they did not state that this supply included all elements, including food and water (for both patients and staff). Less than half of the hospitals maintained more than 10 isolation rooms. Fewer than half of the hospitals maintained stockpiles of chemical antidotes and antibiotics. Finally, 60% of the hospitals diverted patients to other hospitals more than 20% of the time. Altogether, this means that 20% of the time a majority of the hospitals lacks the capacity to handle emergency patients. Although it is possible to immediately cancel elective procedures, it is necessary to identify average patient volumes involving elective procedures in order to estimate the level of emergency capacity. Also, since many procedures are now handled in outpatient surgery centers, it may be that the total surge capacity of the hospital system in LA is woefully lacking, especially in terms of beds in satisfying demand in an emergency. But this issue of preparedness could be surveyed across a number of organizations and services. In a recent issue of the LA times (Jan 25, 2009), it was noted that over the last decade the number of pediatric hospital beds in California had declined by 19%, even when the child population has increased. This has resulted in hospitals moving very sick children from their hospitals in order to make way for even sicker children due to the lack of free beds. The lack of capacity to handle anything out of the norm has been lost.

The fact is that hospitals operate as an independent unit in a larger system. The lack of a system wide perspective may mean that emergency capabilities are less than desired. This same issue may be true for a wide variety of critical needs, ranging from bridge inspectors to fuel storage for emergency vehicles. For example, do the highway patrol and Caltrans maintain resources to supply their workers in the event of an emergency, e.g. water, fuel, and food? Are methods in place to track personnel during an emergency? Is there capability to set up a field unit to support an effort oriented at maintaining quarantine or supporting an evacuation? Should agencies such

as Caltrans train people to assist organizations like the Red Cross and local search and rescue groups in an emergency?

It should be noted that the list of local emergency capabilities can often be expanded significantly by mutual aid agreements, which is a common strategy for fighting large wildfires. Through mutual aid agreements, many cities and counties from across a region may donate needed equipment and crews for a lengthy time to fight a large uncontrolled wildfire. But what is less understood is the capability of handling a large demand locally when it would take too long to respond with mutual aid or when an emergency exists that stretches the ability of an agency to cope with an emergency when no mutual aid agreement exists, or when the time taken in seeking and getting outside aid has exacerbated the initial problem. For example, if the lack of hospital beds and associated care is in short supply, patients may need to be transported long distances to other hospitals or it may be that temporary tent hospitals should be erected. But what is the length of time needed to address this need and can it be accomplished in a timely manner? Regardless of which action is taken, contingency plans for such an outcome need to be made, if an event is to be handled effectively.

Given the many overlapping responsibilities of Caltrans in the event of an emergency, coordination and cooperation with state, county, and local agencies and officials is essential to a successful and efficient response. While divergent planning and capabilities among agencies can make this task seem overwhelming, research such as the Los Angeles County hospital survey can help identify strengths and vulnerabilities within a wide variety of systems and infrastructure critical to emergency management. Regional planning via mutual aid agreements and other predetermined coordination can greatly improve the ability of statewide agencies respond to disasters that often transcend jurisdictional bounds, ultimately protecting critical infrastructure and personal property and saving lives. For example, developing a real time equipment inventory and tracking system for Caltrans may help in responding to large scale events that requires a response involving a larger than average amount of equipment. This type of problem should be modeled within the context of analyzing the time it would take to respond to a place in the state with a level of response that equals or exceeds some pre-specified response.

5. Warning System Location

For some emergencies, timing is so important that it is obvious that a warning system needs to be implemented. The classical approach for doing this is to use a set of warning sirens. For example, many cities and counties in the Midwest have warning sirens, so that people can be alerted to an impending tornado. A warning siren is designed to be loud enough to disrupt virtually everyone within its vicinity, alerting them to take some type of evasive action. More recent systems include the reverse 911 systems, where phones within a target area are called with a prerecorded message for some type of issue like “evacuate immediately, wildfire approaching” Reverse 911 systems are now in vogue as they can be easily targeted to a specific area and can be used with a specific message. The coverage of a reverse 911 systems is based upon homes that have landline telephones as well as those people who have registered their cell phones with system operators. During the recent Tea fire in Santa Barbara County, some people stated that either they didn’t get a 911 call or the call was very late in terms of the value of the warning. Thus, warning sirens have a continued role in emergency warning. Siren systems are used extensively throughout California¹ to warn people of hazards such as a tsunami, dam failure, nuclear accident, or campus emergency. FEMA guidelines dictate that a state or local emergency operations plan should explicitly include the location and geographic reach of warning sirens (FEMA September 1996). One of the fundamental questions when designing an emergency siren warning system is where to locate them so that the configuration of sirens meets the population coverage requirements of an emergency plan.

One of first research papers to deal specifically with emergency siren location is a case study of a tornado that hit Kalamazoo, Michigan in 1980 (Hodler 1982). While tornados are rare enough in California that it is not essential to design siren systems to warn against them, several important transferable findings emerge from this research. The first and most relevant is that geography

¹There are a number of examples in California involving the use of warning sirens. For example, Crescent City uses a warning siren to alert people to a tsunami risk. San Luis Obispo County operates a system of 131 sirens to warn of an accident at Diablo Canyon Nuclear power plant. Ventura County operates a system of 11 sirens to warn of a dam failure at Casitas Reservoir. Cities such as Coronado and Alameda maintain siren systems for emergencies like wildfire, flood, chemical spills etc. and universities like UC Berkeley and UC Riverside maintain campus warning systems. Even industries operate warning sirens. For example, Union Pacific has a warning siren system associated with their operations near Roseville, CA.

matters: Due to the downwind location and scarcity of sirens, more than two-thirds of residents surveyed in the area of town struck first by the tornado reported not hearing them at all. Another interesting finding is that seventeen percent of all survey respondents did not know the meaning of the sirens, despite the fact that they were tested once a month. These results indicate that optimizing the location of sirens is essential to effective warning, as is communication with populations they are intended to protect.

Another important factor in developing an emergency siren warning system is cost. Budget limitations often dictate the type and amount of equipment that is available, thus affecting the spatial extent of siren coverage that planners may work with. Set covering location models can be used to determine where to locate a predetermined number of sirens such that they cover the most population, thus implicitly accounting for cost restrictions. Models of this type allow planners to assess the tradeoffs inherent in using different technologies, siting scenarios, and policy options and can be redeployed to account for changes in population distributions and in the transportation network (Current and O'Kelly 1992). The Current and O'Kelly model can be defined using the following notation:

- i an index used to refer to a small area of population, like a neighborhood
- j an index used to refer to a site for possible siren placement
- $O_i = \{j \mid \text{an omnidirectional siren placed at } j \text{ can be heard at area } i\}$
- $R_i = \{j \mid \text{a rotating siren placed at } j \text{ can be heard at area } i\}$
- c_j^O the cost of locating an omnidirectional siren at site j
- c_j^R the cost of locating a rotational siren at site j
- $X_j^R = \begin{cases} 1, & \text{if site } j \text{ is selected for a rotating siren} \\ 0, & \text{if not} \end{cases}$
- $X_j^O = \begin{cases} 1, & \text{if site } j \text{ is selected for an omnidirectional siren} \\ 0, & \text{if not} \end{cases}$

Using the above notation, we can define the siren placement model of Current and O'Kelly as follows:

$$\begin{aligned}
& \text{Minimize } Z = \sum_{j \in O} c_j^O X_j^O + \sum_{j \in R} c_j^R X_j^R \\
& \text{subject to :} \\
& 1) \quad \sum_{j \in O_i} X_j^O + \sum_{j \in R_i} X_j^R \geq 1 \text{ for each area } i \\
& 2) \quad X_j^O \in \{0,1\} \quad \text{for each } j \in O \\
& 3) \quad X_j^R \in \{0,1\} \quad \text{for each } j \in R
\end{aligned}$$

The above model is a form of the well-known Location Set Covering Problem that was originally defined by Toregas et al. (1971). Essentially, this model selects both the types and locations of the sirens so that the cost of the siren system is minimized while ensuring that all areas are “covered” or are within the warning zone of at least one siren. The objective function minimizes the total costs of the selected sirens. The first constraint establishes that each small area has at least one siren site selected that is within the siren warning zone. There is one such constraint for each area. This is a relative small and compact integer-linear optimization model. It can be applied to relative large regions involving thousands of sites and small areas. General purpose software packages exist which can be used to solve this problem over a range of options or scenarios. Overall, this type model can be used to design a warning system for a region or for a corridor like a highway or coastline.

Another modeling approach for locating emergency sirens is the p -center location problem, whose objective is to minimize the greatest distance of all population units from their nearest warning siren. This problem can be conceptualized as having the smallest possible warning radius around all sirens, given a set number of sirens and people to be served (Suzuki and Drezner 1996). Integrating models such as these into GIS can provide a robust platform for planners seeking to locate warning sirens optimally. Accurate measurement of siren coverage is largely a function how well population is represented, thus current research is focused on comparing points, regions, and polygons as population representation units. In a study locating emergency warning sirens in Dublin, Ohio, researchers found that the optimal solution for each representation used the same number of sirens, with region and polygons best suited to situations where complete population coverage is necessary (Murray, O’Kelly, and Church 2008).

The massive toll of the December 26, 2004 Indian Ocean tsunamis served as a chilling reminder of the danger posed by these hazards. In response to that event, the California Seismic Safety Commission published a report citing the great danger posed to the state by tsunamis and finding that public education, warning systems, and evacuation plans were lacking (CSSC 2005). Sirens are a critical component of a tsunami warning system since they can warn both permanent residents and the transient populations that crowd California's beaches during the tourist season. One important consideration is that warning systems must be designed to withstand the effects of the hazard: a siren will be completely ineffective if toppled by the earthquake that triggers a tsunami (Darienzo, et al. 2005). Likewise, even the most robust siren system depends on public knowledge. If people do not understand the meaning of a siren or are not aware of an appropriate evacuation route, the warning will fail to protect them. It is possible to incorporate warning systems, risk perception, and human response into risk management models that simulate hazards. Research on managing risk associated with volcanic eruptions in New Zealand, along with other associated projects, has led to the development of a five-step approach for effective early warning systems (adapted from Leonard, et al. 2008):

- 1) Develop event detection and public notification infrastructure
- 2) Plan organizational responsibilities, evacuation routes, and communication channels
- 3) Organize communications between government agencies, local emergency managers, scientists, media and the public
- 4) Educate emergency staff and populations at risk
- 5) Perform simulations and exercises

The above steps should be viewed as a continuous feedback loop with any one step informing the others at any stage of warning system development. Methodologies such as these that emphasize human considerations can be used in conjunction with geographic location models to design early warning systems that can better protect the public from disasters.

Warning sirens, reverse 911, and other methods of alerting the public of an impending hazard remain valuable resources for many emergency management agencies. Yet it is important to consider changing communication technologies, personal transportation choices, and hazard vulnerabilities when choosing the appropriate warning system. Increasing intraday travel and

frequent variation on the traditional home to work (or school) travel path require the ability of a system to warn people of hazards based on personal proximity rather than assuming their location at a given point in time. While emergency sirens traditionally fill this role, decreased testing and gaps in public knowledge and awareness often render these systems less effective than would be otherwise. Dependence on land line-based reverse 9-1-1 calls presents obvious pitfalls in an era of ubiquitous cell phone use, and non-compliance with voluntary cell phone registration for these calls may leave a large segment of the population uncovered. One promising new warning technique is an automated system that sends out warning tones and messages to all cell phones within range of cell phone towers in areas likely to be affected by a given hazard. Such a system has been proposed for the State of California by Lt. Governor John Garamendi (it is also called for national implementation in the WARN act. (Christian Science Monitor; May 15, 2007)) Used in conjunction with an automated radio and television-based system, this hazard warning infrastructure could be used to direct threat-specific instructions to a vast majority of threatened people. Dynamic generation of area-specific evacuation routes send via text message is one example the myriad of research projects made possible by this technological advance. Perhaps the ideal system is a combination of warning sirens, reverse 9-1-1 phone and emergency radio broadcasts. In the recent Tea fire (2008) in Santa Barbara, residents of mission canyon complained that the warning given by reverse 9-1-1 was too late or didn't happen and asked why a siren system had not been considered.

Siren systems have been set up in California for a number of purposes. It is important to recognize that as a community grows it may also outgrow the region covered by the system and render the system less than effective. Thus it is important to monitor the coverage of such systems to ensure that they meet the original goals of warning all residents. Identifying specific areas of hazard vulnerability in the state such as tsunami prone coastal highways can help locate warning sirens optimally.

6. Emergency Shelter Location

Locating emergency shelters to meet the needs of people impacted by a disaster is a very important step in the preparedness phase of emergency management. The Louisiana Superdome

and New Orleans Civic Center served as emergency shelters for people displaced by Hurricane Katrina, but inadequate stores of food, water, and medical supplies and the unexpected extent of flooding, among other factors, turned these shelters into the site of disaster itself. Although the academic literature is relatively sparse when addressing emergency shelter location, there is both theoretical and technical research that can help us locate shelters so that future humanitarian disasters may be avoided.

In determining how to locate emergency shelters it is important to first understand a few theoretical concepts so that the problem can be appropriately addressed. Earlier in this report we define social vulnerability, a concept that can readily be applied to the shelter location problem. Bolin's (1991) analysis of sheltering in the wake of earthquakes in several California communities found that temporary shelters were used disproportionately by low income citizens who were more likely to live in older more easily damaged buildings and largely lacked the financial resources to move. While this finding may seem intuitive, it is important that shelters are located where they are needed most. Many Hispanic residents of a neighborhood affected by the 1987 Whittier Narrow earthquake camped in city parks and yards as opposed to returning to damaged but structurally sound buildings due to fear and a lack of Spanish-speaking building inspectors. The Red Cross developed multi-lingual outreach programs to address these cultural and language barriers, thus helping to ensure all residents were aware of the best sheltering options.

Physical vulnerability also is an important factor to consider when locating shelters. After the aforementioned Whittier Narrow earthquake, a Red Cross emergency shelter had to be evacuated due to severe aftershocks. The powerful 1989 Loma Prieta earthquake left nearly 8000 people homeless in Santa Cruz County thus an emergency shelter had to remain open for 66 days, nearly 3 times longer than emergency managers had planned as necessary for shelter operations. While the location of physical vulnerabilities is more difficult to predict than social vulnerabilities, it is essential that emergency shelter location plans take into account a multitude of potential scenarios with varying physical site impacts.

In a review of emergency sheltering and temporary housing in the aftermath of hurricane Katrina, Nigg (2006) concludes that advanced planning for large-scale multi-hazard disasters across agency and political jurisdictions is essential to meet the needs of evacuated populations.

In California, mutual aid agreements can help meet the needs of people requiring evacuation assistance or medical care, but sheltering location is often left to individual city or county departments. Cross-jurisdictional and interagency cooperation and communication in determining the best sheltering options might be aided by geospatial analysis and modeling techniques.

Agencies such as Caltrans may want to use a decision support system for disaster management (DSS-DM) for flexible and robust prediction of earthquake damage and losses. One such system allows emergency management planners to test specific earthquake intensity scenarios to generate estimates of injuries sustained and infrastructure impairment and destruction to determine the need for emergency shelters (Aleskerov 2005) What is missing from this particular system is a determination of the optimal location of these shelters, and especially important question given the widespread damage to buildings and the transportation network that can occur in a large earthquake.

Kar (2008) used GIS to perform a site suitability analysis on existing and potential emergency evacuation shelters in Florida, thus determining a discrete set of the best shelter locations. Findings show that 48% of existing shelters and 57% of potential shelters are located in flood prone areas, are too close to chemical storage facilities, or are located in other physically unsuitable sites. A methodology was developed using a weighted linear combination of qualitative and quantitative factors to determine if a site is suitable for an emergency shelter in the event of a hurricane storm surge in several Florida counties. Proximity to existing evacuation routes, health care facilities, hazardous materials and flood zones are among the factors that are measured and weighted using GIS overlays. One limitation of this study is that the physical characteristics of the shelters themselves are not incorporated into the site assessment methodology. Building material, size, and accessibility all could be included for a more robust suitability analysis.

Other modeling approaches can incorporate site suitability as well as decision making by both emergency managers and evacuees under various scenarios to determine the best locations for emergency shelters. Kongsomsaksakul (2005) proposes a location-allocation model for placing shelters when planning for populations evacuated during a flood event. In this bi-level linear programming problem a planning authority determines the number and locations of shelters with

the objective of minimizing total evacuation time on a given transportation network while a group of evacuees simultaneously decides which shelter to go to by which route given shelter location and capacity. This model is tested through a simulated flood scenario in Logan, Utah where a dam collapses with 21% out of a population base of approximately 5000 people live in the flood inundation zone. Bi-level programming problems can be somewhat difficult to solve to optimality, so a genetic algorithm was employed to solve the problem. This heuristic was used to search for the best set of shelter locations. Perhaps the most important finding to emerge from this research is the trade off between shelter capacity and the number of shelters selected. Higher shelter capacity means fewer are needed to meet the demand of evacuees, thus total evacuation time is lower. The major limitation of this modeling approach is the lack of ability to account for irrational route choice or other complex evacuee behavior. This can be overcome by adding a finer modeling scale to the larger problem such as a traffic microsimulation or cell transmission model.

Another interesting modeling technique for locating emergency shelters is proposed by Yazici and Ozbay (2007). Their cell transmission model takes into account disruptions to vital links in the transportation network that may result from an event such as a hurricane or earthquake and adjusts the locations and capacities of emergency shelters accordingly. Based on the results of simulated evacuation scenarios for Cape May, New Jersey, they find that using a deterministic approach that assumes a specific traffic capacity at vital nodes on the transportation network can leave emergency shelters incapable of providing enough food, water, and medicine to evacuees. This finding is eerily reminiscent of what happened at the Louisiana Superdome during Hurricane Katrina, where unexpected floodwaters cut off essential supply routes resulting in massive shortages of necessary supplies. The solution proposed by these researchers is to calculate the probabilities of disruption for important transportation links, then incorporate these into a stochastic simulation within the model to determine shelter locations and capabilities under the uncertainties inherent in an evacuation. This approach is similar to an approach used to preposition supplies that is discussed in a later section of this report that covers prepositioning and storage of emergency resources.

Schools and other public facilities are often enlisted to serve as emergency shelters due to easy accessibility, sturdy construction, and the layout and floor space necessary to accommodate the needs of large numbers of people. Usually such considerations such as centralized location given the population distribution and multiple access routes via the existing transportation network are taken into account when determining where to place schools, but vulnerability to hazards is often largely overlooked. Doerner (2008) presents a model that can assist in the decision of where to place a school or other public facility taking into account the flood inundation risk from a tsunami, a hazard that threatens many areas of coastal California. This multi-objective model first determines the shortest distance from each population center to the nearest school within the bounds of a maximum acceptable distance, then takes into account the risk of a tsunami, and finally seeks to minimize the costs associated with locating the facilities. This type of multi-objective model is useful to decision makers in that it can take into account many factors that help ultimately determine where a school or other public facility is located. Also, this type of model can be easily reconfigured to account for the risk of other disasters such as wildfires, earthquakes, or chemical spills.

Although few shelter location models have been developed to support evacuation events, perhaps the one that is most appropriate in making advanced decisions for shelter location is the recently developed model of Alcada-Almeida et al. (2009). This model is based upon designing a system to serve a specific region. Each area or neighborhood of the region is identified as a customer or demand. Potential sites for shelters are identified and routes between demand areas and shelters are identified. Each route between a demand area and a shelter site is analyzed within the context of travel time, risk in terms of the route being compromised by the hazard, a risk factor associated with a shelter being overcome by the event, and the times to move injured patients from shelters to the regional hospital. The model optimizes the location of a given number of shelters by minimizing the sum of weighted distances that people would need to travel to their closest shelter, the sum of the demand weighted risks of the assigned evacuation routes being compromised by the event, the sum of the demand weighted risks that individual shelters may be compromised by the events, and the sum of demand weighted distances that injured victims may be transported from shelters to the regional hospitals.

i index used to a demand area or neighborhood where S is the number of areas.

j the set of nodes i

c an index referring the c^{th} candidate path

d_{ij}^c the distance of the c^{th} candidate path between i and j

r_{ij}^c the risk associated with the c^{th} candidate path between i and j .

P the number of shelters being located

E the number of potential sites which can be selected for a shelter

S the number of demand areas

y_i 11, if site j is selected for a shelter
 λ 0, otherwise

r_j the risk associated with shelter site j being compromised.

t_j the transit time from shelter site j to the regional hospital

a_i the demand population at area i

k_j^{\max} the maximum number of evacuees a shelter at j can handle

k_j^{\min} the minimum number of evacuees that is needed to justify opening a shelter at j

x_{ij}^c 11, if demand at i is served by a shelter at j accesses by candidate path c
 λ 0, otherwise

Given the above notation we can structure the following integer-linear programming model, which contains four separate objectives:

$$\text{Min } \bigwedge_i \bigwedge_j \bigwedge_c a_{ij}^c d_{ij}^c x_{ij}^c$$

$$\text{Min } \bigwedge_i \bigwedge_j \bigwedge_c a_{ij}^c r_{ij}^c x_{ij}^c$$

$$\text{Min } \bigwedge_i \bigwedge_j \bigwedge_c a_{ij}^c r_{ij}^c x_{ij}^c$$

$$\text{Min } \bigwedge_i \bigwedge_j \bigwedge_c a_{ij}^c t_{ij}^c x_{ij}^c$$

Subject to:

$$1) \bigwedge_j \bigwedge_c x_{ij}^c = 1 \quad \text{for each } i = 1, 2, \dots, S$$

$$2) \bigwedge_i \bigwedge_c a_{ij}^c x_{ij}^c \leq k_j^{\max} y_j \quad \text{for each } j = 1, 2, \dots, E$$

$$3) \bigwedge_i \bigwedge_c a_{ij}^c x_{ij}^c \geq k_j^{\min} y_j \quad \text{for each } j = 1, 2, \dots, E$$

$$4) \bigwedge_j y_j \leq p$$

$$5) y_j \in \{0, 1\} \quad \text{for each } j = 1, 2, \dots, E$$

$$6) x_{ij} \in \{0, 1\} \quad \text{for each } i = 1, 2, \dots, S \text{ and } j = 1, 2, \dots, E$$

The above contains four objectives: minimize the total distance involved in evacuating all people to shelters, minimize the demand weighted risk of paths chosen, minimize the demand weighted risk of a located shelter not being operable, and minimize the demand weighted distances to the hospital for possible transit of injured people. The first objective ensures that each demand area must assign to a shelter using some route or path alternative. The second constraint ensures that people are assigned to only those locations selected for a shelter and that the total number of people assigned to a shelter does not exceed the capacity of that shelter. The third constraint maintains that at least a threshold level of demand is met at all selected shelter locations. The

fourth constraint specifies that exactly p sites are selected for shelters, and the remaining conditions represent the binary integer requirements on the decision variables. This model was applied to the city of Coimbra, Portugal for the purposes of locating shelters to serve the area in the event of a wildfire. Although this model does have some elements that could be enhanced or improved, it is representative of the style of model that would be ideal for planning shelters and storage locations for disaster recovery. It would be desirable to develop this style of model in conjunction with a GIS in order to support advanced planning as well as guide event operations (e.g. decide which shelters to open during an emergency).

7. Emergency Response

As can be surmised from the topics in the previous sections, there are elements of emergency response and incident management that have been studied intensively. Emergency response is one of those areas. This is especially true in what is called pre-hospital care, or emergency medical services (EMS). At issue is the capability of responding to an emergency within a desired period of time or standard. Quick response is a feature of most public safety services, like police, fire, & EMS. Even though quick response is needed for transportation safety, such services are often provided by local police departments, county sheriffs, the California Highway Patrol, and local fire departments. Caltrans often responds in a role that supports the actions of the CHP, etc. in installing changeable message signs, closing streets with barriers, and inspecting damage. The traditional focus on modeling emergency response has been on fire and EMS, as those services are oriented towards emergencies, rather than a mix of routine business (e.g. patrolling a highway stretch and stopping unsafe vehicles) and emergency response (e.g. responding to an accident or hazardous material spill).

Emergency response services require significant levels of personnel and vehicles. For example cities like Toronto have nearly 120 ambulances operating around the clock. The City of Los Angeles maintains 106 fire stations and has more than 3,900 personnel and serves an area of approximately 471 square miles. This means that on the average one station serves an area of approximately 4.4 square miles or an area with a service radius of approximately 1.2 to 1.5 miles. The Fire Department budget in Los Angeles totaled \$814 million for the fiscal year 2008-

2009. Because the costs of providing such services tends to be high, it is important to be as efficient as possible in providing and allocating them. This has led to a relatively rich literature on modeling the allocation of emergency services. The first attempt to optimize fire services and emergency services in general was proposed by Toregas et al. (1971). Their approach was based upon a rather simple assumption, that is, the cost of providing fire services was a function of the number of stations that were located. Since labor is the highest single cost element of providing fire service and since most stations are allocated a standard number of crew members, then total costs is roughly a function of the number of stations that are located to serve a given area. Given this basic, but powerful assumption, they defined the problem of allocating fire services as:

Minimize the number of stations needed to geographically cover all demand areas and locate them so that each area has a station within a maximum pre-specified response distance or time.

They called this problem the Location Set Covering Problem (LSCP). To solve this problem they proposed the following set of notation:

i index of fire demand zones or blocks

j index of potential station locations or response positions

d_{ij} distance or travel time to fire demand zone i from potential station site j

S_i the maximum allowable distance or travel time in serving a demand zone from a station

$N_i = \{j \mid d_{ij} \leq S_i\}$ the set of sites that can serve demand zone i within the maximum time or distance of response

$X_j = \begin{cases} 1, & \text{if a station is located at site } j \\ 0, & \text{if not} \end{cases}$

The LSCP problem can then be formulated as the following optimization problem:

$$\begin{aligned} &\text{Minimize } Z = \sum_j X_j \\ &\text{subject to :} \\ &1) \sum_{j \in N_i} X_j \geq 1 \quad \text{for each demand zone } i \\ &2) X_j \in \{0,1\} \quad \text{for each site } j \end{aligned}$$

This model is an integer-linear programming problem, which can be solved by special purpose algorithms and general-purpose optimization software. When this model was first proposed, there was limited computer software and computational power to solve a model such as this. But, with the advancement of personal computers and modeling software packages, models like the one presented above can be applied to problems involving thousands of demand zones and sites, providing the capability for easy application. Toregas worked with Public Technology, Inc. for many years and helped to apply this model to more than 100 large cities (by the mid 1980's) in the US for the purposes of locating or relocating fire stations into efficient service patterns. It is important to recognize that many types of applications of this model are possible, from the location of fire stations to the location of road equipment, highway patrol offices, and emergency shelters.

Given a standard of service, *e.g.* fire service within a mile and a half, it may take more stations to cover an entire region than exists in a budget to provide such services. This is especially true if a region contains both rural and urban areas. This has led to two different coping strategies: 1) define a rural level of service (*e.g.* respond in 30 minutes) and an urban level of maximal service (*e.g.* respond within 10 minutes), and 2) relax the assumption that everyone must be served within the stated maximal time or distance standard. Actually, both strategies are used. First, resources are usually not available to offer the same level of service to those that live in rural areas as compared to those who live in denser communities. Thus, it is common to establish different standards for rural and urban services. Second, many communities are not able to offer services to everyone within a maximum time or distance standard. For example, for many ambulance operations it is often stated as a goal to provide service within X minutes 90% of the time. To structure a model that captures this type of objective we can define the following emergency resource allocation problem:

Minimize the needed number of stations or vehicles to provide service coverage within S minutes (or distance) for α percentage of the total population and locate them in such a manner as to accomplish this goal.

This problem statement is a form of the maximal covering location problem of Church and ReVelle (1974). To structure this in a formal mathematical statement, consider the following notation:

a_i a measure of demand (e.g. population) at zone i

Y_i 1, if demand at i is covered within S_i minutes (or distance)
 λ 0, if not

Using the above notation along with the notation introduced earlier in this section, we can define the following optimization model:

$$\begin{aligned} &\text{Minimize } Z = \sum_j X_j \\ &\text{subject to :} \\ &1) \sum_{j \in N_i} X_j \geq Y_i \quad \text{for each demand } i \\ &2) \sum_i a_i Y_i \geq \alpha \sum_i a_i \\ &3) X_j \in \{0,1\} \quad \text{for each site } j \\ &4) Y_i \in \{0,1\} \quad \text{for each demand } i \end{aligned}$$

This model contains two major types of constraints. The first constraint establishes whether a given demand zone is covered by a station. If a station is selected from among the set of sites, N_i , then the sum on the left hand side of condition (1) is 1 or greater, which allows the variable Y_i to equal one in value, thus accounting for the fact that demand zone i is covered. If no facilities are located within the set, N_i , then the sum of selected facilities equals zero, forcing $Y_i = 0$. Thus, constraints of type 1 are used to define if coverage has been provided to a given demand zone. The second constraint states that the total coverage provided across all zones has to equal or exceed α fraction of the total demand population. The other constraints are used to

represent the restrictions on the decision variables, as they must be binary in value. The objective of this model is set to minimize the sum of the vehicle/stations/units that are being located subject to the constraints that establish that a high level of coverage must be provided.

This model is a form of the well-known maximal covering location problem, where the objective is to provide coverage to at least α % of the total demand population while minimizing the resources needed to accomplish this level of coverage. There are a number of variations of this model that are based upon issues that are important in special types of applications. For example, one variant optimizes the resources needed for several types of responding vehicles (e.g. pumper and ladder trucks) where different service distances are set for each type of equipment. The idea is that the above model is quite flexible and can be modified to fit a given problem setting. It has been applied in a number of resource settings, especially emergency response. For example, it would make sense to apply this type of model to assess the costs of providing certain types of response for incidents along major highway sections, or for inspection teams to survey a road system after an earthquake. A related model has been used to locate salt and sand storage piles for winter snow removal, in order to optimize the efficiency of snow and ice removal.

During the 1970's the U.S. Government funded studies that were called Research Applied to National Needs (RANN). These projects involved services such as solid waste management, fire protection, police, and EMS. One of the centers for this work was the Rand Corporation partnership with New York City. The New York City–Rand Fire Department study attempted to integrate new computer planning models into fire services in order to make system delivery more efficient. One of the most famous models developed in New York City was the square root law of emergency response time. Essentially, Kolesar and Walker identified a relationship between response time and distance, which was both intuitive and appeared to fit response time data collected from the fire department. This model has been used to identify response patterns in a number of cities. The square root law estimated response time as a function of distance by segmenting the response into two different distance zones, a nearby distance zone with a nonlinear response time function and a further zone with a linear response time function. This two-part function was fitted to the response time means over a large number of small time intervals. For the data used, the R-square value was unusually high in value, indicating that most of the variance found in the travel time data was explained by the square root model. This model

made it a relative simple task to estimate travel times by using distances, and this allowed either distance standards or response time standards to be applied. The task of estimating response times has been expanded with recent studies that have used large data sets representing 100's of thousands of emergency responses.

There are a number of problems associated with the allocation of resources for emergencies. For example, one problem is to locate shelters so that people can be served away from a disaster site (see the previous section). This can be done with a model such as the maximal covering location problem or the location set covering problem. For example, let's say that a major emergency has impacted an area or region. Then it is necessary to decide which shelter locations to open and operate. From a list of shelter options, a model can then be used to optimize the selection. In Florida, there are a number of options as to which shelters may be open. Along with deciding which shelters to operate it is also necessary to decide how such shelters are going to be provided provisions. For some shelter locations, provisions are already stored for such an event. For other locations, it will be necessary to truck them in from other locations. Even this storage provision location problem can be thought of in terms of a covering model. That is, one can use one of the above models to identify the set of storage provision sites such that any potential shelter site can be provided adequate provisions within a set number of hours. This is an important problem, as it is necessary to store provisions for a possible emergency. This type of provisioning problem must be solved in advance and must be operational long before any emergency support can rely on such a system.

One of the major issues in emergency response is that when a vehicle is being used or is inoperable, it is unavailable to serve. For example, in ambulance services, vehicle crews can be busy as much as 40% of the time on the average. This means that the closest vehicle may be busy and something further away would need to respond. Thus, it is important to take possible vehicle availability into account while allocating emergency vehicles in a region. The problem is that vehicle availability is a function of where other vehicles are placed. For example, if an area of relative high demand has only one allocated vehicle and is often busy 50% of the time, then response times to a given call would be delayed on the average 50% of the time, as the closest vehicle is already busy and something much further away must respond. While if that same area has several allocated vehicles, the workload of each unit can be reduced, and the percentage of

time that a call cannot be served by several local units is reduced. There are several ways in which this type of problem has been addressed. For example, let's assume for the sake of analysis that most emergency calls take an hour to serve². Given this assumption we can then estimate average vehicle business, b_s , in the following manner:

$$b_s = \frac{\sum_i f_i}{24p}$$

where:

f_i the average frequency of calls per day in demand zone i

p the number of service vehicles in operation

Given a level of business of the average vehicle, it is then possible to calculate the probability of whether a response can be made to a given call within the maximal response time standard. If we assume that each vehicle's busyness is independent of other vehicles, then the probability that k independent vehicles are busy is: b_s^k . If k vehicles are positioned within a maximal coverage distance or time of a demand zone, then the probability that it can be served by one of the k vehicles without delay is:

$$q_k = 1 - b_s^k$$

Thus, we can calculate the probability of being served without delay for any number of allocated vehicles, k . This means that if k vehicles are located within a coverage time of demand i , then demand i is covered q_k fraction of the time. To integrate this into the above covering model we need the following variable:

$Y_{i,k}$ 1, demand i is covered by exactly k vehicles or units
 λ 0, if not

²This is an assumption that is often taken in the allocation of ambulances. The 1 hour service time is an inherent assumption of the system status management system of Jack Stout.

We can now formulate an expected coverage model in the same form as the previous model as:

$$\begin{aligned}
 & \text{Minimize } Z = \sum_j X_j \\
 & \text{subject to :} \\
 & 1) \sum_{j \in N_i} X_j \geq k Y_i \quad \text{for each demand } i \\
 & 2) \sum_k Y_{i,k} \leq 1 \quad \text{for each demand } i \\
 & 3) \sum_i \sum_k a_i q_k Y_{i,k} \geq \alpha \sum_i a_i \\
 & 4) X_j \in \{0,1\} \quad \text{for each site } j \\
 & 5) Y_{i,k} \in \{0,1\} \quad \text{for each demand } i \text{ and each level } k
 \end{aligned}$$

This model minimizes the resources needed and allocates them so that coverage is provided α fraction of the time. The main feature is that it accounts for the fact that vehicles are not always available as they may be serving another demand. This formulation is an expanded version of the previous model and can be thought of as a variant of the maximal expected coverage location model of Daskin (1983). The first constraint in this model is used to define the number of units/vehicles that have been located which are within the coverage time of a given zone. It allows a given variable, $Y_{i,k}$ to equal one in value if k units have been located in the vicinity of demand i . The second constraint ensures that coverage for a given demand can be accounted for at only one service level, k . Altogether, the objective forces coverage to be accounted for at exactly the highest provided level. Constraint 3 specifies that at least a certain fraction of all demand must be covered by vehicles that are available (and therefore not busy). Overall, this model can help to allocate emergency response vehicles to provide high levels of service coverage while accounting for the fact that some of the time each vehicle is busy and not available to handle a simultaneous call.

The maximum expected coverage model is based upon an assumption that is not always met. That is, vehicle busyness is not always equal across a system. This might be the case for a dense but small city, but on the average, there can be differences between the busyness of individual emergency units. This is an issue that has been modeled by a number of researchers during the past decade. To address this there have been two principal approaches: the use of a queuing

model like the hypercube model of Larson or the use of local busyness estimates developed by ReVelle and Hogan (1989). The ReVelle and Hogan approach begins with an estimate of the demand for emergency response within a neighborhood or coverage area of zone i . This can be expressed as follows:

$$r_i = \sum_{h \in N_i} f_h$$

Where r_i is the local demand among the zones that are within the coverage standard of zone i . Suppose that there are k vehicles or responding units within the neighborhood of i . Then the demand within the local region can be spread among the k units. This means that the local busyness estimate when there are k vehicles allocated locally can be calculated as:

$$b_{i,k} = \frac{r_i}{24k}$$

Given this local busyness estimate, we can then calculate the fraction of the time that an emergency call in the neighborhood of i can be handled by one of the k local units as:

$$q_{i,k} = 1 - (b_{i,k})^k$$

This estimate allows us to refine the above emergency response model so that it is more accurate within the context of busyness estimates. This can be expressed as follows:

$$\text{Minimize } Z = \sum_j X_j$$

subject to :

- 1) $\sum_{j \in N_i} X_j \geq k Y_i$ for each demand i
- 2) $\sum_k Y_{i,k} \leq 1$ for each demand i
- 3) $\sum_i \sum_k a_i q_{i,k} Y_{i,k} \leq \alpha \sum_i a_i$
- 4) $X_j \in \{0,1\}$ for each site j
- 5) $Y_{i,k} \in \{0,1\}$ for each demand i and each level k

The major difference between this model and the previous model statement is that the busyness estimates that are used in constraints of type 3 are based upon the local busyness estimates rather than global busyness estimates. The description of the objective function as well as the constraints is exactly the same as what was given for the previous model. There are two issues that should be stated here. The local busyness estimates are based upon an assumption that the calls handled from the local region to other areas minus the calls of the local region handled by other areas nets out to be zero. The second assumption is that the vehicles or units within the local region are assumed to be independent. Neither one of these assumptions holds, but this approach is an approximation which yields a tractable model for a problem that is quite difficult to solve analytically. The form of the model given above is a variant of the Local Reliability based Maximal Expected Coverage model developed by Sorensen and Church (2007). The Sorensen and Church model has been tested for a number of problem data sets and has been found to be relatively accurate at estimating expected coverage globally as a sum of local expected coverage estimates, as well to as generate solutions that tend to outperform the original MALP model of ReVelle and Hogan (1989).

Research on modeling emergency/incident response has been concentrated on the provision of fire and EMS services. The difference between these two application areas boils down to the level of individual unit busyness. In fire service provision, most crews are not busy very often handling fire calls, and therefore are usually available to handle a call when received. For EMS response, individual responding units can be quite busy as described above, and being busy impacts potential service for the next emergency call. Good reference papers for this area of modeling can be found in Swersey (1994) and Sorensen and Church (2007).

Few have applied such models to allocating incident management resources for traffic management. In the state of Washington, a study demonstrated that responding very quickly to simple issues like stalled vehicles and stranded motorists could translate to better traffic flow, less congestion, and fuel savings. Providing this kind of incident management can be accomplished by two approaches, roving/patrolling response vehicles along a corridor and posting response vehicles at dispatch points. The second approach has been modeled by Zografos et al. (2002). Their problem involved allocating incident response vehicles (*e.g.* tow trucks) resources at dispatch locations in order to handle stranded cars, accidents, etc. along major

roadways. They developed an incident response logistics decision support system and tested several models, including the maximal covering location model, the location set covering model, and the p -median model. They developed a special form of the p -median location model that appeared to perform the best for the type of problem being solved. This is a unique paper in that it appears to be the only paper in the literature devoted to optimizing resource allocation for roadway incident response. Unfortunately, the main issue that was overlooked in their model is that of vehicle busyness. Overall, it makes sense to fine tune the type of models described in this section and apply them for roadway incident response. This is an important area for continued research development and application for roadway incident response.

8. Prepositioning and Storage of Emergency Resources

One of the issues that has gained attention is the need to make a quick response with emergency resources (*e.g.* water, food, and medical supplies) in the event of a major disaster. For example, during hurricane Katrina, people stranded in New Orleans did not have adequate supplies of food and water. It is also necessary to have a plan for shelters, should evacuation be necessary as well as respond with necessary medical and emergency personnel. Prepositioning can be defined as the storage of critical resources at specific locations in order to ensure that an area or region can be served during or after a disaster with timely delivery of those needed resources.

Recent disasters (like that of the 2004 tsunami in Indonesia which resulted in the deaths of nearly 130,000 people, hurricane Katrina in 2005 which killed more than 1800 people, the cyclone in Myanmar which killed 22,000 people, and the 2008 Chinese earthquake in Sichuan killed nearly 70,000 people) have focused attention on the ability to respond with to an emergency with needed supplies. One of the first references associated with considering the option of supply prepositioning involved an air force operations plan associated with the Berlin blockade after World War II. Since that time, few if any papers have modeled the problem of prepositioning supplies in order to mitigate the effects of an emergency. Our literature search identified only three papers that optimized inventory or located storage facilities for emergency operations. Granted, agencies like the American Red Cross store materials so that they can respond quickly with supplies to support evacuees and house evacuees, but with the exception of these three

papers, no one has modeled supply positions for emergency response using logistics models. The three exceptions are the works of Akkihal (2006), Rawls and Turnquist (2006, and Yushimito and Ukkusuri (2008). These three research papers address this problem using different but related constructs. Akkihal (2006) appears to be the first to model the problem of prepositioning for emergencies. Specifically, he addressed the problem of storing emergency supplies for humanitarian relief.

The United Nations operates a global relief supply depot in southern Europe (Brindisi, Italy), which is known as the UN Humanitarian Response Depot. This depot maintains an inventory of virtually everything, from shelters and tools to food and drugs to help in the emergency relief following a disaster. Akkihal stated that the time to respond was critical and that the UN's current location could respond within 24 to 48 hours to virtually anywhere in the world using aircraft. Akkihal addressed only the time to load and fly, and not the time to seek approval and other stages in the process of providing relief. He argued for the fact that, such a response was possibly too long for some regions of the world. Thus, he proposed a model to locate additional storage around the world. He reasoned that the objective should be to minimize the time to reach expected events weighted by the population at risk. He developed an approach to estimate population at risk for a number of regions throughout the world. His model can be explained by the use of the following notation:

- i index used to refer to a demand area
- j index used to refer to a potential depot site
- d_{ij} the distance between demand region i and depot site j , measured as the great circle arc distance between the two locations
- H_i the mean annual homelessness as a result of natural hazards
- y_j 1, if a depot is located at site j
0, otherwise
- w_{ij} 1, if demand region i is to be served by a depot at j
0, otherwise
- p the number of depots to be located

Akkihah argued that it would be best to “minimize the delivery lead-time to those people who would need it.” Thus he suggested that depots should be located in such a manner as to minimize the average distance from warehouses to people who were likely to require humanitarian aid. He calculated for each region an estimate of the annual average of homelessness that resulted from natural disasters. He used these estimates as a proxy for the demand that such a system would be called upon to respond with aid. With this he set up the following depot storage location model:

$$\text{Minimize } Z = \sum_i \sum_j H_i d_{ij} w_{ij}$$

Subject to:

- 1) $\sum_j w_{ij} = 1$ for each region i
- 2) $w_{ij} \leq y_j$ for each region i and each depot site j
- 3) $\sum_j y_j = p$
- 4) $y_j \in \{0,1\}$ for each depot site j
- 5) $w_{ij} \in \{0,1\}$ for each region i and depot site j

The above model minimizes the total average air distance in serving global disaster-caused homelessness. It assumes that the closest depot will serve each region. This model specifies that p facilities are to be located in the third constraint. Demand regions are forced to assign to one depot site in the first constraint. The second constraint limits regional assignments to only those sites that have been selected to house a storage depot. The objective forces regional assignments to their closest open depot.

Even though this model is specially defined for the location of emergency relief storage depots, it is an exact form of a classic location model called the p -median problem. The p -median model was originally defined by Hakimi (1964,1965). The integer programming model given above is a

model that was first formulated by ReVelle and Swain (1970) for the location of public facilities. When applied for locating a global system of relief storage depots, Akkihal found that the best location for one depot was in south central Asia and not Italy. The best two depot positions would be in south central Asia and Shanghai. The best three-depot configuration is associated with adding a depot in South America. It is surprising that Africa was not selected for a site until a configuration of four or more depots were specified. Thus, optimal solutions to problems that may seem particularly simple may differ from that of general intuition. This underscores the value of using models to aid in analysis and decision-making. In fact, a site in Europe (like that of the existing site) does not prove to be valuable until nine depots are located. This means that the current depot location is not sited at a location that can provide as quick a relief as it might be possible for many parts of the world.

At first it should be a bit surprising to discuss a global relief supply storage problem, when focused on issues of emergency response for a state like California. Yet the same model can be applied at a state rather than a global scale. It may be important to establish major storage depots with adequate supplies for a major emergency along with a transport structure to supply the needs of an emergency in any region of the state. Thus, the logistics model developed by Akkihal could be redefined for a statewide system.

To be prepared for an emergency, it is important to have a plan for the distribution of emergency supplies. Supplies could entail fuel for transport, food, medical supplies, water, and other needed materials. To develop a plan, it is important to identify the region of interest, *e.g.* the State of Florida. Then it is necessary to identify the towns and population centers of interest within the region as well as specify the current road network. From this, we need to identify the demand for resources of interest should a disaster strike a city or town. To do this, we can develop a set of planning scenarios, and for each scenario we need to estimate the amount of resource demand for each city. For example, say a city is impacted only in scenarios 1, 4, and 9. This means that emergency supplies are needed for this city only under those specific scenarios. The overall plan should involve the prepositioning/storage of supplies among the towns or cities. To store supplies at a given location requires the location of an emergency storage facility. The major goal would be to minimize the cost of meeting emergency resource requirements for each city or

town over all scenarios, by locating emergency storage facilities, prepositioning a certain amount of each resource at each supply site, and identifying the least cost logistics plan in distributing supplies for each disaster scenario.

It is also necessary to realize that certain transportation links may not be available during a given scenario, or that the capacity of a given link is reduced due to the event. For example, let us assume that in scenario 5, the main highway to town A may be closed due to flooding. This means that alternate routes may be necessary for transporting emergency supplies to town A during that scenario, or that the emergency supply needs to be prepositioned at that town. It is also possible that a scenario may involve the loss of a given storage facility. This means that in some cases a given supply depot may not be available to supply its own population or nearby towns. It is also possible that a supply or route may be partially compromised during an event/scenario that results in either a reduced transport capacity or the loss of some of the prepositioned supply/resource.

To formally define this problem within the context of a logistics planning model, consider the following notation.

i, j indices used to refer to given nodes or cities

N the set of nodes i

s an index referring to a given emergency scenario

S the set of scenarios s

P_s the probability that a given scenario will occur

k an index referring to a given resource type

K the set of resource types k

l an index used to refer to a given facility capacity level

L the set of possible capacity levels l

$A = \{(i, j) \mid \text{node } i \text{ and node } j \text{ are connected by a road}\}$

$y_{il} = \begin{cases} 1, & \text{if supply capacity level } l \text{ is located at node } i \\ 0, & \text{otherwise} \end{cases}$

r_i^k the amount of resource k that is allocated to node i

q^k is the unit cost of resource k

u_{ij}^s the capacity of arc (i, j) during scenario s

c_{ij}^{ks} the cost of shipping a unit of resource k during scenario s along arc (i, j)

v_i^{ks} the level of demand for commodity/resource k during scenario s at node i

x_{ij}^{ks} the amount of resource of type k shipped through link (i, j) in scenario s

α_i^s the fraction of allocated supply at node i that is available during scenario s

F_{il} the cost to locate a facility of capacity level l at node i

Given the above notation we can structure the following integer-linear programming model:

$$\text{Min } Z = \sum_{i \in N} \sum_{l \in L} F_{il} y_{il} + \sum_{k \in K} \sum_{i \in I} q^k r_i^k + \sum_{s \in S} \sum_{(i,j) \in A} \sum_{k \in K} P^s c_{ij}^{ks} x_{ij}^{ks}$$

Subject to:

$$\begin{aligned} 1) \quad & \sum_{(j,i) \in A} x_{ji}^{ks} + \alpha_i^s r_i^k = \sum_{(i,j) \in A} x_{ij}^{ks} + v_i^{ks} \quad \text{for each } i \in N, k \in K \text{ and } s \in S \\ 2) \quad & \sum_{k \in K} x_{ij}^{ks} \leq u_{ij}^s \quad \text{for each } (i, j) \in A \text{ and } s \in S \end{aligned}$$

- 3) $\bigwedge_{k \in K} b^k r_i^k \leq \bigwedge_{l \in L} M y_{il}$ for each $i \in N$
- 4) $\bigwedge_{l \in L} y_{il} \leq 1$ for each $i \in N$
- 5) $y_{il} \in \{0,1\}$ for each $i \in N$ and $l \in L$
- 6) $r_i^k \geq 0$ for each $i \in N$ and $k \in K$
- 7) $x_{ij}^{ks} \geq 0$ for each $(i,j) \in A$, $k \in K$ and $s \in S$

The above model minimizes the expected costs of distributing enough of each resource to places of need over all planning scenarios by minimizing the cost of transporting quantities from points of supply to places of need in each scenario. It also minimizes the cost of placing storage facilities and prepositioning supply at those facilities. This is a strategic prepositioning model. This particular formulation is based upon the work of Rawls and Turnquist (2006). It is a mixed integer linear programming problem, which can be solved using off the shelf software for medium sized logistics problems. Rawls and Turnquist did not address the issue of the time to respond with supplies to a given town. Their objective was to identify a minimum cost logistics plan. It may make sense to cast this problem in terms of making needed supply distributions within a desired time frame. Without a focus on making a timely response, supplies may not arrive when needed. This is a potential area for future work.

The other major model that has been developed for prepositioning of resources was developed by Yushimito and Ukkusari (2008). They described prepositioning as the storage of inventory at or near the disaster locations for seamless delivery of critical goods. Such a strategy is promoted in order to reduce the lead time in responding to a disaster. Yushimito and Ukkusari build their approach by modifying a form of the location vehicle routing problem (LVRP). The LVRP model is associated with locating facilities and routing vehicles from each facility in order to meet some level of predefined demand at each client location. Routes can be defined in two ways: 1) demand is based upon full truckloads, and 2) demand is based upon less than full truckloads. In the circumstance that demand is high enough that it is represented as full truck loads, then supply trips to clients or needed demand locations are simple routes to and from

client locations and the supply facilities. If demand is less than a full truck load, then deliveries can be made as a set of routes, where each route supplies several clients at once and is represented as a set of stops. There are several approaches that can be used to formulate the LVRP, however, the simplest is a model that is based upon a set of predefined route alternatives (LVRP_PR), where routes are selected simultaneously with the selection of facility locations. This version of the LVRP is conceptually simpler than one in which route are determined simultaneously with site selection, because predefining a series of possible route alternatives eliminates the need to embed multiple travelling salesman sub-problems for each selected facility. The LVRP_PR can be formulated using the following notation:

I the set of client locations

J the set of candidate locations

i, j indices used to index client and candidate locations respectively

k an index of routes for a given candidate facility

f_j the fixed cost of establishing a prepositioned storage facility at location j

P_j the set of feasible routes for candidate facility j

c_{jk} the cost of route k associated with candidate facility j

a_{ijk} 1, if route k associated with facility j serves client location i
 λ 0, if not

x_j 1, if candidate j is selected for a facility
 λ 0, otherwise

y_{jk} 1, if route k associated with facility j is selected
 λ 0, otherwise

The LVRP_PR model can be defined as the problem of selecting sites for distribution/storage facilities while simultaneously selecting routes associated with selected storage facilities to supply clients in a manner that minimizes total prepositioning and routing/delivery costs:

$$\text{Minimize } Z \sum_j f_j x_j + \sum_j \sum_{k \in P_j} c_{kj} x_{kj}$$

Subject to:

$$1) \sum_j \sum_k a_{ijk} y_{jk} = 1 \quad \text{for each client } i$$

$$2) y_{jk} \leq x_j \quad \text{for each } j \text{ and } k \in P_j$$

$$3) x_j \in \{0,1\} \quad \text{for each } j$$

$$4) y_{jk} \in \{0,1\} \quad \text{for each } j \text{ and } k \in P_j$$

The objective involves minimizing costs of site selection/development and the costs of distribution to all clients. The first constraint of this model involves the selection of a delivery routes so that each client is served by a route. The second constraint maintains that the selection of a specific route based at a facility site j cannot be selected unless site j has been chosen as a location for supply prepositioning. This is an integer-linear programming model, which can be solved by a variety of techniques employing a column generation approach associated with the vehicle routes.

Yushimito and Ukkusuri modified the above type of problem for the prepositioning problem for emergency supply. At issue in prepositioning is the fact that a system may be compromised in its ability to supply a set of possible clients. Otherwise, the problem of prepositioning can be approached in exactly the same manner as supply location and vehicle routing in classic logistics problems. In such a case, the formulation above can be used without modification. But, in a disaster certain road links may no longer be available as they may be flooded or ruined. This would render certain routes from being usable. Also, a supply depot may also be unusable as it

could be damaged or destroyed in the disaster. To address these types of possibilities, Yushimito and Ukkusuri assumed that each road link could be assigned a probability of failure. They also assumed that such failure events were independent. They defined the probability of a link between i and k failing as p_{ik} . This means that the probability of a link (i, k) being usable is:

$$(1 - p_{ik})$$

Suppose that a path between i and j is comprised of two arcs, one from i to k and the other from k to j . Then the probability of a path being usable from i and j can be calculated as:

$$(1 - p_{ik})(1 - p_{jk})$$

This was defined as the reliability of the associated path. Such a calculation can be done when the probabilities of edge failure are known *a priori* and are independent across all edges. For every predefined route in the VRP_PR, we can calculate the reliability of the route. This can be designated as R_{jk} . The second assumption made by Yushimito and Ukkusuri is that there are known failure probabilities for each possible facility site, q_j . Thus, the probability that a supply facility is available is $(1 - q_j)$. Using these two elements together, Yushimito and Ukkusuri defined a probabilistic version of the LVRP_PR for prepositioning supply as follows:

$$\text{Maximize } Z \prod_{j \in P_j} R_{jk} y_{jk} (1 - q_j)$$

Subject to:

$$1) \prod_j \prod_k a_{ijk} y_{jk} = 1 \quad \text{for each client } i$$

$$2) y_{jk} \leq x_j \quad \text{for each } j \text{ and } k \in P_j$$

$$3) \sum_j f_j x_j \leq B$$

$$4) x_j \in \{0,1\} \quad \text{for each } j$$

$$5) y_{jk} \in \{0,1\} \quad \text{for each } j \text{ and } k \in P_j$$

This prepositioning involves locating a set of supply facilities that costs no more than an available budget, B . The objective involves maximizing the sum of service reliabilities, where each reliability value is the product of route reliability and facility reliability. In essence, this model maximizes an un-weighted reliability value of serving all demand. Yushimito and Ukkusuri argue that the above model can be solved by identifying the most reliable path to a given client from a storage site. They show that maximizing the reliability in serving every demand can be achieved when the most reliable path is used to reach a given client. Thus, it is necessary to find the most reliable path between a given storage site and all clients. They show that the problem of finding the most reliable path between a facility and a client can be solved as a form of the well-known shortest path algorithm between an origin and a destination. Thus, the set of route alternatives for a given facility would be comprised of the most reliable routes between a given site and each demand. When they overlap and are within capacity they can then be combined. Thus, it is not necessary to use a column generation scheme in solving the maximum reliability prepositioning problem. Unfortunately, the above model may strike a poor balance between reliably serving small clients as compared to large clients. That is, it would not make much sense to increase the reliability of a very small client demand at the expense of reducing the reliability of a very large client demand. Thus, it would make sense to modify the above model objective to:

$$\text{Maximize } Z \quad \bigwedge_{j \in P_j} d_{jk} R_{jk} y_{jk} (1 - q_j)$$

Where d_{jk} equals the number of clients served by route alternative k from facility site j . This objective could be used in place of the objective suggested by Yushimito and Ukkusuri without changing the difficulty of solving the overall model.

Prepositioning of emergency resources is an important way to mitigate the effects of a hazard and prevent it from becoming a full-fledged disaster. If a hazard spirals out of control and

becomes a disaster despite our best efforts, having resources prepositioned at critical locations can greatly improve the effectiveness of the response effort. Despite the obvious benefits of prepositioning, this strategy has been the focus of very little research within the emergency management academic community. The p -median problem can be solved to optimize the location of global relief supply depots as well as supply depot location problem at the national, state, or local scale and thus provides a solid mathematical foundation for addressing this question. A strategic prepositioning model takes into account the cost of transport, storage, and prepositioning of emergency supplies providing valuable information to decision makers given limited budgets and resources. The location vehicle routing problem can be solved to locate supply storage facilities and route delivery vehicles while taking into account the potential for disruptions along the transportation network, and therefore is an effective way to account for the uncertainty associated with the scale, intensity, and duration of many hazards. All of the modeling approaches described above can greatly assist in decision making and planning under a multitude of disaster scenarios, and can be modified to answer the specific questions an agency such as Caltrans must ask to determine the best actions to take.

9. Infrastructure Fragility

Although emergency planning often addresses issues like that of backup power, there does not appear to be a part of the modeling literature that is devoted to public vulnerability due to the lack of backup power. For example, water supply districts often locate backup generators so that water pressure can be maintained during times of power outages. In addition, sewer districts often maintain backup generators for pumps at critical lift stations, in order to ensure the system works during power outages. Similarly, telephone companies have maintained backup power for landlines by keeping banks of batteries at switching facilities. Cell towers often do not have long-term back-up supplies, so that some services are not guaranteed to operate. Maintaining communication systems during emergencies is an emerging problem as more households are increasingly relying on cell phones as their only form of communication. This trend may also be exacerbated by the use of cable-internet connections, which are also vulnerable to power outages and do not usually have backup power systems. Consequently, it is important to address the fragility of infrastructure in emergency planning.

There is, however, a growing interest in identifying vulnerabilities, especially with respect to infrastructure. In terms of transportation, there are a number of vulnerability issues should something fail or be intentionally taken out. For example, when a trestle fire destroyed a Union Pacific railroad link in downtown Sacramento, CA in March of 2007, most trains had to be rerouted about 125 miles in order to get to their destination. That is, the loss of a structure approximately 300 feet long resulted in rail cars being detoured nearly 125 miles. The sudden loss of infrastructure can result in a significant impact, either limiting transportation or requiring detours that are quite long. In a recent study, Peterson and Church (2008) modeled all freight flows destined for or originating from the State of Washington. This principally involved the Class 1 railroads serving Washington, namely BNSF (Burlington Northern Santa Fe) and UP (Union Pacific). Peterson and Church proposed a methodology for determining the impact of losing a railroad bridge in terms of the needed rerouting of freight. For the State of Washington, there are approximately 999 origin-destination route pairs involving the Washington as either an origin or a destination in the Bureau of Transportation Statistics rail freight database. About a third of these routes typically cross the BNSF bridge at Sandpoint, Idaho. If this bridge is lost due to some type of accident or terrorist event, all traffic that would have used this bridge will need to be rerouted. Without considering issues of track capacity, rerouted distances averaged 350 miles more than what would occur with the bridge. That is, the loss of a rail bridge in Sandpoint, Idaho could have a significant impact on freight associated with the State of Washington. Peterson and Church (2008) also suggest how capacity data could be used to model routes after a possible bridge interdiction. They suggested that since some routes are already operating close to capacity, it may be that detours could be even longer than what had been estimated or that the capacity to handle such traffic along other routes does not exist and some freight might need to be curtailed.

The Legislature of the State of Pennsylvania has considered requiring their Department of Transportation to establish a contingency plan to reroute rail traffic due to a loss of railroad infrastructure such as a bridge, tunnel, or yard. Approximately 30% of the nation's freight uses rail. This statistic is likely to increase with increasing fuel costs as rail is 4 times more fuel efficient than truck. In terms of moving towards more sustainable activities (like that suggested in California's AB32), it is clear that rail will play a larger role in freight transport, especially for

distances that exceed 800 miles. Since the Ports of Long Beach and Los Angeles combined handle approximately 40% of all containers imported into or exported out of the U.S., it plays a major role in global transport flows. Most container traffic heading into California through any California port will be placed on rail if the trip exceeds 1000 miles. This means that rail infrastructure within California as well as bridges and tunnels outside California could have a detrimental impact on the ability to handle freight if they should be compromised. It is important to develop an understanding of the major vulnerabilities in advance of a disaster as well as to develop the best possible contingency plans for coping with such disruptions.

Infrastructure could be compromised by either a natural disaster or an intentional terrorist strike. For example, a heavy storm in December 2007 resulted in the closure of a 20-mile section of Interstate 5 near Chehalis, Washington for nearly a week. This would be considered “a piece of cake” event as compared to the events that are possible should the levee system in the Central Valley of California be compromised by a major storm or earthquake. It is imperative to understand the risks and locations of such events and develop appropriate plans to handle such a disaster. The road system in Central California could be compromised to the extent that traffic for many communities could be entirely cut off, something that California has not experienced to any great extent. The fact is that priorities for upgrading levees should be set not just in terms of protecting property and safety, but also within the context of protecting supply routes and evacuation routes for an area. This also means that Caltrans and other State agencies need to coordinate with water resource agencies, flood and levee operations districts so that emergency plans are coordinated with the state of such systems as levees, reservoir operations, etc.

The issue of intentional harm is not one to be taken lightly. The disruptions caused by the terrorist acts of 9/11 are quite small to what could possibly occur or what natural disasters might do in harming infrastructure. There is a growing literature associated with identifying infrastructure that is especially vulnerable or critical. If an element is critical but not very vulnerable within the context of a natural disaster, then the only way in which that element might be compromised is due to an intentional strike. Some of the research literature is directed at identifying those elements that are particularly important in system operation (facilities, networks, & protocols). For example, Church et al. (2004) presented two models that can be used in supply

logistics systems that are aimed at identifying the critical points of supply and the impacts of a worst-case interdiction. Their presentation also gives a relatively complete list of research papers associated with military interdiction of supply routes. Gubescic et al. (2008) discuss a number of approaches that can be used to assess critical elements of a network system. The basis for much of this work has been to analyze the range of possible outcomes, from worst-case to expected case damages, should a system be compromised by the loss of certain components, *e.g.* a bridge or a road.

The basic idea is that transport, communication systems, electrical transmission, and pipeline networks should be analyzed in order to identify the range of possible outcomes in terms of the loss of system operability as well as identify strategies in which to lessen those risks and potential damages. For example, a highway may have one bridge that is especially vulnerable to an earthquake or to flooding which might undermine the foundation. Whatever the risk is, it may be that this one component is especially at risk. What if the entire route is useless if that element is damaged? Then, it may be important to ensure that this one component is strengthened or protected so that the risk of losing an important route is substantially reduced. The overall strategy would be to identify the elements that if protected or reengineered could keep lifeline support systems in operation, *e.g.* water transportation, food, supplies, and communications. Each system needs to be analyzed within this perspective. The transportation system is a critical element in securing many of the lifeline systems (food, medications, personnel) in the event of an emergency so the transport infrastructure should be given a high priority for analysis as well as strengthening. The problem of re-engineering or fortifying a system component in order to minimize losses in the event of a disaster has been addressed only recently (see Church and Scaparra (2007) as an example).

Designing a transportation system so that it can provide lifeline services, like food and emergency services as well as support evacuation when needed was recently proposed by Viswanath and Peeta (2003). Suppose that there exists a region with an existing road network. The network represents roads or highways that connect towns or cities. The major cities represent the origins and destinations of specific services or commodities. The idea is that routes of commodities or services between all major towns should be supported if at all possible.

Although a route between a given origin/destination pair should be efficient, the route cannot traverse along a given road unless that road has been seismically upgraded to withstand a major earthquake. Viswanath and Peeta optimized road improvements subject to a budget constraint so that as many OD pairs are supported by a seismically safe route. The objectives were to maximize the population that were covered by these major routes and hence served by a specific commodity type as well as optimize the efficiency (distance) of each of the routes. Consider the following notation:

i, j, m indices used to represent towns and cities

$A = \{(i, j) \mid \text{a road connects towns or cities } i \text{ and } j\}$

$E_m = \{(i, j) \mid \text{area } m \text{ is accessible to road link } (i, j)\}$

k index of commodity or type of service

$O(k)$ the origin node i for commodity route k

$D(k)$ the destination node i for commodity route k

c_{ij}^k the unit cost of routing commodity or service along link $(i, j) \in A$

f_{ij} the cost of seismically upgrading road $(i, j) \in A$

The Viswanath and Peeta model contains the following three decision variables:

x_{ij}^k 1, if there is a unit of flow of commodity k on link (i, j)
 $\lambda 0$, otherwise

y_{ij} 1, if link (i, j) is used in a commodity flow path
 $\lambda 0$, otherwise

z_m 1, if demand m is accessible from a link on a flow path
 $\lambda 0$, otherwise

The formal multi-objective optimization model can then be stated as follows:

Maximize $\sum_m a_m z_m$

Minimize $\sum_{k \in K} \sum_{(i, j) \in A} (c_{ij}^k x_{ij}^k + c_{ji}^k x_{ji}^k)$

Subject to:

- 1) $\bigwedge_{(i,j) \in EA} x_{ij}^k - \bigwedge_{(j,i) \in EA} x_{ji}^k \leq 0, \text{ if } i \in B(k) \quad \forall i, k$
 $\leq 0, \text{ otherwise}$
- 2) $\bigwedge_m z_m \leq \bigwedge_{k \in (i,j) \in EE_m} (x_{ij}^k + x_{ji}^k) \quad \text{for each area } m$
- 3) $x_{ij}^k \leq y_{ij} \quad \text{for all } k \text{ and } (i,j) \in E$
- 4) $x_{ji}^k \leq y_j \quad \text{for all } k \text{ and all } (i,j) \in E$
- 5) $\bigwedge_{(i,j) \in EE} f_{ij} y_{ij} \leq B$
- 6) $\bigwedge_{(i,j) \in EA} x_{ij}^k \leq 1 \quad \text{for all } i \text{ and } k$
- 7) $\bigwedge_{(i,j) \in EA} x_{ij}^k \leq 1 \quad \text{for all } k \text{ and } j \in D(k)$
- 8) $\bigwedge_{\substack{(i,j) \in EA \text{ where} \\ i,j \in Q}} x_{ij}^k \leq |Q| - 1 \quad \text{for all } k$
- 9) $x_{ij}^k \in \{0,1\} \text{ and } x_{ji}^k \in \{0,1\} \quad \text{for all } k \text{ and } (i,j) \in EE$
- 10) $y_{ij} \in \{0,1\} \quad \text{for all } k \text{ and } (i,j) \in E$
- 10) $z_m \in \{0,1\} \quad \text{for all } m$

The above model can be used to identify which routes should be made safe so that services can be transported to as many communities as possible and so that feasible evacuation routes exist after an earthquake. The basic idea is to design the best “safe-routes” system within budget limitations and serve as many communities as possible as well as make the hardened routes as efficient as possible. Although it may be the object to upgrade all bridges over time, such a model can be used to prioritize the upgrading process. Further, all bridges may be upgraded to some standard that is deemed acceptable, however, it may be valuable to then use the above style of model to consider which bridges or road links to upgrade to an even stricter standard, so that should a particularly powerful earthquake hit, there still represents a backbone of roads that can survive and be used in an emergency.

It should be pointed out that the model just described was cast within the context of providing routes that would survive an earthquake. But there are other dangers that might be of great

importance to consider within this context. One is potential flooding. A recent TRB report discussed possible impacts of climate change on transportation infrastructure. The greatest such impact is the possible flooding of low coastal areas due to storm surges and sea level rise. The TRB report suggests that virtually all transportation planning adopt a new perspective of dealing with possible climate change impacts. To do this requires a two step process: 1) identify possible infrastructure risks due to climate change, and 2) mitigate possible risks by planning in light of such risks. The model given above is an example of modeling to provide transportation services given an earthquake, but it could be modified to handle issues like that of extreme weather events, coastal flooding, etc.

Natural disasters such as earthquakes and flooding and human-caused disasters such as a terrorist attack both pose substantial risks to the transportation network. Mitigating the potential impact of these events requires careful identification of critical elements of transportation infrastructure so that steps can be taken to protect them from the multitude of hazards they face. Infrastructure can fail without warning, as demonstrated by the complete collapse of the I-35W freeway bridge in Minneapolis in 2007. Modeling techniques can be used to assess infrastructure fragilities on railways, freeways, levee systems, and any number of other important transportation features to help agencies take necessary steps to mitigate the impact of a worst-case disaster scenario.

10. Findings

This report has covered a number of elements associated with planning, mitigating, and managing events involving a disaster. To adequately serve a region with appropriate transportation, shelter, and life supporting resources it is important to anticipate, plan, train, and maintain an adequate mix of resources and personnel to respond appropriately. Thus far this report has focused on the role of modeling in disaster management, including modeling possible evacuations, prepositioning emergency supplies, designating shelter locations, modeling infrastructure fragility, designing systems so that they operate during disasters, designing plans for response, and designing interoperable communication systems. Yet even the most well thought out models and system designs may suffer from flaws that can only be rectified through careful design and real world validation. The first step in this process is to identify some of the

major shortfalls in current practice involving agencies responsible for emergency disaster response. To this end, the literature review above was complemented by a series of interviews conducted with emergency management personnel from several agencies in California.

The subjects of these interviews included Caltrans personnel, geospatial information specialists, and emergency management professionals from the campus to the county level. Interviews followed a semi-structured format, which allowed us to expand upon interesting topics while keeping focused on the subjects most relevant to the problem at hand. Santa Barbara County has faced four major wildfires in the past three years, thus these events comprised one major focus, along with earthquakes, chemical and nuclear accidents or attacks, tsunamis and other threats specific to the central coast region. Interviews were often followed by impromptu tours of the subject's workplace, including facilities like a Caltrans Traffic Management Center (TMC), an Emergency Operations Center (EOC), several Geographic Information System (GIS) hardware and software installations, and an emergency shelter utilized during the 2009 Jesusita Fire. In the interest of candid and informational discussion, we choose to maintain the confidentiality of our interview subjects³. The following findings are informed by both our literature review as well as the series of interviews we conducted:

- 1) **It is important to identify areas within the State of California that face a significant disaster risk and also face a significant risk in evacuating safely.** This type of analysis would require modeling evacuation vulnerability and mapping event risk, and should be coordinated with data from OES, water resources agencies, MPO's and other relevant organizations to provide a comprehensive risk map. One such area that was previously modeled (see section 3) is the Mission Canyon neighborhood in Santa Barbara. Due in part to this research, Mission Canyon residents were particularly well organized and actually evacuated before the official order came through during the May 2009 Jesusita fire. Also during this event, an evacuation contingency plan that was developed during the Zaca Fire was used to split most of the Santa Barbara area (Goleta, Santa Barbara, Montecito) into zones that could be evacuated in 1.5 hours or less. These zones were used to conduct a staged evacuation by identifying mandatory evacuation areas and evacuation

³ A complete list of interview subjects can be found in the references section of this report.

warning areas based on the latest fire and weather conditions assessed by fire officials and CHP. It would be useful for emergency management purposes to have the entire county broken into these 1.5-hour zones using population densities, road network characteristics, and hazard probabilities. This method is not infallible however, as the Jesusita fire was only 40 minutes from Montecito at one point but the threatened area was not under mandatory evacuation. Wildfires remain a threat, as Montecito, Carpinteria, and some areas west of State Highway 154 still have intact chaparral of considerable age and vulnerability in the event of a wildfire. Flooding is now a major concern for the city and county given the extensive fire damage in many watersheds and the El Nino prediction for winter 2009-2010. Maps showing the areas of greatest concern could be helpful for planning purposes, and evacuation procedures for flood-prone areas should be determined well in advance of an event. Earthquakes and the tsunamis they may cause remain a major concern, and the uncertainty of the timing and spatial extent of such events presents a unique challenge in identifying and protecting areas at risk. Another area of concern to central coast emergency managers and Caltrans traffic engineers is the Diablo Canyon Nuclear Power Plant and the surrounding communities of Pismo Beach and San Luis Obispo. A contraflow evacuation plan has been developed for this area but might be improved through modeling and simulation. This topic is further discussed in the third recommendation of this section.

- 2) **For areas that face specific risks designate emergency evacuation routes and ensure such routes will be as safe as possible based upon infrastructure design and condition.** The 2007 Zaca fire was a significant event but progressed at a speed, which allowed for extensive evacuation contingency planning. Evacuation routes were designated using major arteries as the primary routes out of fire-prone canyon communities, with planned work-arounds should these primary routes be inaccessible. Since the fire never reached highly populated areas, most of these evacuation plans were not executed. Evacuation operations are legally a law enforcement function, with Caltrans assisting with road closures, traffic direction, and signage. Collaboration and data sharing between these two agencies could improve route designation and traffic flow, in particular information on current road construction projects and closures. Other

data used for evacuation routing includes cadastral parcels, Verizon point-of-presence (POP) locations, as well as the locations of nursing homes, day care centers, and schools to determine where assistance to vulnerable populations may be required. These data should be shared amongst agencies as well. Several issues that arise frequently during evacuation that may impede safety are that people will follow habitual routes rather than the routes they are directed to use and often think they can outrun hazards such as wildfires.

- 3) **Test and refine evacuation simulation models across multiple scales covering options such as contraflow, and develop the capability of analyzing evacuation flows on-the-fly using transportation, census, cadastral and employment datasets in a Geographic Information System (GIS).** Caltrans personnel designed the Diablo Canyon Nuclear Power Plant contraflow evacuation plan in December 2007. There seems to be considerable doubt within the agency as to whether the plan could be successfully implemented due to the considerable CHP and Caltrans manpower required to control traffic. Currently there is not a contraflow plan for the City of Santa Barbara, as the current staged evacuation method seems to work adequately given the relatively slow spread of recent wildfire events. The major challenge in designing a Santa Barbara contraflow plan is finding and allocating the manpower required to control the numerous 101 Freeway on/off ramps. Cities that have successfully implemented contraflow such as New Orleans have more spacing between freeway access points thus reducing the manpower required. There are two trends that have emerged in recent events requiring evacuations: The first is encouraging voluntary early evacuation so that emergency personnel have more time and resources to focus on vulnerable populations if/when the mandatory evacuation order is made. The second is rethinking the necessity of ordering a mandatory evacuation, with a greater focus on teaching people how to create defensible space and to ‘stay-and-defend’ during wildfires. One important task is to develop methods to estimate and model evacuation needs of special needs, like the elderly and youth using public assets like transit buses. Santa Barbara Metropolitan Transit District (MTD) bus drivers are required to pull over and immediately report any hazardous situation (wildfires, floods, traffic accidents, etc) thus might provide a novel source of

geoinformation as well as accessible transportation for vulnerable populations during a disaster. Especially vulnerable populations include transients, tourists, and recent immigrants with limited English comprehension. Integration of real-time traffic flow data from Caltrans into a GIS would be of great use to emergency managers during both the planning and operational phases of emergency evacuations. Major issues include the large percentage of the workforce that commutes to Santa Barbara from other parts of the county, thus leading to major differences in on and off peak traffic flow.

- 4) **Model shelter locations and supplies for ease of access, size, and capabilities in supporting an emergency.** According to emergency management personnel, sheltering operations in response to the Jesusita fire went well. Wednesday, May 6, 2009 and Thursday, May 7 were the days when the fire posed the biggest threat to the community, and thus the number of evacuees needing shelter was greatest during these days as well. Overall, the number of evacuees needing shelter was much less than the 20% of the evacuated population that the Red Cross generally assumes. The ability to provide adequate sheltering during this event was largely due to the short time of the mandatory evacuation order. The longer an event and the subsequent evacuations persist, the more difficult it becomes to provide shelter to evacuees. Although the Jesusita Fire emergency shelter on the UCSB campus was well staffed and stocked with supplies, it is notable that this was the third facility that had been used to house this shelter. The initial location proved too small to accommodate the influx of evacuees, and the subsequent shelter location was closed when threatened by the fire itself. This lack of suitable shelter locations and on-the-fly relocation may become significant impedance to evacuee safety during future events, especially those that strike without advanced warning such as earthquakes or terrorist attacks.
- 5) **Develop resource requirement models so that the need for resources to support special needs like bridge inspections is understood, and plans for infrastructure inspection after a disaster can be quickly carried out.** One of the biggest concerns for Caltrans in the event of a major earthquake is ensuring the structural integrity of bridges and freeway on and off ramps. The large scale and chaotic nature of an earthquake makes

it especially important to quickly assess freeway damage to provide access to rescue teams and evacuees. Significant damage to freeway infrastructure occurred in the San Francisco Bay Area during the 1989 Loma Prieta earthquake and more recently in the Los Angeles Basin during the 1994 Northridge earthquake. There is a general concern within the emergency management community that the central coast region is 'overdue' for a major earthquake and may be unprepared to handle the immediate infrastructure inspections necessary to facilitate rescue operations and ensure safety along major transportation corridors.

- 6) **Model emergency supply storage and placement in order to estimate what will be needed statewide to respond adequately in a timely fashion, with a focus on locating equipment in hot spot regions of the state.** CMS boards are essential in notifying the public of the road closures and designated evacuation routes when hazardous conditions exist. The primary role of Caltrans during emergency events is to respond by closing roads and controlling the placement of and messages on CMS boards. Once the lead command (Fire Department or CHP) determines that a road closure is necessary, a Caltrans maintenance crew places barricades, which are then usually staffed by CHP or local police. These signs are often left in places where they are likely to be put to use: one example is State Highway 192, a major transportation corridor and evacuation route for the foothill neighborhoods of Santa Barbara. There are many factors that should be taken into account when modeling placement of CMS signs, including visibility and the extended traffic queuing that may occur during evacuations.

- 7) **Develop models that route rapid response vehicles to incidents in areas with significant congestion in order to maximize the value provided by such a service.** One type of event that agencies such as Caltrans may not be prepared for during emergency operations is a secondary event that forces a road closure at a critical link along the transportation network. An example of such an event is the trailer fire that occurred next to the 101 Freeway during the Jesusita Fire evacuation that forced a temporary closure of the freeway, causing massive traffic gridlock. Fortunately, motorists stuck on the 101 and surrounding side streets were not directly threatened by the wildfire

itself, but the impact of such secondary events on evacuation safety should be modeled to improve agency preparation and response time.

- 8) **Analyze, test, and deploy communication systems that can provide geographic information over a wide area to mobile units of different agencies.** The flow of geographic information between agencies and personnel during emergency operations is often disjointed. During the Jesusita Fire, CalFire mappers uploaded fire perimeter GIS layers based on information from personnel in the field to a State OES FTP site, which was then accessed by mappers at the County EOC to create maps. These county mappers were then responsible for creating operational maps incorporating utility, population, and road closure data for use by emergency officials, as well as electronic and hard copy maps for the general public. There were issues in maintaining sufficient mapping personnel to keep up with map requests, as well as making sure that the latest and most accurate geoinformation was used. City GIS personnel were unable to access the map layers they needed and there was considerable redundancy in the maps that were produced, resulting in a large degree of uncertainty regarding the latest and most accurate geoinformation. During the 2008 Tea Fire, the demand for updated fire maps far outpaced the city's ability to produce them. Part of the problem was that there was no data connection between city GIS server and Emergency Operations Center (EOC) server. This lack of accurate geoinformation led to severe consequences: Several police officers were burned by this fire because they were stationed too close to the active front. Better coordination between the city and county is needed, and a mobile device-based or Internet system that provides consistent reliable information could greatly assist emergency managers in decision-making. The City of Anaheim has an Enterprise Virtual Operations Center that integrates, synthesizes, and distributes real time data (GIS, responder locations, communications) via the Internet for decision support. A tool that incorporates real time traffic information and the latest event maps would be very useful in developing and altering evacuation routes, especially if it could be used in conjunction with the radios already used by emergency personnel. The ability to instantly locate personnel and share information (pictures, text, etc) within defined user groups could also be helpful, provided the system was reliable and easy to use.

- 9) **Establish a mechanism to use participatory/voluntary data provided by people with cell phones, allowing them to send video and images along with descriptive text to a central clearing house, thereby allowing people to provide data on an event as it unfolds.** Organized volunteer data gathering by people in the area of harm may aid in their rescue and evacuation by providing valuable information. Since a 911 call center may be overwhelmed by calls during an emergency, many calls providing information cannot be handled. If an individual can send a text message with GPS coordinates (e.g. from an iPhone) or an image, this data could be streamed directly to support personnel in a mobile command center allowing for better information about an event. There is considerable debate concerning the role of citizens in developing and accessing emergency management information. Any disaster information provided by citizens should be crosschecked for reliability, although sometimes the best disaster information comes from the media or from outside of official sources. The Santa Barbara county GIS department used a Google Map to display official evacuation zone and fire perimeter information during the Jesusita fire, but it was difficult to ensure accuracy and maintain this map with other more pressing duties such as providing maps to officials and decision makers. A group of graduate students created a competing Google Map of evacuation zones and fire perimeters relying on data from numerous sources, which one emergency manager found to be more accurate and useful than the official county map. It is very important to strike a balance between volunteered geographic information (VGI) and official sources of geographic information during emergencies so that the public stays informed but people are not overwhelmed and confused by conflicting information.
- 10) **Develop formal emergency communication links and systems so that emergency managers can quickly and effectively convey the most accurate and up-to-date information to the public.** Currently there are a multitude of systems used to alert people living in the Santa Barbara area of potentially hazardous situations. As of February 2009 more than 28,000 users had signed up for the UCSB campus alert system with 9,345 wireless devices registered to receive automatic text message alerts. The Santa Barbara City Reverse 911 system uses Verizon phone connection data and GIS to

determine the size of polygons representing the areas to be notified. Goleta uses a different notification system that had several notable mishaps during the 2008 Gap fire, including instructing residents of the seaside community of Isla Vista to evacuate. The best way to convey spatial information during an emergency and exactly what information should be provided remain open-ended questions. For example, the danger in making evacuation routes public is that evacuees may blindly follow them and ignore instructions that route them around hazards such as spot fires that occur far in front of the main flame front. Traditional sources such as television and radio remain important communication outlets for emergency information, but are losing ground to the Internet and mobile devices. The county is considering developing an ESRI ArcIMS site to help disseminate spatial information quickly and coherently over the Internet, including evacuation zones and road closures. Another option is to develop a mobile disaster decision support system (MDDSS) which allows people to access emergency information from official sources as well as volunteered information from other users within their disaster support network (DSN). Such a system could also show the locations of all members of the DSN, and provide a routing service that takes into account road closures and hazard location, all on a mobile device such as an iPhone or Blackberry.

11) Model the fragility of infrastructure and its potential impact on public safety.

During the Jesusita Fire, the Santa Barbara county emergency operations center (EOC) had to be relocated to the UCSB campus when the fire threatened its downtown location. Computers and other equipment were moved because there is insufficient funding for two fully operational EOCs, and there was an approximately one hour delay after the move before the phone lines were connected, leaving a dangerous communication gap while the new EOC was set up. Obviously, a non-operational emergency operations center poses a major hazard to the public when a fast-moving wildfire is threatening property and lives. One possible solution to such infrastructure vulnerabilities is development of portable self-contained emergency management units such as the trailer used by CalFire for GIS services. Models should be developed to locate new facilities in such a way that minimizes risk from events such as wildfires, and ensures designs that can withstand the shaking of an earthquake and the strong winds produced by storms.

11. Conclusion

A devastating event such as Hurricane Katrina often leads both the public and the government agencies charged with serving them to rethink disaster preparedness, mitigation, response, and recovery and to ask the omnipresent question, “What would I do if the unthinkable happens?” The power of this tragedy to spurn such questions is one reason why it is mentioned frequently throughout this report. It is important to review the lessons learned from Hurricane Katrina and other recent disasters when developing a research agenda for the hazards that affect California.

One of the few things that went right during Hurricane Katrina was the successful implementation of a contraflow evacuation plan. As detailed in the evacuation section of this report, everyone with access to private transportation who chose to evacuate the city was able to do so and in less time than anticipated by planners. This success would not have been possible without extensive research performed at academic institutions such as the Louisiana State University Hurricane Center. A variety of modeling techniques were employed to determine the best strategy, leading to “the most effective highway-based evacuation in the history of the Gulf Coast and, perhaps, in the history of the entire United States.” (Wolshon, 2006, p.1) Of course few would argue that the overall emergency management of Hurricane Katrina was a success. The destruction and subsequent abandonment of large portions of the city and the death of nearly one thousand city residents exemplifies the severe deficiencies that occurred in all four stages of emergency management. Some might argue that the overwhelming and unexpected magnitude of the storm lead to inevitable outcomes, but most hazards researchers agree that more could have been done to accommodate the needs of vulnerable people who were disproportionately affected by this event. It makes sense to expand the notation of the an “area at risk” to an “area at risk with the potential for disproportionate impacts on specific demographic sectors.” The majority of current emergency evacuation research is centered on people who own and drive vehicles, not those who are old, infirm, young, poor, or those with disabilities such as the blind. Emergency operations needs to be based upon good demographic data so that everyone can be considered covered within the plan.

The City of New Orleans was devastated by Hurricane Katrina, a natural event whose effects were amplified by human decisions made over multiple time and spatial scales. Most disasters fit this description: they are a function of both the geographic characteristics of the hazard itself and the vulnerabilities and actions of the people whom it affects. Although government and citizens alike were aware of the destructive potential a direct hit from a strong hurricane posed to New Orleans, they were woefully underprepared for this 'worst case' scenario. Many cities in California face similar dire threats, whether from flooding, earthquakes, wildfires, tsunamis, chemical spills, nuclear accidents, or the actions of a terrorist group or rogue state. Much like New Orleans, the cities and the agencies responsible for protecting them are for the most part unprepared for the potential impacts of a major hazard.

The Jesusita Fire nearly became a major disaster for the City of Santa Barbara. The original Red Cross shelter was moved when it was threatened by the fire, thus reducing the number of possible shelter sites increasing the risk of not being able to meet the needs of vulnerable populations. Likewise, the EOC was moved when threatened by the fire, a contingency action that was actually discussed during the Gap Fire, yet still resulted in 'downtime' making active management difficult. Despite doubling the size of the sheriff's department via mutual aid an event such as the 101 Freeway trailer fire would have pushed manpower requirements and planning abilities to the limit had it persisted. Models should be designed that account for such unexpected events to increase the odds of successful emergency management and reduce the probability of destruction of property and loss of human life. We conclude this report with what is perhaps our most important recommendation: We must assume that the 'worst case' disaster scenario will occur and prepare our citizens and government agencies accordingly.

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Zacharias Hunt, County of Santa Barbara
Yolanda McGlinchey, City of Santa Barbara
Frank Quon, Caltrans District 7
Rick Sachse, Global Traffic Technologies
Fred Samuel, University of California, Santa Barbara
Shayne Sandeman, Caltrans District 5
Shashi Shehkar, University of Minnesota, Twin Cities
David Ybarra, Caltrans District 5

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First Responder Support Systems Testbed (FiRST)
Contract # 65A0257
Cross-Cutting Cooperative Systems

TRACK III – Interoperable Communications

Final Report

Principal Investigator: Dr. Richard Church
University of California Santa Barbara

Contract Manager: Ramez Gerges, Ph.D., P.E.

Interoperable Communications: Interoperability between first response agencies had been enacted in California. Nationally, the FCC has addressed the radio spectrum shortage and made available a vast frequency spectrum for the ITS Dedicated Short Range Communications(DSRC) and public safety (PS) use at the 5.9 GHz and the 4.9 GHz bands, respectively.

This report documents the research efforts at the FiRST Testbed that complemented the national standards development activities (IEEE 802.11p, IEEE 1609, and SAE J2735). Additionally, it investigated the feasibility of interoperable communications that may be applicable to both the ITS & PS bands. The report include the following chapters:

- Chapter 1: Best Field Practices For Wireless Broadband Deployment
- Chapter 2: Multihop Networks: An Alternative Wireless Broadband Communications for ITS & PS
- Chapter 3: Broadband Channel Emulation: A Protocol Testing & Validation Tool for DSRC & Public Safety Wireless Environment



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1 Introduction

The FiRST Testbed provides this report as an example of current best practices for wireless broadband deployment. This effort started in support of Caltrans' needs to investigate the feasibility of installing wireless broadband services at the Safety Roadside Rest Areas (SRRA) statewide.

The goal of this effort has been to develop and validate specifications, acceptance test, and pilot installation of wireless broadband at the FiRST Testbed (UCSB -East Gate). The task investigated both commercially available Wi-Fi services and specially designed infrastructure. An earlier version of this report was delivered to Caltrans in 2008 to support the SRRA Engineering Integration Work Group (Chair: Ferdinand Milanes - Maintenance). Based on our work Caltrans developed and issued the SRRA request for proposal (RFI # 010208). The research team also participated in evaluation the technical merits of the RFI responses and provided input to the PATH researchers. Service related issues and business models (e.g. build and operate) have been out of Task 3-3 scope and were addressed and reported under a separate contract with PATH (TO6100).

This report addresses the technical issues associated with wireless broadband in general. Chapter 2 (Backhaul Analysis Results) and Chapter (Specification & Acceptance Template) provides more details than what was developed for the Caltrans' SRRA RFI. Chapter 4 (Pilot Installation) discuss the pilot installation and the observed best practices to be used for deploying Wi-Fi traveler information services at more than 80 SRRA's statewide. Appendices A and B reflect Caltrans input from the SRRA Engineering & Integration Work Group input.

2 Backhaul Analysis Results

A backhaul analysis was conducted to investigate the feasibility of servicing the 87 statewide SRRA's by using the state-owned microwave towers. The locations for both the towers and the SRRA have been provided by Caltrans-Office of Radio Engineers and District 6 respectively. The study has been performed to identify if the RF path and link budget lend them to a point-to-point or point-to-multipointsolution.

2.1 Approach & Assumptions

2.1.1 Requirements

The backhaul analysis used data provided by Caltrans for the rest area sites and microwave towers. We have assumed a tower height of 45 ft. and a height at the rest-stop locations of 20 ft. We have utilized available GIS databases for terrain and images. The terrain layer utilized is modeled as terrain samples at every 30m or 1 ArcSec and the layer for the state of California is illustrated in Figures 1 and 2 below. The image layer utilized as background for plots and screen captures is derived from 1:3,000,000 scale maps.

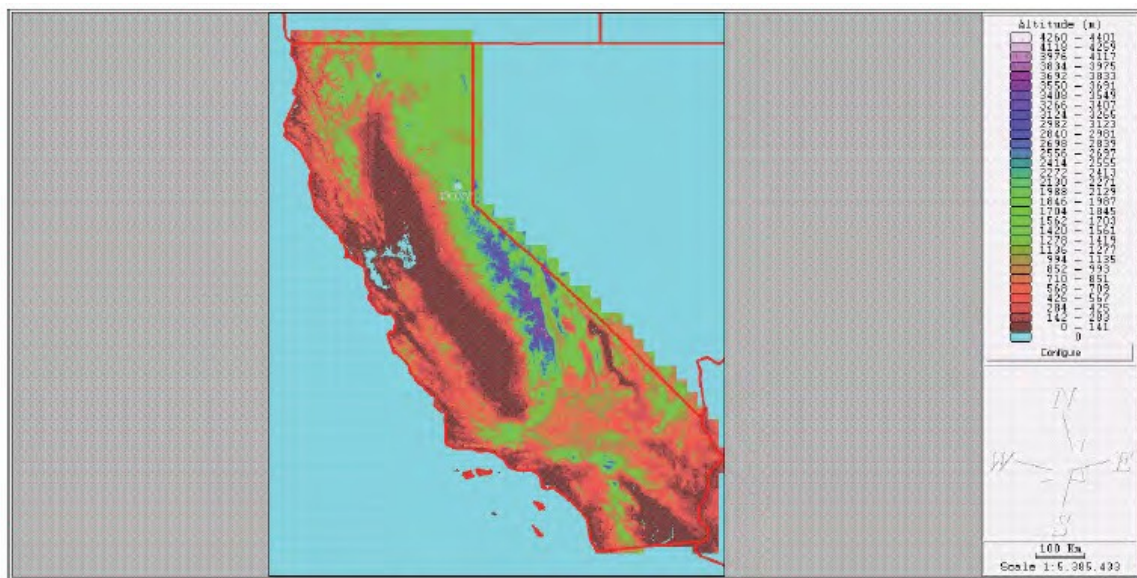


Figure 1 Terrain Database (1 ArcSec Resolution)

2.1.1 Analysis Methodology

We first needed to identify backhaul tower candidates for each SRRA, and then perform a PTP analysis for each of the candidates for the specific SRRA, reviewing LOS from a terrain perspective. To qualify the links, we analyzed typical LOS distances for WiFi-based PTP/PMP solutions with a 20MHz bandwidth channel operating at 4.9GHz. The following table provides the radio performance levels for a typical WiFi (802.11a) based radio with its respective modulation and coding schemes utilized on the analysis.

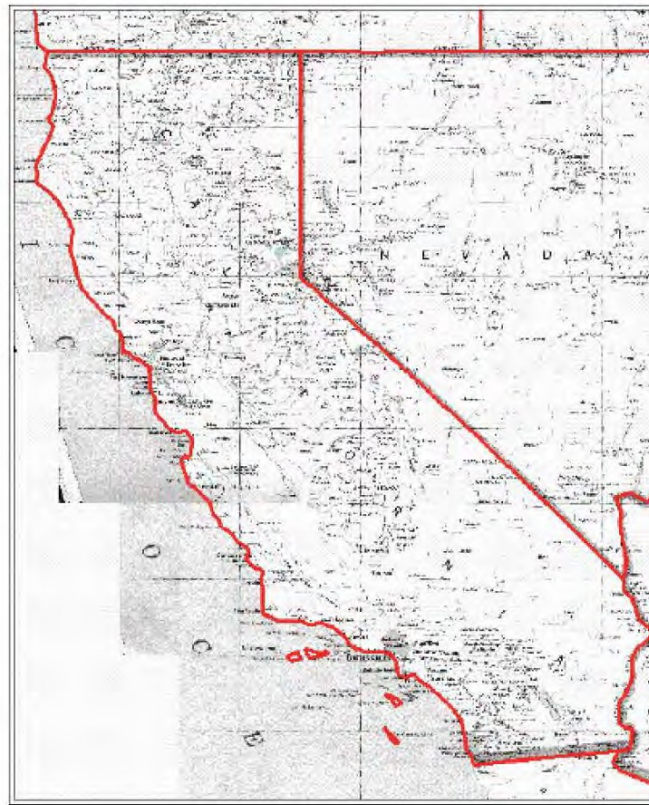


Figure 2 1:3,000,000 Image Layer

CelPlan - Modulation Schemes									
Active	Scheme	Coding Ratio	Max Data Rate (Mbps)	Coding Gain (dB)	Sensitivity @ Default Noise Figure (dBm)				
					BER 10 ⁻¹	BER 10 ⁻²	BER 10 ⁻³	BER 10 ⁻⁴	BER 10 ⁻⁵
<input checked="" type="checkbox"/>	BPSK	1/2	6	1.505	-98.129	-90.484	-86.744	-84.724	-83.335
<input checked="" type="checkbox"/>	BPSK	3/4	9	0.625	-97.249	-89.604	-85.863	-83.844	-82.455
<input checked="" type="checkbox"/>	QPSK	1/2	12	1.505	-93.018	-86.328	-83.484	-81.554	-80.204
<input checked="" type="checkbox"/>	QPSK	3/4	18	0.625	-92.137	-86.048	-82.604	-80.673	-79.323
<input checked="" type="checkbox"/>	16-QAM	1/2	24	1.505	-89.372	-80.73	-76.851	-74.792	-73.386
<input checked="" type="checkbox"/>	16-QAM	3/4	36	0.625	-88.491	-79.85	-75.971	-73.912	-72.506
<input checked="" type="checkbox"/>	64-QAM	1/2	36	1.505	-84.51	-74.724	-70.715	-68.62	-67.198
<input checked="" type="checkbox"/>	64-QAM	3/4	54	0.625	-83.63	-73.844	-69.834	-67.74	-66.318

Figure 1 802.11a WiFi Performance Parameters

2.1.1.1 Antenna Specifications

The antenna pattern (Figure 4) was considered for both the SRRA and Microwave Tower locations in order to optimize the available data rate for each potential link.

2.1.1.1 Propagation Model

In order to analyze link feasibility, we have utilized the LOS propagation model using free space path loss attenuation through every single path analyzed. The formula of free space path loss propagation model is described below as a reference:

$$L_{dB} = 32.44 + 20 \log_{10} f_{MHz} + 20 \log_{10} d_{Km}$$

Figure 2 Free Space Propagation Model

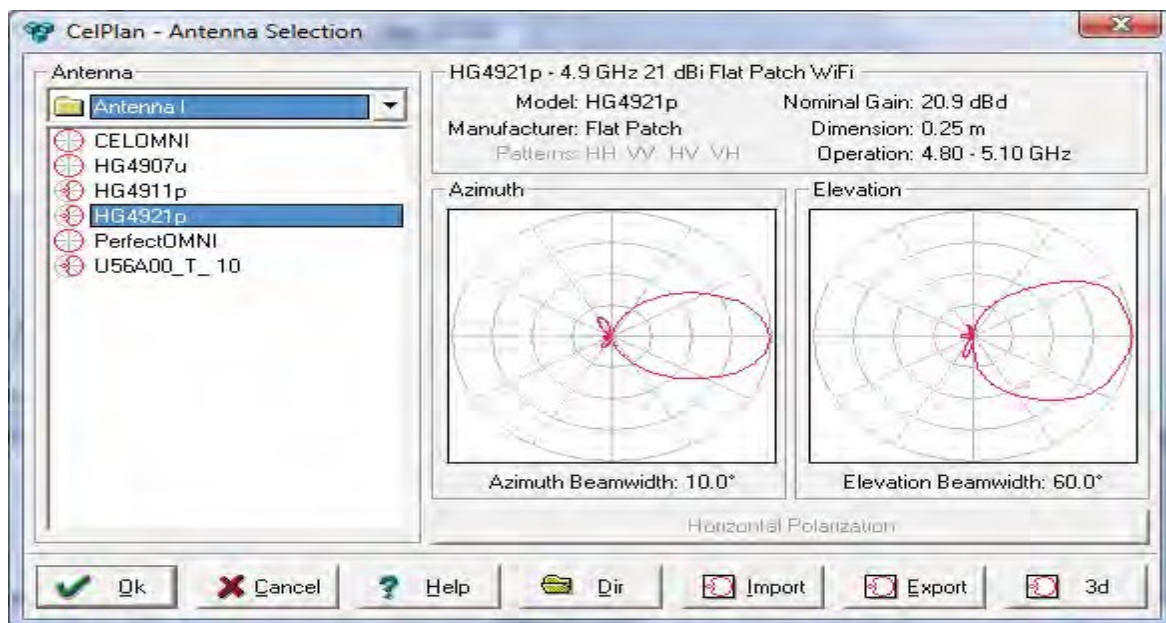


Figure 3 Antenna Pattern (21dBi patch panel)

Figures 6 and 7 illustrate the terminal and environment configurations of the modeled microwave tower, and assuming an environment fading margin of 8.3dB.

2.1 Results

After importing the SRRA locations, we obtained a network topology as illustrated in Figures 8 and 9.

In cooperation with advanced analysis tools provided as a service by Wi4Net, we were able to complete analysis of all sites. Find below multiple figures to illustrate the SRRA's connected to potential Microwave Towers throughout the state of California in 5 zoom areas:

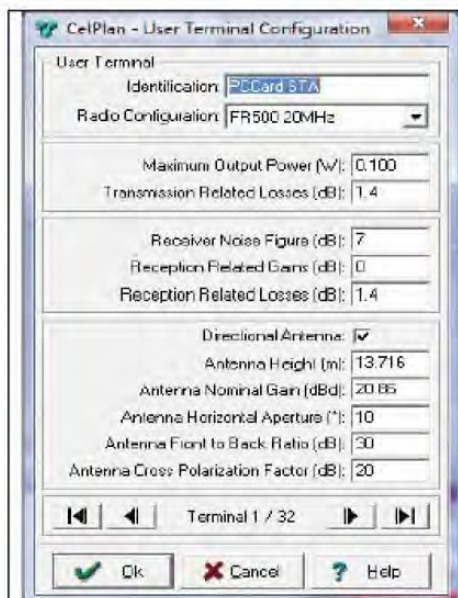


Figure 6 Terminal Configuration

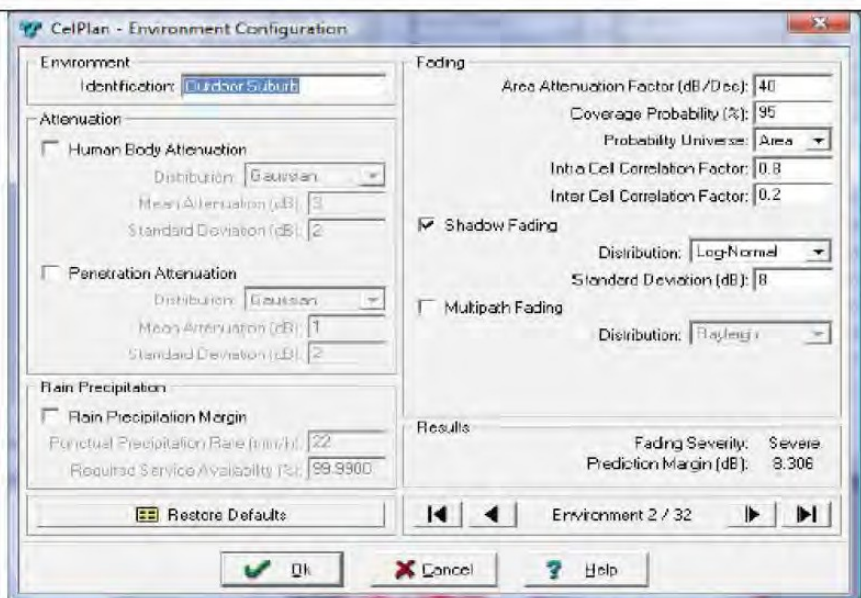


Figure 7 Environment Configuration

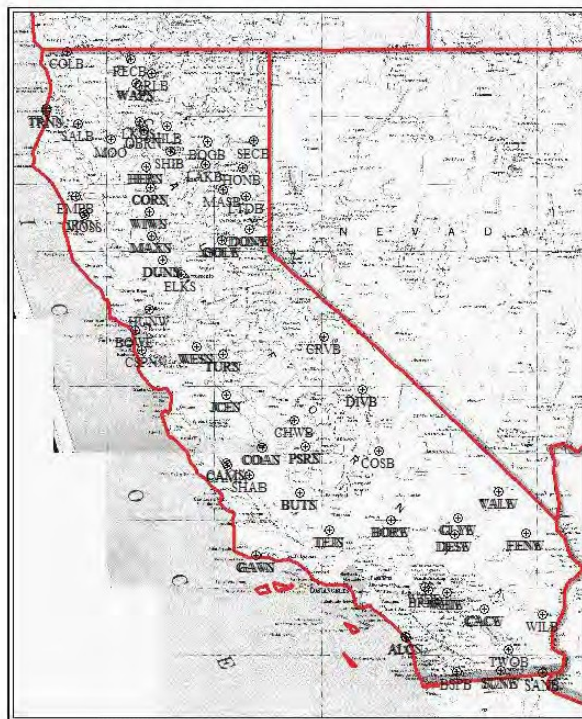


Figure 4 SRRA Topology

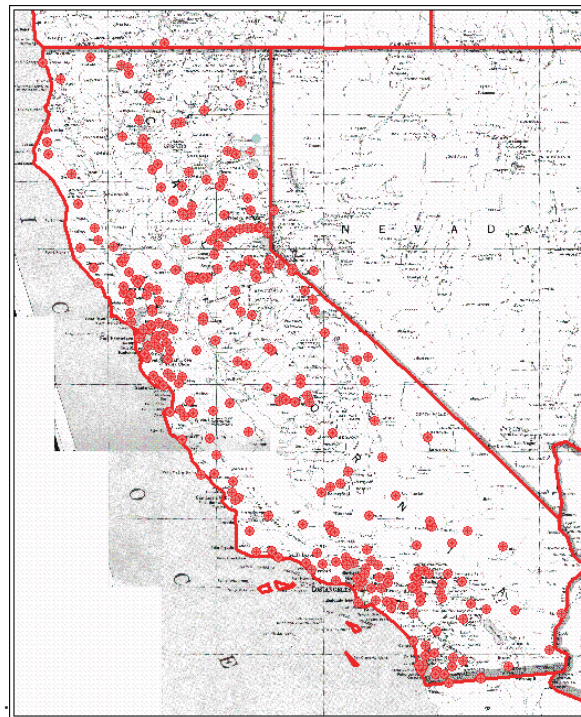


Figure 5 Microwave Tower Topology

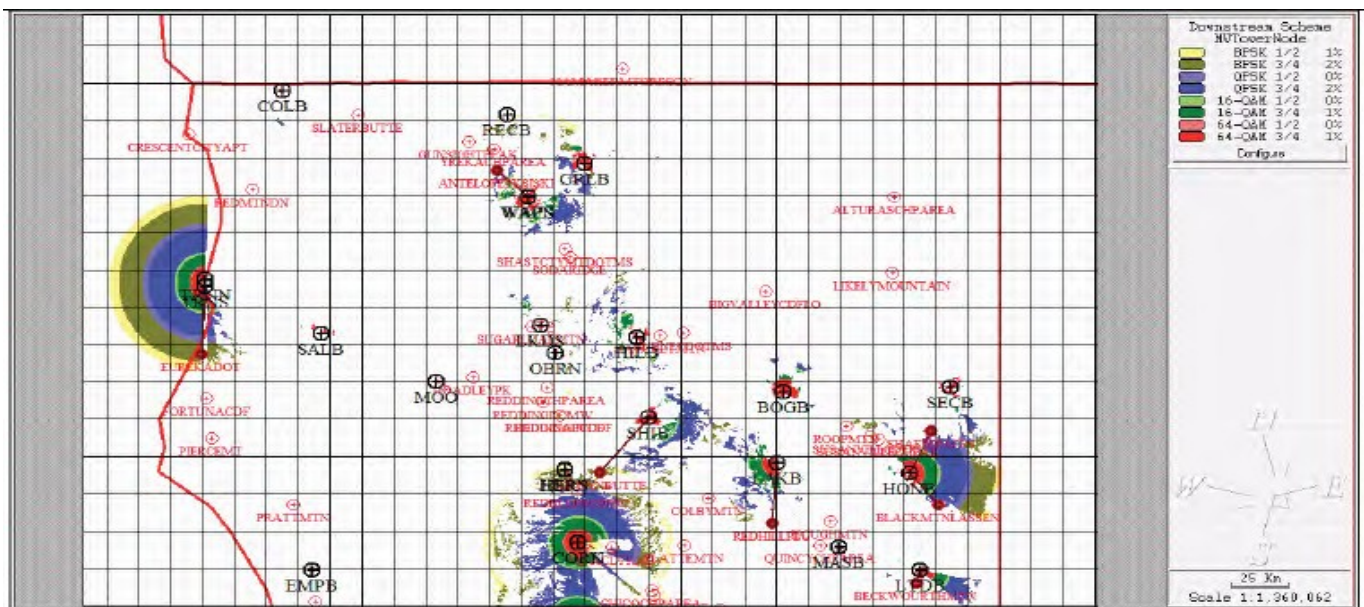


Figure 10 SRRA to MW Tower Links with Overlaid Modulation Scheme Prediction (Zoom Area 1)

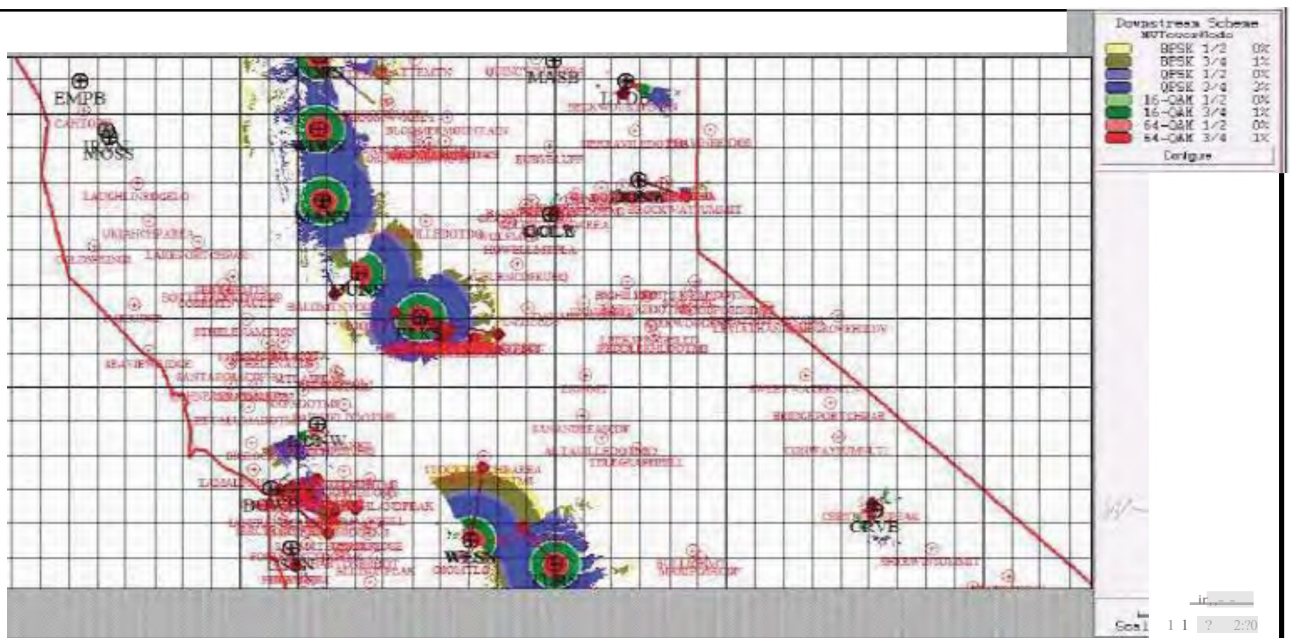


Figure 11 SRRA to MW Tower Links with Overlaid Modulation Scheme Prediction (Zoom area 2)

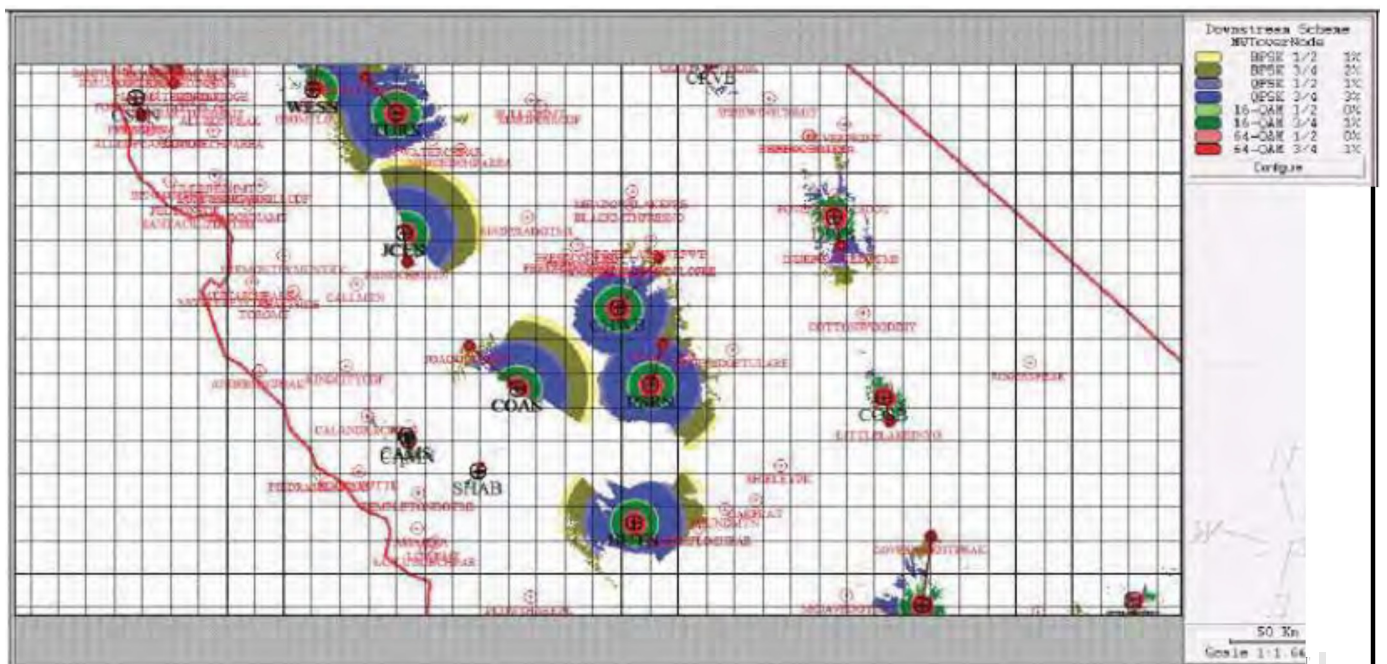


Figure 12 SRRA to MW Tower Links with Overlaid Modulation Scheme Prediction (Zoom Area 3)

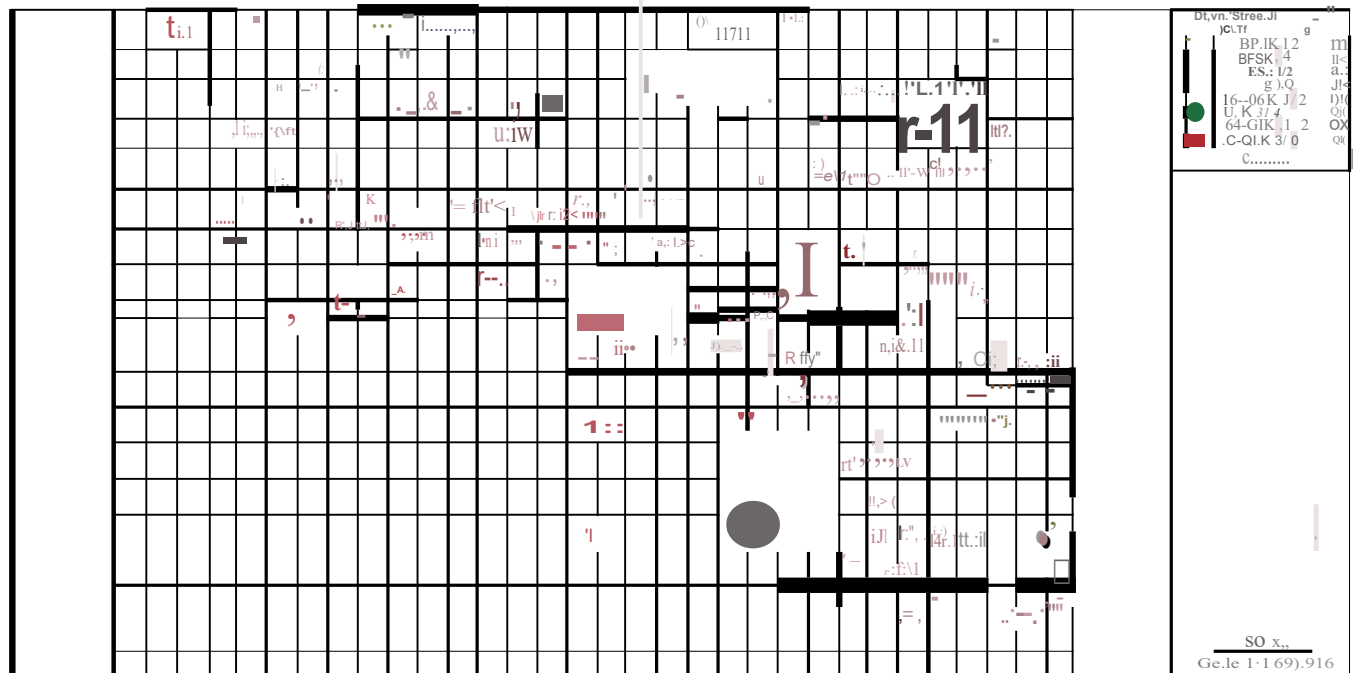


Figure 13 SRRA to MW Tower Links with Overlaid Modulation Scheme Prediction (Zoom Area 4)

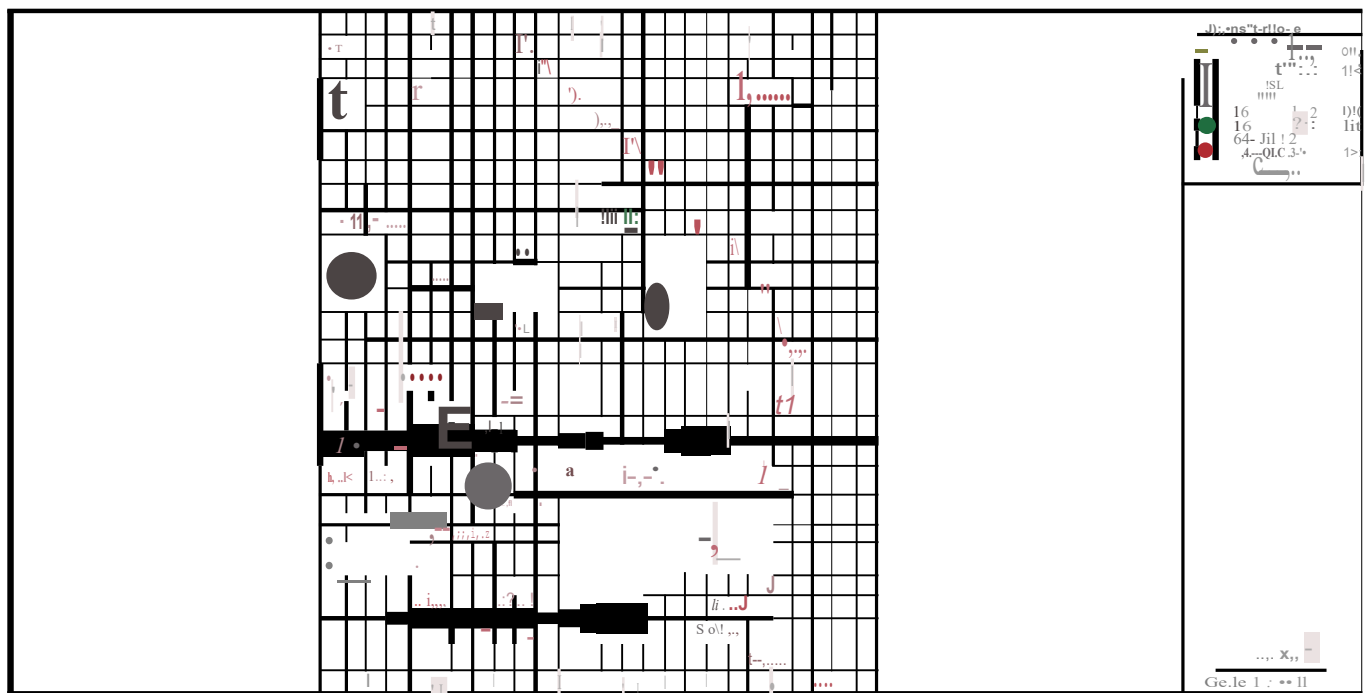


Figure 14 SRRA to MW Tower Links with Overlaid Modulation Scheme Prediction (Zoom Area 4)

2.1.1 Profile Results

As an example, we have included examples of potential successful links (Figures 15 and 16), as well as links that were rejected (Figures 17 and 18).

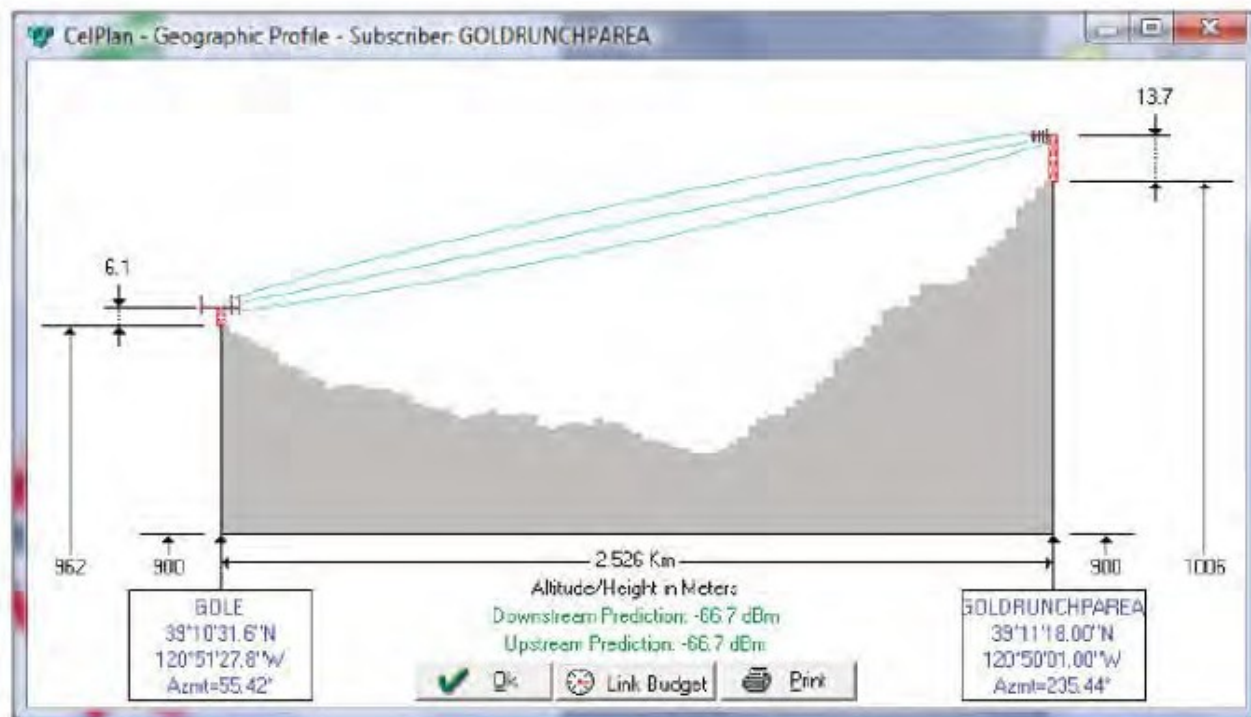


Figure 15 Successful Link Sample 1

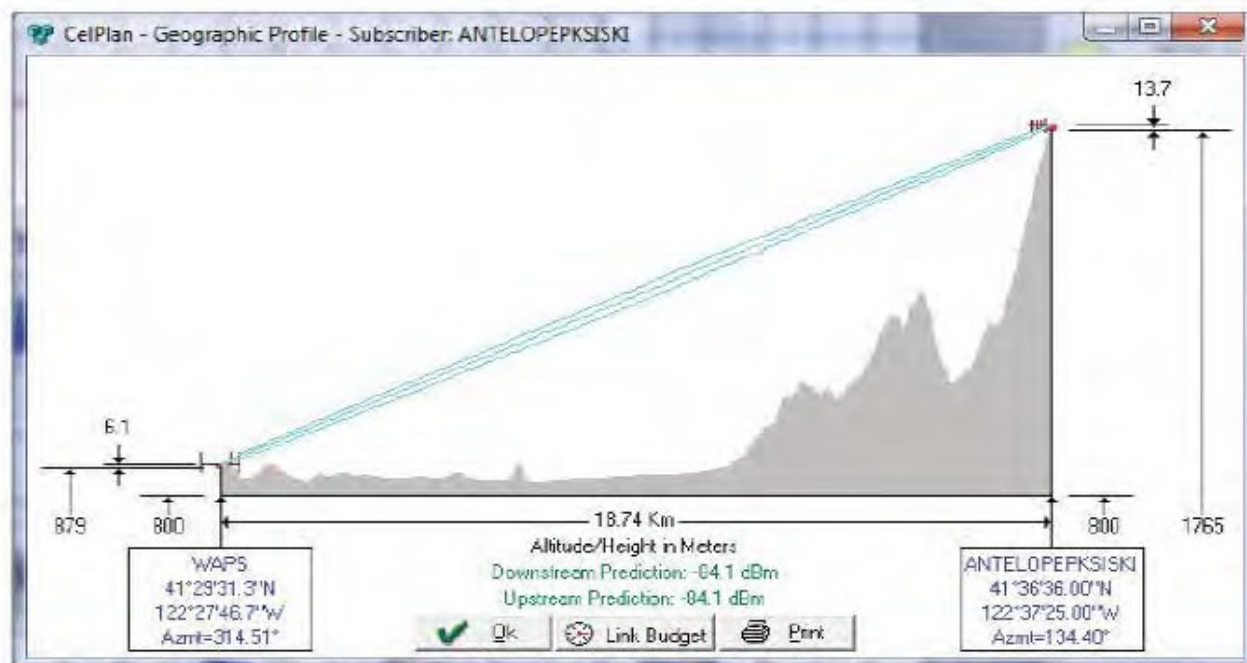


Figure 16 Successful Link Sample 2

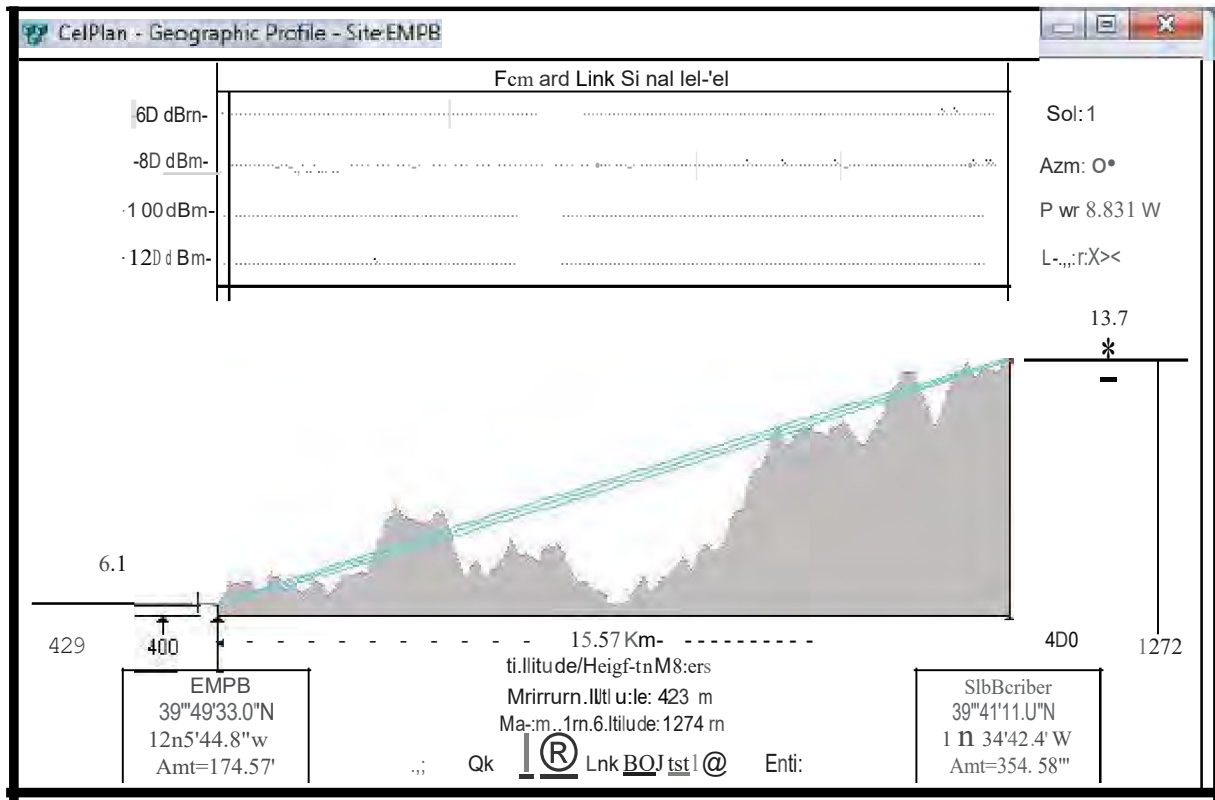


Figure 17 Fai ed Unk Sample 1

3 Specifications & Acceptance Template

3.1 Introduction

The FiRST Testbed research team has developed a template of specifications, installation guidelines, performance measures, and acceptance test that can be used for a generic SRRA site. In collaboration with the ORC, Caltrans will apply and secure statewide licenses for both the 4.9 GHz and 5.9 GHz bands. Initially, we will use the equipment procured under the DHS-ITEP and that were transferred to the FiRST Testbed. These are Wi4Net radios (FR2003) that can be used for WiFi Access (2.4 GHz), as well as the 4.9/5.9 GHz bands. Based on District 6 observations at the SRRA, it is safe to assume an average of 20 simultaneous users at any given time, with mixed data rates. Support for Video Surveillance Overlay specifications at the SRRA assumes using the 4.9 GHz.

Basically, we assume availability of some form of backhaul at each SRRA, with wireless backhaul as the main option. Alternatives to Wireless Backhaul are considered outside of the scope of this project. In general, throughout this chapter, reference is made to "Wireless Backhaul" as means of backhaul to each SRRA.

3.2 Definitions

Annex A and Annex B include a list of acronyms and units referenced in this document.

3.3 Radio Specifications

Vendor shall provide for Wireless Access at each SRRA utilizing the 2.4 GHz band (WiFi based) for wireless access by SRRA visitors, with optional overlay (in addition to 2.4 GHz) of 4.9 GHz and/or 5.9 GHz access (WiFi based) for government purposes. Where feasible, Vendor will provide for Wireless Backhaul from the statewide (microwave) network to the SRRA. Caltrans will provide optimum Microwave tower location for establishing the backhaul connection, with signal interface point (Ethernet). Where such Wireless Backhaul is not available, Caltrans will provide an alternative form of backhaul. Where applicable, Vendor will provide for a short haul wireless link that connects the Northbound / Southbound SRRA's or Westbound / Eastbound SRRA's, so that one of SRRA's leverages the backhaul of the other.

3.3.1 Wireless Access

Vendor shall meet the following specifications:

- a) Transceiver type: Broadband, Time Division Duplex, OFDM, Non Line Of Site capable
- b) Transceiver frequency (standard): 2400-2483.5 MHz
- c) Transceiver frequency (optional): Public Safety 4940-4990 MHz; ITS 5850-5925 MHz
- d) Channel Bandwidth: 5, 10, 20 MHz
- e) Antenna type: Omni-directional, 6dBi gain or more, diversity (two antenna) implementation
- f) Power Output (from radio): +20dBm minimum, adjustable
- g) Receiver sensitivity: Exceeding values in table below

Receiver sensitivity in dBm	Bandwidth in MHz			
Transmission Data Rate (Mbps)	20	10	5	
54	-72			
48	-74			
36	-81			
24	-84	-77		
18	-86	-84		
12	-88	-87	-80	
9	-89	-89	-87	
6	-91	-91	-90	
4.5		-92	-92	
3		-94	-94	
2.25			-95	
1.5			-97	

- h) Data protocol: WiFi-based, 802.11 a/g-based
- i) Security: AES, WPA, WPA2, TKIP
- j) QoS: IEEE 802.1p / 802.1q, WME
- k) Remote Management: SNMP, TelNet
- l) Digital connection type: RJ45
- m) Environmental: Designed and rated for full weather exposure
- n) Mounting provisions: Brackets and band clamps for attachment to pole (round aluminum, octagonal concrete, round wood, and round steel)

3.3.2 Wireless Backhaul

Vendor shall meet the following specifications:

- a) Transceiver type: Broadband, Time Division Duplex, OFDM, Non Line Of Site capable
- b) Transceiver frequency (standard): Public Safety 4940-4990MHz
- c) Channel Bandwidth: 5, 10, 20MHz
- d) Antenna type: Directional, 21dBi gain or more
- e) Power Output (from radio): +20dbm minimum, adjustable
- f) Receiver sensitivity: Exceeding values in table below

Receiver sensitivity in dBm	Bandwidth in MHz			
Transmission Data Rate (Mbps)	20	10	5	
54	-72			
48	-74			
36	-81			
24	-84	-77		
18	-86	-84		
12	-88	-87	-80	
9	-89	-89	-87	
6	-91	-91	-90	
4.5		-92	-92	
3		-94	-94	
2.25			-95	
1.5			-97	

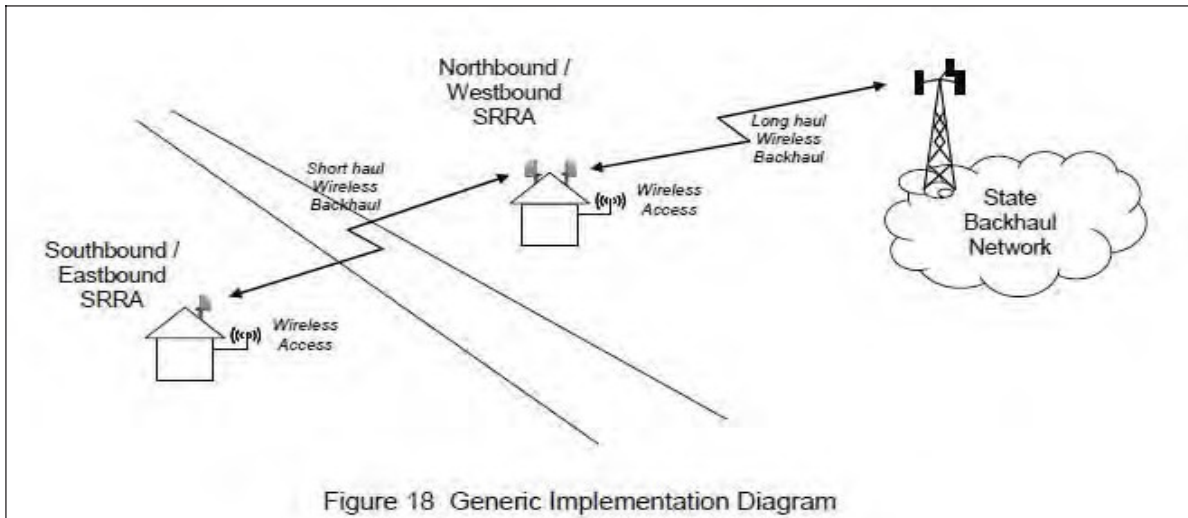
- g) Data protocol: WiFi-based, Pre-WiMAX-based or WiMAX-based (Vendor shall specify recommendation)
- h) Security: AES
- i) QoS: IEEE 802.1p / 802.1q (Vendor shall specify other QoS features)
- j) Remote Management: SNMP, TelNet
- k) Digital connection type: RJ45
- l) Environmental: Designed and rated for full weather exposure
- m) Mounting provisions: Brackets and band clamps for attachment to pole (round aluminum, octagonal concrete, round wood, and round steel)

3.4 Wireless Generic Implementation

3.4.1 Generic Implementation

As described in Section 3.3, the basic concept assumes a form of backhaul to each of SRRA, with wireless backhaul as the main option. Alternatives to Wireless Backhaul are considered outside of the scope of this project. In general, reference is made in this document to "Wireless Backhaul" as means of backhaul to each SRRA. It is assumed that a "Long haul Wireless Backhaul" will connect either the Northbound/Westbound SRRA or the Southbound/Eastbound SRRA to the State Backhaul network. It is assumed that the SRRA with backhaul connection (whether to the State Backhaul Network or an alternative form of backhaul) will connect to the other SRRA (if applicable) through a "Short haul Wireless Backhaul". The following diagram depicts this concept in more detail. Wireless Access would be provided in 2.4 GHz as a standard, with the option to also provide Wireless Access in the 4.9 GHz band and/or 5.9 GHz band. The radio specifications in the previous section are written accordingly.

For the wireless backhaul connections, the licensed 4.9GHz band is assumed. Caltrans will comply with the rules governing the use of this band, and its applicability to the SRRA application. Alternatively, unlicensed spectrum (in the 5.x GHz bands) could be considered, and should yield similar results (assuming the unlicensed spectrum to have open channels available) in terms of the analysis presented in Chapter 2.



With regards to the number of simultaneous users, and throughput that may be expected, we are providing the following diagrams, assuming various possible average frame sizes. The average frame size will depend on the application (and particular mix of application at a given time), where, for example, a VoIP application would have a small average frame size, and a FTP application a large frame size. The following graphs assume a frame size of 1024 bytes, 512 bytes and 128 bytes, respectively.

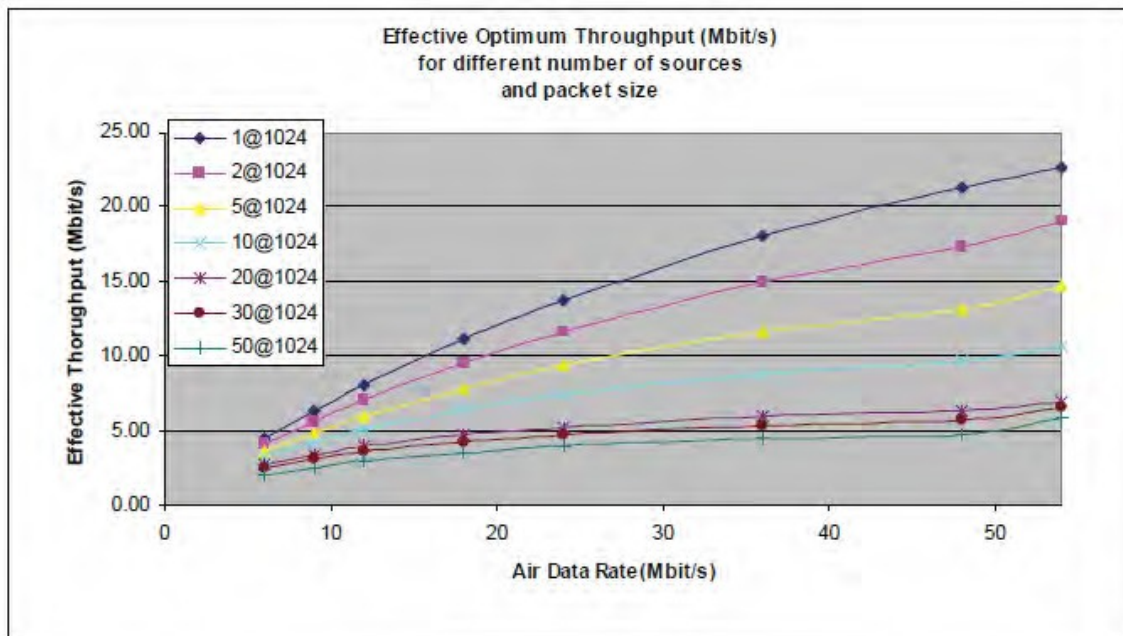


Figure 19 Throughput Versus Number of Users (1024 byte packet size)

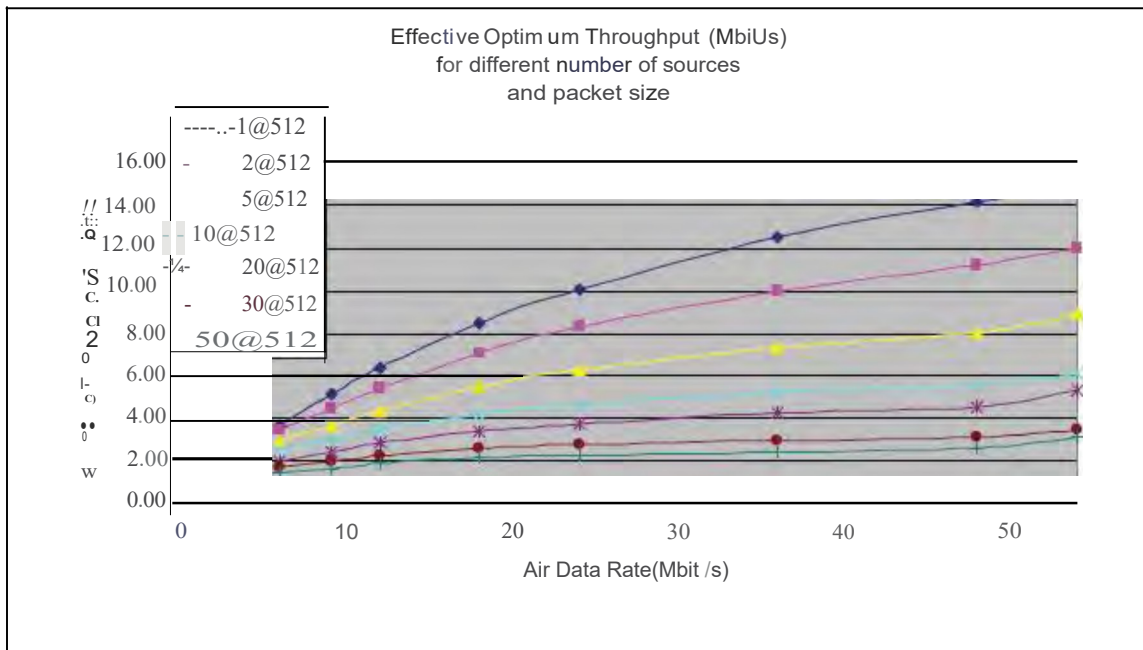


Figure 20 Throughput Versus Number of Users (512 byte packet size)

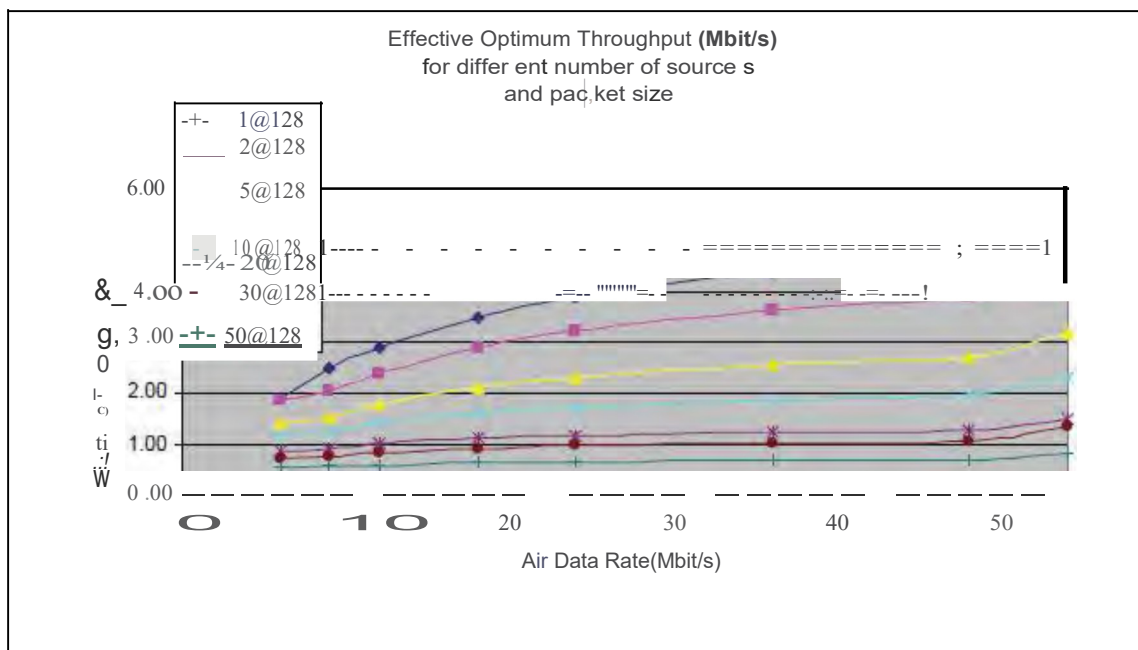


Figure 21 Throughput Versus Number of Users (128 byte packetsize)

It should be realized that the graphs depict **simultaneous** sessions. Typically, many more users are in fact connected to the same AP at the same time, but the actual number of users actually sending or receiving data is much smaller than the number of people connected. This is because of the nature of typical applications of the users, such as e-mail and web-browsing. The graphs reference the number of users actually sending and receiving information.

There are 8 modulation levels identified for each of the lines in each graph in accordance with the IEEE 802.11-2007 standard specifications. For a 20 MHz channel, under ideal conditions, an "Air Data Rate" of 54 Mbps applies, but under reduced link conditions, this will drop to one of seven lower modulation levels, as depicted in the graphs. Based on the above graphs, and assuming an average package size of 512 bytes (Figure 20), and an average modulation level 4, the throughput with 5 users is about 5 Mbps. This means that each user on average experiences a throughput of 1 Mbps. However, the actual number of connected people may be well over 20, since typically only few of the connected users are actually transmitting or receiving data at the same time. Therefore, based on this example, the user experience of 20 connected users can be expected to result in a 1 Mbps connection rate. The above example assumes that the backhaul will be able to support the aggregate 5 Mbps capacity, or possibly more than this if traffic from a Northbound/Westbound and Southbound/Eastbound SRRA is combined over the backhaul.

3.5 Video Surveillance Overlay Design

Caltrans is planning to implement a video surveillance overlay implementation at the SRRA sites. It is assumed that the central monitoring & control location shall be accommodated with server and viewing station, with a scalable, software Digital Video Management Solution (DVMS). At selected SRRA locations, a PTZ camera shall be added, in combination with a weatherized equipment enclosure to accommodate encoder (if not using an IP camera), power supply and local storage capability. Local access shall be possible through the 4.9 GHz band, and remote access and viewing shall be provided for utilizing the SRRA backhaulconnection.

The PTZ camera shall either be co-located with the Wireless Access radio (using wired Ethernet connection), or, in case a different location at the SRRA would provide for a better camera position, the camera shall be equipped with a 4.9 GHz wireless connection to connect to the backhaul point at the SRRA.

3.5.1 System Requirements

Vendor shall propose a video overlay option with the following system requirements:

- a) At SRRA, the following equipment shall be offered:
 - i. PTZ Camera
 - ii. Encoder (if PTZ camera is analog)
 - iii. Local Storage
 - iv. Optional Wireless Connection (if camera and Wireless Access physical location at SRRA are different, based on optimum camera location, from field of view perspective)
 - v. Outdoor Equipment Enclosure
- b) At central monitoring & control location, the following equipment shall be offered:
 - i. Server
 - ii. Storage capability
 - iii. Viewing Station with monitors
 - iv. DVMS

The following diagrams provide a schematic of the video overlay system implementation.

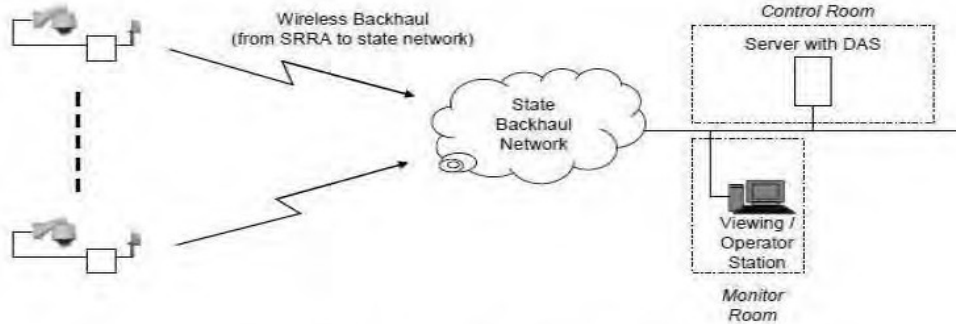


Figure 22 Video Overlay Concept Diagram

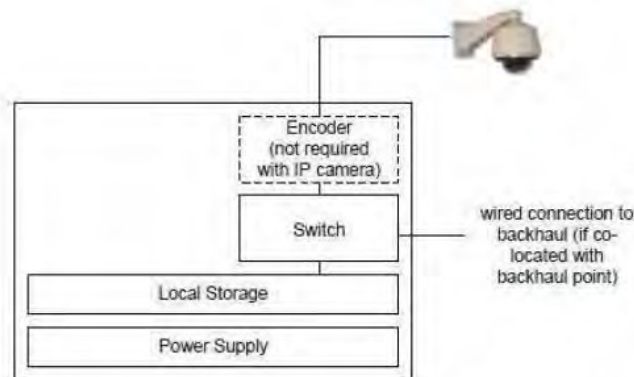


Figure 23 SRRA Video Solution (Co-location with Backhaul Point)

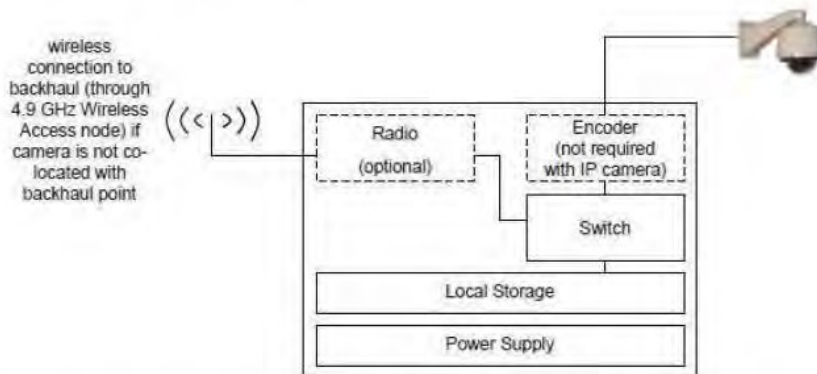


Figure 24 SRRA Video Solution (Wireless required to connect to Backhaul Point)

3.5.2 Camera Requirements

Caltrans should select a preference with regards to optical zoom for the cameras. The standard industry options for professional level PTZ cameras are 23X, 26X or 35X. The higher this number, the more expensive the camera (but better quality video is achieved at further distances). We assumed 35X in this document for reference purposes only.

Vendor as a minimum shall meet the following specifications:

- a) Camera Type: Analog video camera, with PTZ capability and IP interface (IP Camera).
- b) Pan Range: 360 degreecontinuous rotation range.
- c) PTZ format: Pelco and Competitive Control Protocol or similar.
- d) Format: NTSC color, with Black & White capability (auto switching)
- e) Lighting Level: At ½ second shutter speed, 0.1 LUX (color), 0.02 LUX (Black & White)
- f) Shutter Speed: ½ -1/30,000 second, automatic
- g) Resolution: Up to 4CIF (userdefinable)
- h) Lens zoom range: 35X optical (with an additional 12X of digital zoom)
- i) White Balance and Gain Control: Automatic, with manual override/disable
- j) Optical Zoom Speed: 3.0 secondsminimum
- k) Window blanking: User defined rectangular shapes, 8 minimum, to mask camera view
- l) Camera dome housing and mountrequirements:
 - i. Environmental Requirements: -30°C to +60°C, full operation
 - ii. Environmental rating: NEMA 4X
 - iii. Mounting means: Arm attached to a pole, holds camera assembly approximately 2 feet from the pole.
 - iv. Pole attachment requirements: Arm shall attach to round aluminum, octagonal concrete, round wood, and round steel utility poles. Mount shall not require holes to be drilled into utility poles. Also include building mounting solution, where needed.
 - v. Maximum wind surface area: 1 square foot.
 - vi. Housing heater: Thermostatically controlled, designed to maintain full camera operation down to -30°C

3.5.3 Encoder Requirements

Vendor shall meet the following specifications:

- a) Basic purpose: Conversion of analog video signal from cameras to IP format
- b) Input Signal: Standard 1.0 volt Peak to Peak, 75 ohms, NTSC format
- c) Control Input Signal: RS232/422/485 Serialformat
- d) Output Signal: IP format, 10/100 Base T auto sensing
- e) Digital Video Streams: 2 each, MPEG-4 standard
- f) Frame Rate: Individual selectable, up to 30 per second (adjustable), 700 horizontal, 480 vertical

- g) Output connection type: RJ45

3.5.4 Local Storage Requirements

The following table reflects the needed capacity for 4CIF resolution and based on average motion. A 250GB of local storage capacity yields about 17 days of storage at 15 FPS. Typical field numbers may result in 17-30 days of actual storage capacity (based on our experience).

Storage Requirement per day per camera (GB)								
FPS	1	2	4	6	8	10	15	30
QCIF	0.06	0.12	0.24	0.36	0.49	0.61	0.91	1.82
CIF	0.24	0.49	0.97	1.46	1.95	2.43	3.65	7.30
2CIF	0.49	0.97	1.95	2.92	3.89	4.87	7.30	14.60
4CIF	0.97	1.95	3.89	5.84	7.79	9.73	14.60	29.20

Vendor shall meet the following specifications:

- a) Video Storage Capacity: 250 GB minimum
- b) System must be fully compatible and integrated with central DVMS system
- c) System shall allow local access for configuration of all system parameters (frame rates, resolution, PTZ patterns, motion detection, etc.)
- d) Local Storage system shall allow for the system to work independently, with all features available at the Central Monitor Station, even if no backhaul connection to the Central Monitor Station is available.

3.5.5 Enclosure Requirements

Battery back-up function shall be considered for each individual site. A sample requirement is referenced in the video overlay portion of the requirements, but could be requested also for the Wireless Backhaul and Wireless Access radios. Furthermore, equipment housing type should be based on Caltrans requirement. Stainless steel is suggested for reference purposes only.

Vendor shall meet the following specifications:

- a) Equipment housing: All pole mounted equipment, with the exception of the camera and its associated camera housing, shall be contained within an equipment housing
- b) Housing type: stainless steel, hinged door, bolttable, NEMA 3R minimum
- c) Housing Size: 12" wide x 16" high x 7" deep, maximum
- d) Housing Mounting: brackets and band clamps for attachment to pole (round aluminum, octagonal concrete, round wood, and round steel)
- e) Penetrations: All entry into this housing shall be weather rated
- f) Required Input power: 120 Volts AC.
- g) Power source attachment: Provide a weathertight power connection.

- h) Transient protection: Provide suitable means to protect all pole-mounted equipment from electrical disturbances and transients originating from electrical powersource.
- i) Brownout/ Blackout protection: Provide means to keep all pole mounted equipment full function during a power source outage of up to 15 minutes.
- j) Fusing: Overcurrent protection of all pole mounted equipment. Install internal to equipment housing. Provide external pilot light (red, visible from ground level) that indicates overcurrent protection is open.

3.5.6 Central Monitoring & Control Requirements

Caltrans shall specify monitoring requirements for individual SRRA, as a starting point, two (2) 19 inch screen are suggested. With regards to central storage, the required capacity depends on the number of cameras and storage policy. The resolution and frame rate of the video to the central location will depend on the backhaul capacity. It is recommended to request a scalable Direct Attached Storage (DAS) solution as a cost-effective starting point. This solution is recommended to be expandable at least to 6TB of raw capacity. The following table allows for calculation of required storage, based on the actual architecture.

Storage Requirement per day per camera (GB)								
FPS	1	2	4	6	8	10	15	30
QCIF	0.06	0.12	0.24	0.36	0.49	0.61	0.91	1.82
CIF	0.24	0.49	0.97	1.46	1.95	2.43	3.65	7.30
2CIF	0.49	0.97	1.95	2.92	3.89	4.87	7.30	14.60
4CIF	0.97	1.95	3.89	5.84	7.79	9.73	14.60	29.20

Vendor shall meet the following specifications:

- a) Vendor solution must include software that can control the pan, tilt and zoom (PTZ) capabilities of all cameras that are part of the system.
- b) Vendor solution must include color analog cameras that have the capability of monochrome night vision that is automatically activated by built in sensors that detect light level or by use of motion detection.
- c) Vendor solution must include software that has built in security functionality to control user account access and an audit trail for all files accessed.
- d) Must have three (2) 19" widescreen LCD displays with software that allows user definable views from one to 16 cameras per screen.
- e) Central Monitoring Station must be able to control 50 cameras minimum.
- f) All digital video signals from the cameras must be able to be recorded.
- g) Central Monitoring Station must be equipped with Direct Attached Storage (DAS) solution, incorporated with the server machine, with the capability to expand to 6TB of raw capacity.
- h) Video output can be used on analog and or DVI standard monitors.
- i) Software must provide a logical map of cameras and associated equipment locations.
- j) Software must have the capability to rename the cameras on the logical map.

-
- k) Preset PTZ locations must be selectable on the system software Central Monitoring Station.
 - l) Software must support an unlimited number of user accounts.
 - m) Vendor solution must include software that has built in security functionality to control user account access and an audit trail for all files accessed.
 - n) Vendor solution must include a database (e.g. Microsoft SQL) that stores activity logs and audit trail information.
 - o) System must offer definable levels of system access and control including, but not limited to, specific cameras for specific users.
 - p) Any network PC must be able to be used as an additional monitoring station and control the camera used.
 - q) Video (live or archived) can be made available for viewing over the WAN/network.
 - r) Security and authorizations are required.
 - s) Logging of all such activity is required.
 - t) System must use MPEG-4 or h.264 video compression.
 - u) Vendor solution must have the ability to detect motion and activate camera recording upon detection of motion with a pre-event buffer.
 - v) Must have browser based access control and management of cameras.
 - w) Joystick required for manual selectable remote control of the cameras at the Central Monitoring Station.
 - x) System must have the capability of accepting other video feeds (i.e., DOT cameras, IP based).
 - y) System must offer search and playback capabilities for each camera in the forward or reverse direction, frame by frame, and from beginning to end.
 - z) Reviewed images can be zoomed in or out and be printed to a local or network printer.
 - aa) Still images must be exportable as a JPEG, TIFF or other acceptable equivalent file type.
 - bb) Must have/provide capability/equipment to transfer archived video onto removable digital media (CD/DVD) in a secured format to maintain integrity of the video and maintain chain-of-custody evidence requirements.
 - cc) Videos transferred onto removable digital media (CD/DVD) must be able to be played back on any Windows based PC.
 - dd) Provide all software and hardware to remotely monitor and control the cameras.
 - ee) Provide all necessary equipment for one complete workstation capable of viewing and controlling video images and camera operations.

3.6 Training & Documentation Requirements Language

Vendor shall provide Training according to the following minimal requirements:

- a) Vendor shall prepare, administer and conduct on-site training program designed for 10 designated personnel to fully and efficiently operate and maintain the installed system. Training will be of sufficient scope and depth to

ensure all designated personnel who complete the program shall be fully qualified, certified and capable of operating the system and subsystems as installed, including system configuration. All training shall be completed at least seven (7) days prior to scheduled start of the system.

- b) Vendor shall provide a copy of all training aids and operational manuals to Caltrans
- c) Vendor shall provide name and contact information of the person(s) or organization(s) that will assist the Caltrans with any technical questions for a minimum of six (6) months starting from the date of acceptance.
- d) Description of complete training program including:
 - i. Duration of the training.
 - ii. What are requirements for training facility (to be provided by Caltrans)
 - iii. Any optional training that is not included in the price of the proposal, but available for additional fees that is to be provided.
- e) The Training Program is expected to address at a minimum:
 - i. Basic radio installation procedure
 - ii. Radio configuration procedure (local and remote)
 - iii. Basics of radio planning (as relevant to deployment) and overview of implemented radio channel plan
 - iv. How to manage system
 - v. How to operate the hardware and software to control camera capabilities such as zooming, panning, focusing, etc.
 - vi. How to record and retrieve data, as well as storage and backup procedures
 - vii. How to conduct a search and retrieval process of pre-recorded video from the server according to time stamps and any other identifier that may be used

The Vendor shall provide Caltrans the following minimum documentation:

- a) Operations manual and specifications of all installed hardware and software
- b) Overall network diagram and IP addressing scheme
- c) Site generic wiring / connection diagrams for radio sites and camera sites
- d) Radio plan and FCC licensing information for all wireless radios and links

3.7 Maintenance & Support Requirements Language

Vendor must provide complete details on provided maintenance & support services addressing the following minimum issues and requirements:

- a) Period of maintenance coverage shall be 1 year from the date of acceptance
- b) Phone support and procedure. Vendor must indicate whether this service is offered 24/7 or otherwise.
- c) Describe response procedure for:
 - i. First-time response to service calls
 - ii. Escalation calls

- d) Equipment replacement procedures and policy for maintaining spares locally. Maintenance shall provide for replacement of any failed equipment with related services.
- e) Emergency response service with a guaranteed response time, location of dispatch by responding party and process to be followed for the following events:
 - i. Backhaul radio outage
 - ii. Access radio outage
 - iii. Network control and monitoring center outage
 - iv. Camera outage
- f) Maintenance coverage for routine services on a periodic basis, including cleaning (for cameras), filter replacements, and other applicable required routine maintenance. Vendor shall detail what the routine maintenance services comprise of and how many times per year they will be performed.
- g) Maintenance plan shall include software and firmware patches, upgrades, and related implementation services.
- h) Suggest optional maintenance service plans and reasons for recommendation. Vendor shall include option for extended maintenance for period of 5 years from the date of acceptance.

4 Location for Pilot Installation



4.1.1 Limitations of the Gaviota Site

Originally we surveyed the Gaviota site as a pilot for the SRRA installation. The Gaviota site includes both a Northbound and Southbound SRRA. Based on our site survey, we determined that a Short haul backhaul between the two sites would be feasible. Also, a small building is available to mount equipment and connect to power. The limitation of the site is that a Long haul Wireless Backhaul to the State Backhaul Network, according to our study in Chapter 2 of this report, is not possible. An alternative form of backhaul would need to be considered to be able to utilize this SRRA for a test implementation. Also, an additional wireless repeater may be used here to achieve a backhaul connection.

4.1.2 UCSB - HWY 217 Pilot Site

Based on the above limitations, we chose to use the UCSB-East Gate (EG) located at HWY 217 as an alternative test site to validate the SRRA technical requirement and other future testing required for the FiRST Testbed Interoperable Communication task. This location provides an acceptable view from the camera, easy access for the UCSB backbone fiber optic network, and will allow the research team easy access to the test facility in a safe manner.



The EG pilot implementation would allow verifying all specifications with an actual implementation, and with actual measurements. The FiRST Testbed will validate the above template of specifications, installation guidelines, performance measures, and acceptance test. We intend to use hardware from various vendors for a generic Wi-Fi (802.11a/g) and wireless broadband at 4.9 and 5.9 GHz spectrum (Wi4 Net), as well as DSRC standard compliant devices (Denso, Siemens, ARADA, etc.)

The pilot will validate the video overlay requirements as addressed in the above section. We chose to install the PTZ camera collocated with the Wireless Access radio, and connected through the fiber optic backbone provided by UCSB at the EG cabinet. Alternatively, the camera could be placed away from the Wireless Access radio, with a wireless link. The FiRST Testbed will have access to the West Gate camera controlled intersection, and will tap in to the video feed and provide a self-contained solution that includes also local storage with video stored at this unit at 15 or 30 FPS (and 4CIF resolution). Remote viewing and control at variable rates to test video quality at different compression methods and wireless bandwidths. The variable frame rate will be available on a continued basis, or just on demand. Any stored video will only be used for the FiRST Testbed and other research needs and in accordance with the UC rules and regulations.

4.2 Best practice Installation Procedure

4.2.1 Site Survey / Pre-Installation Activities

- a) Identify geographic locations for each system component (e.g. radio, enclosure, camera, etc.) and make note of geographic references such as GPS latitude/longitude coordinates street intersection with corner identification, pole numbers from city plates, etc.
- b) Check LOS/non-LOS scenarios between radios, and assess LOS conditions for access point locations and camera locations. Report / justify recommendation of location of each component.
- c) If feasible, perform link throughput test with test radios until the minimum necessary throughput is obtained between nodes on each link. Take note of the equipment used such as antenna model numbers, cables lengths/losses and antenna height.
- d) Take pictures of the system component locations. Identify mount locations, and Caltrans interface points (signal and power). Determine applicable cable length.
- e) Verify unlicensed channel utilization at each location, for applicable bands.
- f) Generate an RF channel plan for all radio components.
- g) Generate summarized report describing the information above for each system component location in the network.

4.2.2 Installation

- h) Create a plan establishing dates for installation of each system component and site.

-
- i) Provide pre-configured radios with adjusted cabling to field crew, in accordance with project schedule.
 - j) Notify the Caltrans project manager that the installation will start 2 days prior to the first visit, identifying the names of the field crew personnel involved and the description (make/model/color) and license plates of any vehicles that will be used throughout the installation process.
 - k) Before the work at a given site, confirm readiness of interface points (signal and power) with the Caltrans.
 - l) At the first site visit to install the system components, verify readiness of Caltrans interface points (signal and power). Also, confirm any differences in cable lengths, compared to prepared cabling and cable length as measured during the site survey. Confirm mount brackets and mount location.
 - m) Install Long haul Wireless Backhaul link and antennas. Power the components and verify that all devices are powered up. Connect a laptop to the Ethernet connector at the subscriber location and telnet to the radio controller that serves as an AP. Verify the connection. Verify that signal levels and modulation schemes achieved are accepted. Throughput tests can be run to ensure proper individual link performance. Verify antenna pointing to be optimized.
 - n) Install Short haul Wireless Backhaul link and antennas. Power the components and verify that all devices are powered up. Connect a laptop to the Ethernet connector at the subscriber location and telnet to the radio controller that serves as an AP. Verify the connection. Verify that signal levels and modulation schemes achieved are accepted. Throughput tests can be run to ensure proper individual link performance. Verify antenna pointing to be optimized.
 - o) Install Wireless Access AP and antennas. Power the components and verify that all devices are powered up. Utilize a WiFi enabled laptop to verify connection. Verify that signal levels and modulation schemes achieved are accepted, nearby the AP. Throughput tests can be run to ensure proper individual link performance.
 - p) If applicable, install camera overlay components. If wireless connection to the backhaul point is required, wireless link needs to be verified (following instruction as in item f) above). Local Storage device shall be programmed to adjust camera automatically (create pattern), program encoder and set archiving settings.

4.3 Best practice System Testing & Commissioning

- a) Report on measured signal level, modulation scheme and throughput for applicable wireless backhaul connections.
- b) Perform drive-test / walk-test to assess coverage in the accessible areas of the site. The coverage map should justify the selected location for the Wireless Access radio(s). Report with coverage map indicating measured modulation scheme.
- c) If applicable, report on local settings of video system such as resolution/frame-rate for each stream, areas of interest programmed into the pattern, and recording settings). Commission each

camera at the central monitor station, assuming a sufficient bandwidth backhaul connection is in place.

- d) Report to Caltrans about site completion, and provide summary report.

4.4 Best practice Acceptance Test Procedure

Acceptance test will have the following basic template format.

Test	Description	Target	Actual	Date	Pass/Fail
1	Report on Long haul Wireless Backhaul Connection				
2	Report on Short haul Wireless Backhaul Connection				
3	Report on drive-test / walk-test for Wireless Access (in all implemented bands)				
4	Report on wireless link to camera (if applicable)				
5	Successful Visualization of a Live Video Stream at camera site				
6	Successful Launching of Archive Player at camera site				
7	Successful Visualization of a Recorded Video Stream				
8	Successful implementation of PTZ pattern (with summary of areas of interest)				

Test	Description	Target	Actual	Date	Pass/Fail
1	Successful Visualization of each Live Video Stream at Workstations				
2	Successful Visualization of all Live Video Streams at Workstations Simultaneously				
3	Successful Launching of Archive Player from Workstations				
4	Successful Visualization of a Recorded Video Stream from Remote Site Archiver for each Camera				
5	Successful Visualization of a Recorded Video Stream from Local Archiver for each Camera				

Appendix A – Caltrans SRRA Steering Committee (SC) Questions & Assumptions

SRRA- Key Questions

- **Key Question 1:**
Are there regulations or laws that constrain Caltrans' SRRA vision?
- **Key Question 2:**
What is the optimum balance between the system's needs (Caltrans) and the travelers' needs?
- **Key Question 3:**
What is the impact of the new 3rd Generation (3G) digital cellular technologies and services from the Cellular industry on the Wi-Fi business model?
- **Key Question 4:**
Is there a sustainable business model that can deliver the proposed service at minimum cost to the state?
- **Key Question 5:**
How to quantify the benefits to Caltrans?
- **Key Question 6:**
Would the SC set a threshold for the benefit/cost for the SRRA initiative?

SRRA- Assumptions

- **Assumption 1:**
The project primary goal is to provide a cost effective way to enable interactive (user selected) traveler's information at statewide SRRA's.
- **Assumption 2:**
The project primary approach is to engage the WG's to identify key questions and issues that need to be addressed in the RFP, and develop criteria to select a successful implementation of the Wi-Fi at the statewide SRRA's.
- **Assumption 3:**
The project primary deliverables are:
 - To investigate the feasibility of a cost effective implementation for the state that uses (most probably) Wi-Fi technology at the statewide SRRA.
 - To issue a quality RFP that encourages public/private partnership to deliver the required services at the SRRA's.
 - To select a vendor, negotiate and execute a multi year agreement for the service

Appendix B – Caltrans SRRA Workgroup Input

SRRA- Engineering & Integration Workgroup

- **Scope:**
 - Address technical and related regulatory issues leading to the RFP (including input to the RFI's).
 - Identify telecommunications infrastructure for Internet Access.
 - Evaluate alternative engineering (cost effective, sustainable, and timely) approaches to satisfy other WG requirements.
 - Assess technology risks and ways to mitigate them (e.g. wireless security).
 - Assess infrastructure needs to add future services (e.g. TES, cameras, etc).
 - Develop functional and performance specifications for the RFP.
 - Develop selection criteria and acceptance tests for the technical proposals.
 - Assess the proposed technical soundness and maturity (standard compliance).

SRRA- ENG WG Questions

- Is free Wi-Fi to the traveler still the goal of this project? How?
 - Turnkey solution with no cost to Caltrans and free (but limited) service to the traveler
 - Address the Internet Access (Backhaul) element at the SRRA
 - Get BOINGO (or similar service) at SRRA (\$21/ month)
- Will the Cellular high speed data services (3G-3rd Generation) replace the Wi-Fi technology?
 - It is not the complete solution, it is one element of the solution (see next 2 slides)
 - It is somewhat affordable (free card with 2 years commitment and \$ 60 /month for unlimited data)
 - New phones (iPhone) have both Wi-Fi and cellular data service (Edge)
 - Need to validate 3G coverage (availability) at all the SRRA (RFI)
- How to minimize the Caltrans' cost (TCO) of providing the Wi-Fi service?
 - Look at Backhaul Solution other than T1
 - Integrate other IP services (Payphone, TSE) that needs the backhaul/access infrastructure
 - Outsource the Web Portal Hosting (Public-Private partnership)
 - Implement Wireless Security (phased approach)
- Do we have a cost effective solution for the current traffic load at SRRA? How much?
 - Yes (next slides)
- What are the most critical measures of success?
 - Need SC guidance
- More questions:
 - Is wireless mesh networking/ MuniFi a good fit for the SRRA?
 - Is WiMax technology a cost effective alternative to replace traditional T1 lines?
 - Is broadband over power line (BPL) technology a good fit for SRRA?
 - Is it feasible to Implementing VOIP at the SRRA?
 - How can we ensure wireless security at the SRRA?
 - How can we leverage Caltrans' "Air Space?"
 - Do we have a delegation from DTS to use the CALNET II master service agreement (MSA)?
 - Do we have a specification for the Web Portal/Reports Outsourcing?

SRRA Internet Access Alternatives

- urnkey Solution
 - Performance metrics?
- T1/DSL
 - Current solution, not cost effective (\$ 2000 + \$ 600/site/month)
- 3G/Wi-Fi
 - Cost Effective for the current traffic load (# Users-Brt rate)
 - Fast deployment
 - Mesh technology , if needed
 - Multiple carriers (Availability Coverage CSSI)
- iMax / Wi-Fi
 - Use existing microwave towers
 - Scalable, capacity for future Internet traffic

SRRA-T Traffic Data



#	Location Name	Daily Session Count	MTD Session Count	MTD Minute Count
1	10500-Tipton CA	29	419	10939
2	10501-Turlock CA	5	163	4209
	Total Count	34	582	15148

SRRA- Cost Effective Internet Access

Current SRRA Traffic

- Number of users is about 50/day
 - Tripton has more Wi-Fi traffic than Turlock (5times)
 - 8 users/hr (Peak hours 12- 4 PM and 6 -8 PM)
- Using 3G cellular Router {pending validation & verification}

- 14 simultaneous user (pending test)
- No video downloading
- Most Cost effective
- Scalable (for the near term traffic)
- Shortest installation time
- Best unlimited rate
- State contracting issue (CSSI)
- Coverage (RFI)

Rough Order of Magnitude (ROM) costs

- 550 sq ft site (below the DGS delegation or a 11SR RA 's)
- monthly cost/Site (- \$100 :about 15 % of the cost of T1)

3G-2-WiFi

- Identified alternative products:
 - Multi earner solution (AT&T, Verizon, Sprint, T-Mobile)
 - Multiple Vendors
 - Different packaging, power, etc
- Testing soon



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First Responder Support Systems Testbed (FiRST)
Contract # 65A0257
Cross-Cutting Cooperative Systems

TRACK III – Interoperable Communications

Final Report

Multihop Networks: An Alternative Wireless Broadband Communications

Link Quality Metrics and Measurements in Public Safety & ITS Communications

Principal Investigator: Dr. Richard Church
University of California Santa Barbara

Contract Manager: Ramez Gerges, Ph.D., P.E.

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1 Abstract

Wireless networks are very different from wired networks. The nature of the medium strongly impacts the performance of network's protocols. Also, wireless networks offer greater control and flexibility as several network parameters such as topology, coverage and link rate can be controlled. New protocols have been developed which take advantage of distinctive wireless channel characteristics such as diversity and topology control. This report summarizes the developed metrics to capture and evaluate wireless link quality, proposed measurements techniques to acquire these metrics, and then some of the network systems to exploit link quality metrics.

2 Introduction

In recent times there has been a great proliferation of wireless devices, and growing popularity of 802.11 based wireless networks. These networks come in the form of enterprise networks, wireless hotspots, and more recently wireless mesh networks. The common underlying requirement of each of these networks is to provide good performance either improved throughput or satisfying QoS constraints. However the nature of the wireless medium, and 802.11 MAC protocol make it much harder to provide these guarantees when compared to a wired network. A wireless link experiences diversity, i.e., highly varying loss rate and bandwidth. Hence, maximizing throughput, guaranteeing fairness or QoS pose several challenges. This is further accentuated by artifacts of the 802.11 MAC such as the well known hidden node problem. Also, protocols developed for wired networks do not account for the characteristics of the wireless channel and this reduces their usability over wireless networks.

Wireless channels experience several distinctive characteristics. Being a broadcast medium, interference has a huge impact on protocols, both from within the network and from external sources. In addition, RF propagation characteristics cause great diversity in the channel. It has been shown that it is very hard to abstract wireless channels with a simple model. The rest of this report is defined as follow: Section 3 gives an overview of the wireless channel's characteristics and challenges; Section 4 summarizes the developed metrics for wireless link qualities in literature, Section 5 lists the proposed measurements schemes to capture and monitor link quality metrics, then the paper ends with Section 6 in which examples of network systems that exploit link quality metrics are provided.

3 802.11 Wireless Link Challenges

Compared to wired link, wireless communication suffers from high transmission errors and its performance changes frequently and dramatically, highly depending on the channel quality, which usually exhibits great variability. The sources of variation include user mobility, environmental changes and interference. The rapidly varying channel condition results in changing packet error rate (PER), therefore making network bandwidth a highly dynamic resource. Due to the dynamic variability, the wireless link quality needs to be measured and provided to wireless applications and protocols, in order for wireless networks to most effectively utilize and manage resources. Many performance improvement mechanisms depend on this information. For example, in order to perform load-balancing or power-control in WLANs, the link quality between access points and clients must be measured (1), (2).

Moreover, routing protocols seek effective routes, which consist of high-quality point-to-point links, in multi-hop deployments; therefore the goodness of the component links along a path needs to be periodically evaluated (3), (4). Similarly, link quality affects the performance of wireless sensor networks, including network lifetime, network throughput, resource usage and reliability (5), (6), (7), (8).

As indicated, among the main factors affecting link quality are RF Propagation characteristics. The mechanisms involved in RF propagation are diverse, but can be attributed to reflection, diffraction and scattering. The resultant signal experiences two kinds of effects, large scale path loss and small scale fading.

- **Large scale path loss:** The average received power for a signal drops off with distance, and this is referred to as large scale path loss. There are many models which predict received power/signal strength. Some examples are Free Space ($P_r \propto P_t / d^2$) and Two Ray Ground ($P_r \propto P_t / d^4$) where P_r is the received power, P_t is the transmitted power, and d is the distance between transmitter and receiver. Both theoretical and measurement based models indicate that the average signal strength decreases logarithmically with distance. Large scale path loss determines the coverage of a transmitter, thus its interference region. Actual coverage of the transmitter depends on the obstacles present, interference and other factors.
- **Small scale fading:** Signals transmitted from a radio arrive at the receiver at slightly different times due to different paths followed, this phenomenon is called multipath. These waves combine at the receiver antenna and cause the resulting signal to vary widely in amplitude and phase. This causes rapid fluctuation in signal quality over small periods of time or distance and is called small-scale fading. These effects are further amplified when the obstacles are moving objects. This causes fluctuations in channel bit error rate, causing fluctuations in packet loss (9), (10).

Both these factors affect the strength of the received signal at the receiver. The packet is received by the card if the received signal strength is greater than a threshold. Received signal strength, and noise floor can be used to indicate the goodness of the link and the average signal strength can be used to compute the transmitter receiver distance. Researchers have used signal strength stability to detect and ignore bad links in routing protocols (11), (12). Signal strength has also been used for indoor positioning of a wireless device in some coordinate space (13), (14), (15), which can then be used in geographic routing protocols (16), (17).

The network's dynamic nature, combined with adverse signal-propagation effects, raises issues that are difficult to address. In order to study the sensitivity of wireless link quality to adverse signal-propagation effects, authors in (18) ran extensive series of outdoor experiments to assess 802.11 link qualities, examining twelve factors that potentially influence it. All the conducted experiments used standard, off-the-shelf two hardware nodes that periodically sent messages to each other directly over the medium access control layer with a 2-Mbit-per-second transmission rate and maximum transmission power. For each received packet, authors recorded the link quality and used it to assess possible influencing factors. Signal strength of the received packets used as a measurement of link quality in these experiments. Signal strength responds quickly to changes in link quality, and current 802.11 cards use a large scale to describe it.

Experiments conducted by authors in (18) identified the following factors were highly influential:

- **User orientation:** In most wireless applications, users carry portable devices such as PDAs or notebooks. Because such nodes are rarely completely still and their antennas are often not strictly omni-directional, experiments assessed the influence on link quality of a node's orientation for all three axes in space. Results indicated that link quality is affected only slightly, and the resulting minor link quality fluctuations can be ignored. However, a node's orientation is typically changed when the users holding the node changes the orientation of his or her own body. Thus, this user's body shadows the link if the body blocks the line of sight between the two communicating nodes. Experiments consisted of placing two nodes at a fixed distance facing each other, while a person holding the node turned around. When the turning user faced away from the other node (around 180 degrees), the user's body reduced the signal strength to such an extent that packets were lost. In further experiments, we found that the user's shadowing reduced the transmission range from 250 meters in open space to approximately 150 meters. Because people often change their orientation, such frequent and significant link quality fluctuations are likely to occur.
- **Dynamic object shadowing:** In urban environments, dynamic objects such as people and cars are common. Obviously, these objects can shadow links and influence link quality. However, the significance of such shadowing varies. It is still possible, for example, to listen to a radio even if people are gathered around it, reducing the received signal. Experiments conducted to observe the affect of people and cars on link quality depends on their distance from the nearest node. Results showed that a single car between two nodes that are 100 meters apart is sufficient to cause packet loss if the car is 1 meter away from either node. Even at 5 meters, the car continues to exert considerable influence. Similar results were found for people, although their effect is weaker. Placing a single person in front of a node reduced signal strength severely (corresponding to shadowing by a user's own body), and the influence was still considerable at a distance of 1 meter. Because cars and people appear frequently in urban environments — especially in groups — severe link quality fluctuations are likely.
- **802.11 card models:** By definition, 802.11 wireless cards comply with the same specification; thus, if their transmission power is equal, we would expect the same behavior. However, cards from different makers can perform differently. In this experiment, authors recorded the received signal strength at different distances with either two 802.11 Brand A cards or two Brand B cards. The range, signal-strength decay, and packet-loss threshold differed in the experiments with the two types of cards. This is most likely caused by differences in radio frequency design and signal processing algorithms.
- **Node height:** In the conducted experiments, node height also significantly influenced link quality. If one node was below belt height, link quality degraded independently of the other node's height. Thus, the performance of nodes placed at ground level is particularly poor and designers should avoid such placements in sensor networks. In military and disaster-recovery applications, frequent node height changes can occur and thus cause strong link quality fluctuations. For most applications, however, node placement is less significant as people typically carry nodes at a sufficient height.

- **Additional Issues:** Authors assessed other candidate factors as well, but found them to have little or no influence on link quality. For example, the type of ground surface (such as sand or grass) had only a slight influence. Moreover, small-scale node movements (as when nodes are carried by a person, for example) had no affect on link quality. Large-scale movement at different speeds (evaluated up to 50 kilometers per hour) was also irrelevant for link quality (the Doppler shift is relevant only at much higher speeds). They also found no influence from communication patterns including message length, payload pattern (random content versus 0/1 alternating bits), and communication load (such as a low versus high number of transmitted messages per unit time). However, a high communication load can cause collisions and thus packet loss due to the hidden terminal problem because nodes incorrectly sense that the busy communication channel is idle. This is particularly noticeable in areas where many nodes are located close together.

4 Link Quality Metrics

As we seen, link quality should be considered in developed protocols and schemes for optimum network performance. Several parameters and properties of the network are used to measure and control link quality. We can categorize these parameters to:

- **Controllable Parameters:** These comprise of tunable parameters such as transmit power, carrier sense threshold, link rate, and operating channel. These parameters affect topology of the network, including loss rate, connectivity, interference etc, and play a key role in link quality and corresponding protocol performance.
- **Observable properties:** These comprise of properties such as signal strength, bit error rate, and transmission time. These properties allow us to infer the current channel conditions and link quality and to make more informed decisions regarding which parameters to control.

The wireless link quality needs to be measured and provided to wireless applications and protocols, in order for wireless networks to most effectively utilize and manage resources. In this section we summarize major link quality metrics proposed in literatures. Authors in (19) indicates that major studies for link quality typically employ one of the following four metrics in order to capture point-to-point link qualities. Each of these metrics provides an average estimation of the link quality over a period of time.

- **Received Signal Strength Indication (RSSI):** is a dimensionless quantity, which represents the signal strength observed at the receiver's antenna during packet reception. RSSI values vary from 0 to R_{max} ; the maximum value depends on the chipset of the wireless card. For example, wireless cards with the Atheros chipset report $R_{max} = 60$, Cisco cards have $R_{max} = 100$, while in Intel cards the RSSI provides the actual received power in the negative dBm scale (for example, $RSSI = -55$ for the Intel cards implies a received power equal to -55 dBm). Note that the specifications of each card provide a formula for translating the RSSI values to power (dBm).
- **Signal to Interference plus Noise Ratio (SINR):** represents the extent to which the power of the received signal exceeds the sum of noise plus interference at the receiver. Various models have been developed to map the SINR to the Bit Error Rate (BER) or the Packet Error Rate (PER) in presence of white noise or fading. Recent studies have

considered SINR to be the most appropriate metric for quantifying the quality of a link (20). However, having an accurate SINR is not simple.

- **Packet Delivery Ratio (PDR):** is the ratio of the correctly received packets at the receiver to the total number of packets sent by the sender. PDR is the most popularly used metric for assessing a link's quality. The product of PDR with the transmission rate derives estimation for the link throughput; this has been used in many studies, as a main determinant for routing or rate selection decisions.
- **Bit Error Rate (BER):** is the ratio of bits with errors to the total number of bits that have been received over a given time period. While the concept of BER is simple, measuring the BER is a non-trivial task; BER measurements consider a pseudorandom data sequence transmission.

Several recent studies propose new metrics as functions of the above listed metrics for link quality. Authors in (21) define a framework called Efficient and Accurate Link quality monitor (EAR) for accurately measuring link quality information. EAR metric focuses on link cost and capacity as link-quality parameters, which are defined as follows. First, the link cost is defined as the inverse of the delivery ratio d of MAC frames. This definition reflects the expected transmission count of each data frame. Specifically, the cost C of link $A \rightarrow B$ is calculated by

$$C = 1/d_i \quad \text{and} \quad d_i = (1 - a) \times d_{i-1} + a \times N_s/N_t \quad (1)$$

where d_i is the smoothed delivery ratio and function of PDR, a a smoothing constant, N_s the number of successful transmissions, and N_t the total number of transmissions and retransmissions during a measurement period of the i^{th} cycle. EAR also measures link capacity by using the data rate obtained from MAC frame transmissions.

Paper (3) presents the *expected transmission count* metric (ETX), which finds high-throughput paths on multi-hop wireless networks. ETX minimizes the expected total number of packet transmissions (including retransmissions) required to successfully deliver a packet to the ultimate destination. The ETX metric incorporates the effects of link loss ratios, asymmetry in the loss ratios between the two directions of each link, and interference among the successive links of a path. In contrast, the minimum hop-count metric chooses arbitrarily among the different paths of the same minimum length, regardless of the often large differences in throughput among those paths, and ignoring the possibility that a longer path might offer higher throughput. The ETX of a link is calculated using the forward and reverse delivery ratios of the link (i.e., PDR metric). The forward delivery ratio, d_f , is the measured probability that a data packet successfully arrives at the recipient; the reverse delivery ratio, d_r , is the probability that the ACK packet is successfully received. The expected probability that a transmission is successfully received and acknowledged is $d_f \times d_r$. A sender will retransmit a packet that is not successfully acknowledged. Because each attempt to transmit a packet can be considered a Bernoulli trial, the expected number of transmissions is:

$$\text{ETX} = 1 / (d_f \times d_r) \quad (2)$$

ETX has several important characteristics: a) ETX is based on delivery ratios, which directly affect throughput, b) ETX detects and appropriately handles asymmetry by incorporating loss ratios in each direction, c) ETX can use precise link loss ratio measurements to make fine-grained decisions between routes, d) ETX penalizes routes with more hops, which have lower throughput due to interference between different hops of the same path, e) ETX tends to

minimize spectrum use, which should maximize overall system capacity. In addition, ETX may decrease the energy consumed per packet, as each transmission or retransmission may increase a node's energy consumption.

An extension to ETX metric is proposed in (22) that assigns weights to individual links based on the Expected Transmission Time (ETT) of a packet over the link. The ETT is a function of the loss rate and the bandwidth of the link. Authors defined the ETT of a link as a "bandwidth-adjusted ETX." In other words, link quality starts with the ETX (number of expected transmissions) and then gets multiplied by the link bandwidth to obtain the time spent in transmitting the packet. We can formalize this as follows. Let S denote the size of the packet (for example, 1024 bytes) and B the bandwidth (raw data rate) of the link. Then:

$$ETI = ETX * S/B \quad (3)$$

Note that this definition of ETT does not incorporate backoff time spent waiting for the radio channel; it only reflects the time spent actually using the channel.

Authors in (23) develop a modified version of ETX, called mETX, to model long-term link quality and short-term link dynamics. mETX corrects ETX shortcoming that it doesn't cope well with short-term channel variations because it uses the mean loss ratios in making routing decisions. In addition a new routing metric called effective number of transmissions (ENT) is defined. Both the mETX and the ENT capture the time-varying characteristics of a wireless channel in a form that could be directly translated into network and application layer quality constraints. These metrics project both the mean and the variance of certain parameters of the physical layer onto the space of networking parameters using tools from large deviations theory and effective bandwidths.

Another link quality metric assessment method for mesh networks is defined in (24) and named *QUEST* (QUality ESTimation). QUEST is based on a delivery ratio vs. SNR (Signal to Noise Ratio) mapping table called *profile* that can be managed offline. QUEST estimates the quality of a target link as the delivery ratio by performing profile lookup for any incoming messages including broadcast

hello, beacon, data packets, etc. Therefore, no designated protocol to achieve the delivery ratio information, with the form of (delivery ratio, target neighbor, transmission rate)-tuple, is

```

Algorithm 1: QUEST
1: for  $RX$   $NR_i$   $\in$   $N$ 
2:    $dri_i \leftarrow Delivery$ 
3:   if  $fr_i$   $mod$   $re_i$ 
4:      $dpr_i \leftarrow I$ 
5:   end if

```

required in QUEST. The QUEST algorithm is defined in Figure 1.

The *link inefficiency* (I) is proposed as **link** cost metric in (25). Authors model a link i to have a certain Packet Success Probability (PSP _{i}) at time t , such that every transmission is successful with probability PSP _{i} (t) independently of the others, then the mean number of transmissions is $1/PSP_i(t)$. Since the energy used for each re-transmission is assumed to be similar, the energy to transmit the packet successfully is proportional to $I = 1/PSP_i(t)$. While the perfectly efficient link

is $I=1$, this metric grows as a link gets worse, *i.e.*, the inefficiency increases corresponding to a larger amount of energy spent on that link due to retransmissions.

Extending the work in (25), authors in (26) focus on two classes of estimators, Packet Counting (PC) and SNR-based. PC estimators measure the packet success probability (PSP) directly by calculating the ratio of the number of successful packet transmissions to the total number of transmissions. The advantages of PC-based estimators are that they are simple, intuitive, and require little or no a priori information. Their disadvantages are the accuracy, timeliness, and overhead of the measurements. The precision of PC-based estimates depends on the number of transmissions of the packets of interest. On the other hand, a large number of transmissions incur latency in the estimate, which can make it obsolete in time-varying conditions. Furthermore, since packet success rate, in general, depends on the size of the packet and the data rate (*i.e.*, the modulation-coding scheme) at which packets are transmitted, PC-based estimates are specific to the bit rates and packet sizes of the counted packets.

SNR-based link quality estimators in (26) make use of SNR measurements obtained from the physical layer of the communications stack. They rely on the assumption that there is a strong correlation between the measured SNR and the current PSP of a link. The advantages of SNR-based estimators are that they potentially require fewer measurements, are more timely, and are more accurate than PC-based estimators in time-varying conditions. Their primary disadvantage is that they require prior information on the mapping between the SNR and PSP, which is environment and radio dependent. Authors in (26) surveyed the accuracy of SNR-based metric in previous literatures. A thorough study of an outdoor in (10) for static IEEE 802.11b network concluded that the SNR reported by the physical layer is not predictive of link reliability. However, the study also demonstrated that the multipath delays experienced outdoors far exceeded the delays tolerated by the radios that were used, generating significant inter-symbol interference. A subsequent indoor study in (27) of a static 802.11 network operating at the 2 Mbps data rate showed a strong correlation between measured SNR and PSP, and one that follows the theoretical relationship quite closely, provided external interference is limited. In (28), the authors showed an SNR-based estimator to converge more rapidly than a PC-based estimator on a link experiencing a sudden change in transmission power. This estimator maps Kalman-filtered SNR measurements to PSP using an empirical model. In other related work, (29) describes a hybrid approach using both SNR and packet counting to classify links as “good” or “bad”. However, authors of (26) mitigate the bias of using SNR measurements from only successfully received transmissions. The results suggest that SNR-based schemes have the potential to provide better and more efficient estimates of link reliability than PC-based schemes, especially as the time variability (or Doppler spread) of the channel increases.

Papers (30), (31) present ongoing work on short-term link estimation (STLE) that takes fine-grained link dynamics - in the order of milliseconds - into account and increases the prediction quality for successful packet transmissions, especially, for highly dynamic links. STLE integrates into routing protocols by adapting neighbor tables to accurately reflect the current situation of a dynamic link. Overall, short-term link estimation has three key contributions: (1) to predict the probability of successful packet transmission of any link type by taking short-term dynamics into account, (2) to suggest links of low to intermediate quality for routing when they have become temporarily reliable, and (3) to integrate easily with today’s long-term link estimators and routing protocols.

5 Measurements Techniques for Link Quality Metrics

There is an increasing amount of research effort on measuring wireless link quality. Accurate link-quality measurement is essential to solve the problem associated with varying link-quality, as one can see from the following use-cases.

- **Selection of the best relay node:** Accurate link-quality information can reduce the recovery cost of lost frames caused by link quality fluctuations.
- **Supporting Quality-of-Service (QoS):** Wireless link-quality information enables applications and network protocols to effectively meet users' QoS requirements. For example, applications, such as VoIP and IPTV, can dynamically adjust their service level that can be sustained by varying link-quality in the network. On the other hand, link-quality-aware routing protocols can accurately locate a path that satisfies the QoS (e.g., throughput and delay) requirements based on the link-quality information.
- **Network failure diagnosis:** Link-quality statistics can be used to diagnose and isolate faulty nodes/links (or faulty areas), facilitating network management. This is very useful in case of wireless sensor networks in monitoring and covering scenarios since it is required to have a clear picture of local link conditions for network troubleshooting.
- **Identifying high-quality channels:** Link-quality information helps network to identify high-quality channels. Due to the use of shared wireless media, link-quality differs from one channel to another, and hence, determining the best-quality channel is of great importance to channel assignment algorithms.

It is important to remember that measurement techniques have their failings and the accuracy of the result depends on the methodology used. Measurement techniques have to address several challenges. Among those challenges:

- **Accuracy and efficiency.** A measurement technique must yield accurate results at as low a cost as possible.
- **Link-asymmetry-awareness.** Measurement schemes must be able to identify and exploit wireless link asymmetry that results from interference, obstacles, or weather conditions. For example, if there is interference in the vicinity of node *A*, then signals from a remote node *B* to *A* might be disrupted, whereas signals from node *A* are normally strong enough to overcome the interference. While *B* might reach *A* via node *C* that has high-quality links to both *A* and *B*, node *A* can use the direct link to *B*, thus saving network resources.
- **Flexibility and feasibility.** Measurement techniques must be flexible enough to cope with time-varying link-quality.

Measurement techniques could be classified to three main categorizes: Active measurements, Passive measurements, and hybrid measurements that combine between active and passive measurements. In the following subsection we summarize the research efforts within these categories.

5.1 Active Measurements for Link Quality

In this category, nodes usually probe link quality by injecting certain probe packets on the corresponding link and observe the objective metrics. Two popular assessment methods to obtain link quality: *broadcast probings* and *unicast probings*. Broadcast probings (4), (3), (22) are further categorized to *broadcastFR* (broadcast with Fixed Rate) and *broadcastMR* (broadcast

with Multiple Rates). *broadcastFR* measures the delivery ratio using a fixed, lowest transmission rate. Therefore, it does not need to send a probe packet, which is typically a *hello* message, to all one-hop neighbors with different transmission rates. However, considering the multiple transmission rates feature in the current 802.11 devices for data communications, relying on only the lowest transmission rate for the link quality measurement is undesirable. *broadcastMR*, an improved form of *broadcastFR*, performs periodic hello message broadcast at different transmission rates. Although it incurs a small overhead (e.g., 1 packet per second), broadcasting does not always generate the same quality measurements as actual data transmissions due to different PHY settings (e.g., modulation). Thus, *broadcast probing* provides inaccurate link-quality measurements. Moreover, its use of an identical type of probing in *both* directions of a link generates *bi-directional* results, thus un-/under-exploiting link asymmetry.

On the other hand, unicast method (22)[19] scores high on accuracy as it utilizes all the available transmission rates for the delivery ratio measurement and uses the same data rate for probing a link as that for actual data transmissions over the link. However, frequent probing of link to each neighbor incurs a significant overhead. As the number of neighbors increases, probe packets might throttle the entire channel capacity and degrade the performance of the network due to its per-neighbor/-rate probing.

Expected transmission count (ETX) (3) and Expected transmission time (ETT) (22) use broadcast packets to probe the links. For the ETX metric, a node A for example, sends out a broadcast packet every time period. All of A's neighbors keep track of the packets received in the last T periods, and compute the delivery ratio of the link from A to themselves as ratio (N_r/T), where N_r is the number of packets received in T. Broadcast packets sent are of some standard packet size, and are sent out at the lowest rate and hence do not account for differences in packet sizes and link rates on each of the unicast links. In addition, broadcast packets are not acknowledged; hence link directionality information is not recorded.

On the other hand, to accurately measure link bandwidth in ETT (22) they propose a packet pair technique. In the packet pair technique, node A for example, sends a pair of packets back to back to a neighbor B, first one small (137 bytes) and second one bigger (1137 bytes). The first packet serves as a marker to measure the beginning of the second packet. The time difference between the receipts of the two packets is used as the transmission time of the second packet, and is used to measure the link bandwidth. Minimum value of last 10 consecutive cycles is used as an estimate. When the link is using auto-rate mechanism, this measurement granularity becomes very coarse. A finer granularity measurement is also not possible since the technique involves actively sending packets and incurs a lot of network overhead.

SNR-based estimation, proposed in (26), mitigates the bias of using SNR measurements from only successfully received transmissions. It does so by employing measurement of broadcast probes transmitted at a lower (and, hence, more reliable) data rate than that of the data packets of interest. The scheme optimizes the parameters of each estimator, and compares their performance over a range of channel variability speeds.

5.2 Passive Measurements for Link Quality

Passive monitoring is the most efficient and accurate since it uses actual data traffic. However, it may incur overhead in case of probing idle links. For example, QUEST (24) uses passive monitor scheme to estimate the delivery ratio by performing profile lookup for any received management, control or data packet. Ideally, it should have *zero* time duration overhead. However, in a wireless mesh network, a node needs to disseminate the link quality estimate for all links with other nodes in its transmission range, in order to assist the routing protocols in route establishment decisions. Accordingly, QUEST has the same overhead as broadcast probing, but it provides the link quality estimate for all transmission rates as compared with the broadcast probing, which provides the link estimate for only the lowest rate.

Another passive monitor scheme is proposed in (32) to monitor and measure the Packet Error Rate (PER) over a link. This scheme depends on that whenever a node transmits a data frame to neighbor n , the MAC-layer reports whether the transmission was successful or not. Using an indicator variable F where $F=1$ when a frame exchange failed, and $F=0$ otherwise. Then, the proposed scheme infers the PER of wireless link to neighbor n as follows:

$$PER_n \leftarrow (1-a) \times PER_n + a \times F \quad (4)$$

where a denotes the weight parameter. Authors suggested to use $a=0.1$ while the default PER value is set to 0. To track the link quality change even when no packets are forwarded to n , authors suggest using an aging scheme and periodically reducing PERs of unused links. When this reduction makes the estimated PER become lower than the actual one, packets may be forwarded to n , but the estimated PER will increase after transmission failures. The magnitude and frequency of reduction should balance such overhead and prompt adjustment. Paper suggests to multiply PERs of unused links by 0.9 every 30 seconds.

The short-term link estimator (STLE) (30), (31) does not send probe packets to test for link availability, it bases on packet overhearing. Hence, a node overhears packets sent by neighboring nodes and collects statistics on the current reachability. When a node considers the incoming direction of an unreliable link temporarily stable and concludes that it offers a routing improvement, it sends a message to the link neighbor to inform it about short-term link availability. The neighboring node may then consider routing subsequent packets over the newly available link. If the node is selected as next hop, link-layer acknowledgments continuously provide information about link availability.

The pattern of link quality and behavior of several link quality estimators for sensor networks are studied in (6), (33). These works explore the temporal correlation in the link quality to each individual neighbor sensor node based on a sequence of packets that a sensor node hears/overhears from the monitored sensor node over time. In this study, link quality is defined as: packets received in t / max (packets expected to be received in t , packets received in t), where t is a time window. Thus, for an estimator to measure the link quality, a minimum rate for message exchange between neighbor sensor nodes is required. Authors suggested a message exchange every 30 seconds.

Authors in (34) propose a novel approach, based on a *weighted regression algorithm*, to allow each sensor node to capture the spatial correlation in the quality of its links. The intuition

behind spatial correlation is that sensor nodes geographically close to each other may have correlated link quality. Authors show that the spatial correlation in link quality of neighbor sensor nodes can be captured to estimate the link quality with substantially less transmission cost than the link quality estimators based on temporal correlation. The history information of link quality for one node may be used for estimating not only its own link quality but also that of other neighbor sensor nodes geographically close. By categorizing the links into classes in accordance with their quality ranges and then employing a separate regression model for each class, the link quality at a given geographical point can be very accurately estimated.

A recent study (35) defines the design of an online learning link adaptation system through the formation of databases that hold channel information and the associated performance for each physical layer parameter set. Although machine learning has been applied to link adaptation (36), an online learning framework is not yet available. Online learning, which is accomplished here through real-time database updating, allows link adaptation to adjust to changing mitigating factors. Using a machine learning classification procedure based on k-nearest neighbor we harness database information to predict the best parameter set for a given wireless channel realization without explicit knowledge of the wireless channel input/output model.

5.3 Hybrid Measurements for Link Quality

In this category, measurement schemes combine between active and passive measurements. As an example, Efficient and Accurate Link quality monitor (EAR) frame work proposed in (21) gathers link information using three methods - (a) Passive, (b) Cooperative, and (c)Active. The Passive method is employed when the node is currently sending data on the link, and EAR records statistics based on outgoing packets. If a link, say A-B, is not currently active, but A-C link is active and B can overhear C, A informs B that it is going into a cooperative mode. In this mode B records number of packets received on the A-C link and are on the same rate as previously reported on A-B. This is reported to A and taken as the N_s parameter. A can then derive link cost since it knows the total number of transmissions and retransmissions on the A-C link (N_t). In the Active mode, node A sends unicast probe packets every probe period to node B on its last recorded rate. To reduce network overhead, this probing period is exponentially increased if the link is either stable or idle. By exploiting data traffic in the network as probe packets, and dynamically and adaptively selecting the most effective of the three schemes, EAR not only reduces the probing overhead, but also decreases the measurement variations, thanks to the large number of “natural” probe (i.e., real traffic) packets.

6 Examples of Network Systems Exploiting Link Quality Metrics

As discussed in Section 3, there are several network applications that benefit and exploit monitoring and measuring link quality. In this section, we describe two set of applications: 1) Opportunistic Routing, and 2) Link Adaptation.

6.1 Opportunistic Routing for Multihop Networks

Opportunistic routing is routing protocol that consists of high-quality point-to-point links in multi-hop deployments. Therefore, the goodness of the wireless links along a path needs to be periodically evaluated for seek effective routes.

There are two main classes of opportunistic transmission policies for wireless ad hoc networks. The first is to exploit time diversity of individual links by adapting the transmit rate to the time-varying channel condition (37), (38). In (38), authors proposed the Opportunistic Auto Rate (OAR) scheme, in which a flow transmits with higher data rate and more back-to-back packets when its channel condition is better. Exploiting multi-user diversity is another class of opportunistic transmission, which jointly leverages the time and spatial heterogeneity of channels to adjust rates. In wireless networks, a node may have packets destined to several neighboring nodes. Selecting instantaneously an “on-peak” receiver with the best channel improves the channel utilization efficiency(39), (40), (41), (42). For example, Opportunistic packet Scheduling and Auto Rate (OSAR) scheme (40) and Medium Access Diversity (MAD) scheme (41) are proposed to exploit multiuser diversity, in which a sender multicasts a channel probing message (e.g. Group RTS in MAD) before the data transmissions. Each receiver replies the current channel condition and then the sender schedules the rate adapted transmission to the receiver with the best channel quality.

Another multi-user diversity opportunistic routing scheme that exploits ETX metric is proposed in (22). In such scheme, each node maintains an exponentially weighted moving average of ETX samples. The default path is the shortest path between the source and destination in terms of ETX. Node i selects the forwarding nodes that satisfy the following conditions: 1) The forwarding node’s ETX to the destination is lower than i ’s ETX to the destination, 2) The forwarding node’s ETX to i is within a threshold. The first constraint ensures that the packet makes progress. The second constraint ensures that i hears the forwarding node’s transmissions with a high probability to avoid duplicate retransmissions.

ExOR (43), (44) is a seminal multi-user diversity opportunistic routing protocol. In ExOR, senders broadcast a batch of packets (10-100 packets per batch). Each packet contains a list of nodes that can potentially forward it. In order to maximize the progress of each transmission, the forwarding nodes relay data packets in the order of their proximity measured by the ETX metric to the destination. To minimize redundant transmissions, ExOR uses a batch map, which records the list of packets each node has received; every forwarding node only forwards data that has not been acknowledged by the nodes closer to the destination. ExOR imposes strict timing constraints among the forwarders to facilitate coordination in the relay process. Only one forwarder can be active at a time, and spatial reuse of the wireless spectrum is reduced. Furthermore, ExOR’s forwarding paths can easily diverge, *i.e.*, nodes on the different forwarding paths may not hear from each other and cause duplicate forwarding. These difficulties make it unclear how well ExOR supports multiple simultaneous flows.

MORE (45) applies network coding to opportunistic routing in a clever way. Since random coding can effectively generate linearly independent coded packets with a high probability, the forwarding nodes in MORE do not need to coordinate which packets are forwarded by which nodes. However, MORE selects forwarding nodes in a similar way as ExOR and does not prevent diverging paths, which can lead to waste of resource usage. Furthermore, it does not rate-limit the initial transmission of packet batches, and may cause degradation in aggregate network performance and fairness.

ROMER (46), another opportunistic routing protocol, tries to forward the packets simultaneously along multiple paths. It incorporates a credit based scheme to limit the number of transmissions that a packet is allowed before reaching the destination. Even with the credit based scheme, there is still significant overhead since a packet is allowed to be forwarded by multiple nodes at each hop. Also, setting the credit is non-trivial and static credit has difficulties in coping with different topologies. As a result, ROMER only supports a single flow.

In addition to opportunistic routing protocols for mesh networks, researchers have also designed opportunistic routing protocols for ad-hoc and sensor networks. For example, (47) and (48) both dynamically select forwarding nodes based on recent link quality. However, in both protocols, only one forwarding node is selected before transmissions, and they cannot take advantage of transmissions reaching nodes other than the previously selected forwarder. (49) balances the energy consumption rates of different nodes in a sensor network by opportunistically incorporating forwarders' energy consumption.

6.2 Link Adaptation for Wireless Links

Rate adaptation is a critical component to ensure optimal system performance in these dynamic mobile environments. The IEEE 802.11 protocol specifications allow multiple transmission rates at the physical layer (PHY), which use different modulation and coding schemes. For example, the 802.11p PHY offers eight different bitrates, ranging from 3 to 27 Mbps, from which transmitters can choose. Higher data rates allow high quality links to transmit more data, but have a higher loss probability on low quality links. On the other hand, a low data rate is more resilient to low quality links, but fails to achieve a high throughput in a high quality link. *Rate Adaptation* is the problem of selecting the best transmission rate based on the real-time link quality, so as to obtain maximum throughput at all times.

Several rate adaptation schemes have been proposed in the literature. Receiver Based AutoRate (RBAR) (50) is a signal-to-noise ratio (SNR) based scheme that uses feedback from the receiver to select the sender's optimal rate. In this scheme, the sender sends an RTS frame before every packet, and receiver measures the SNR of the link and compares it with SNR thresholds from an a priori calculated wireless channel model, calculates the optimal rate, and sends it back to the sender as part of the CTS frame. SNR-Guided Rate Adaptation (SGRA) (51) performs a measurement study of SNR as a prediction tool for channel quality.

SampleRate (52) is a throughput-based scheme that aims to minimize the mean packet transmission time. It chooses the bit-rate that it predicts will provide the most throughput based on estimates of the expected per-packet transmission time for each bit-rate. SampleRate uses the idea of active probing, in which it periodically sends packets at bit-rates other than the current one to estimate when another bit-rate will provide better performance.

On the other hand, Robust Rate Adaptation Algorithm (RRAA) (53) uses passive measurements to calculate packet loss by using an estimation window and measures it against empirical low and high packet loss thresholds for different bitrates, in order to choose the correct bitrate. RRAA's approach is to minimize the delay due to the estimation window by using a short-term loss ratio and making the estimation window's size adaptive.

Recently, a Context-Aware Rate Selection (CARS) (54) algorithm that makes use of context information (e.g. vehicle speed and distance from neighbor) is proposed for link adaptation in high speed environments such as vehicular networks. The core idea of CARS is to make use of context information from the application layer, in addition to the frame transmission statistics received from the lower layers. Figure 2 shows the overall system architecture of the CARS scheme. The context information used in CARS broadly consists of information about the environment that is available to the node and which has an effect on the packet delivery probability. Such information could include the position, speed and acceleration of the vehicle, the distance from the neighboring vehicle, and environment factors such as location, time of day, weather, and type of road and traffic density. Authors in (54) chose the two most significant of these parameters; distance from the receiver and the vehicle's speed for the current implementation of CARS. Vehicles in CARS are assumed to use periodic broadcast probes to gain information about their position and speed as well as the position and speed of their neighbors.

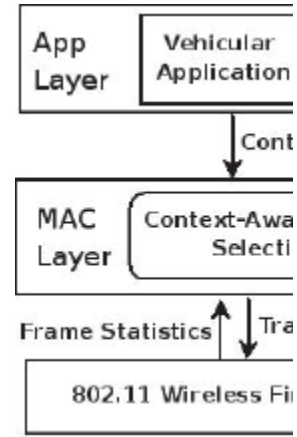


Figure 2: CARS System Architecture

The key idea of the CARS algorithm is to estimate the link quality packet error rate (PER) metric using both context information as well as past history. The CARS rate selection algorithm estimates the packet error by means of a weighted decision function involving two functions, EC and EH . The function EC , through learned empirical model, estimates the packet error rate using the context information (ctx), transmission rate and packet length as input parameters. The function EH uses an exponentially weighted moving average (EWMA) of past frame transmission statistics for each bitrate, similar to schemes such as SampleRate. Hence the PER is computed as follow:

$$PER = a \times EC(ctx, rate, len) + (1-a) \times EH(rate, len) \quad (5)$$

where a determines whether to give preference to the context information or to the EWMA. a is assigned based on the vehicle speed. When speed is zero, there is no opportunity for doing any prediction of link quality using context information, so EWMA is given preference. On the other hand, when vehicle speed is high, context information is given preference.

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28. *A Kalman filter based link quality estimation scheme for wireless sensor networks*. **M. Senel, K. Chintalapudi, D. Lal, A. Keshavarzian, and E. J. Coyle**. 2007. IEEE GLOBECOM.
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37. *A rate-adaptive MAC protocol for multi-hop wireless networks*. **G. Holland, N. Vaidya, and P. Bahl**. 2001. ACM MobiCom.
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51. *A practical snr-guided rate adaptation*. **J. Zhang, K. Tan, J. Zhao, H. Wu, and Y. Zhang.** 2008. IEEE Infocom.
52. **Bicket, J. C.** *Bit-rate selection in wireless networks*. MIT. 2005. Masters Thesis.
53. *Robust rate adaptation for 802.11 wireless networks*. **S. H. Wong, H. Yang, S. Lu, and V. Bhargavan.** 2006. ACM MobiCom.
54. *CARS: Context-Aware Rate Selection for Vehicular Networks*. **Pravin Shankar, Tamer Nadeem, Justinian Rosca, and Liviu Iftode.** 2008. IEEE ICNP.



Broadband WirelessChannel Emulation

A Protocol Testing & Validation Tool for DSRC & Public Safety Wireless Environment

This document explains how to setup and run the Electrobit (Annite) PropSim F8 Channel Emulator

http://www.elektrobit.com/download/1944/datasheet_eb_propsim_f8/pdf

EB PropSim® F8

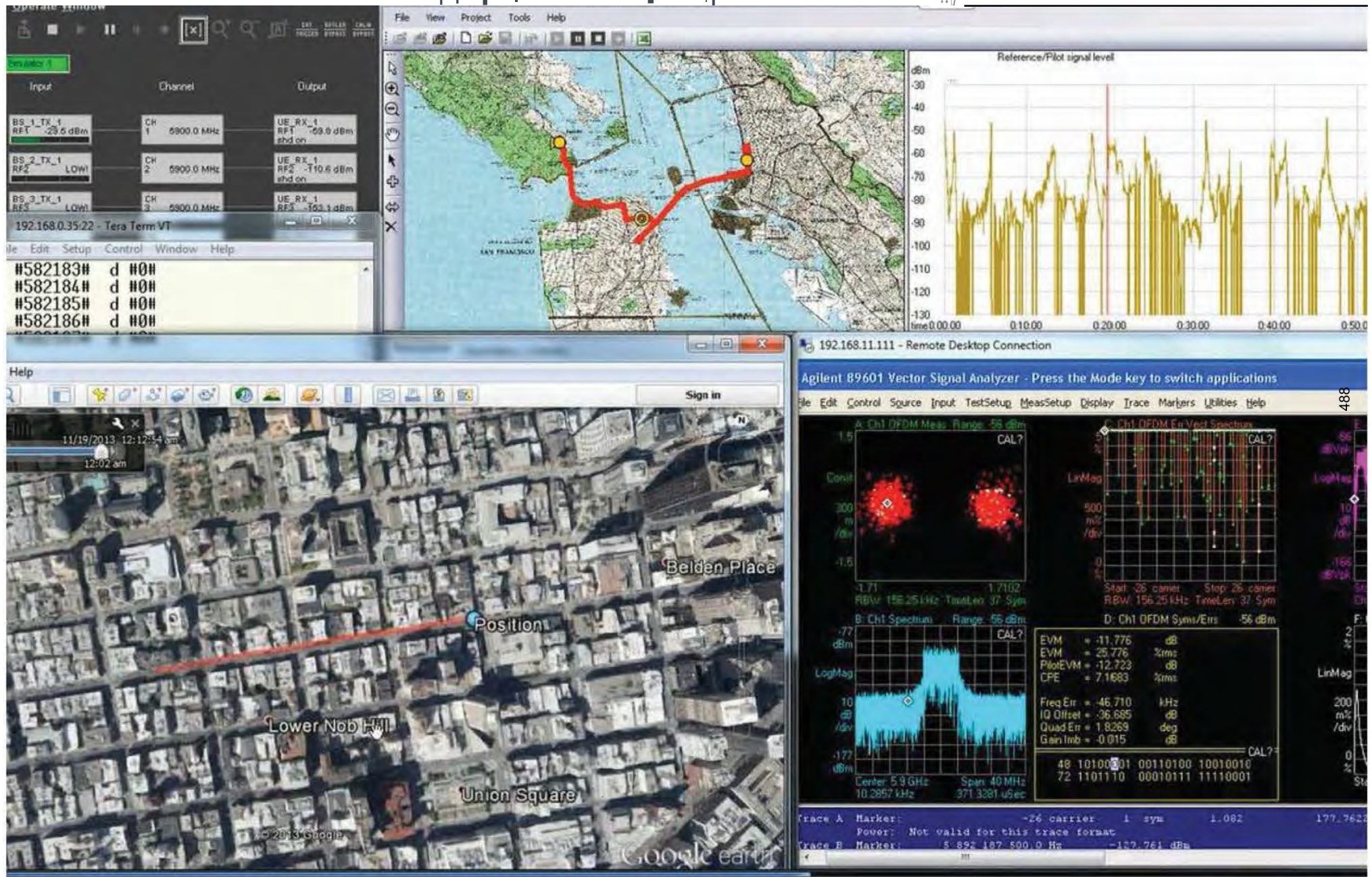
EB PropSim® F8 is a versatile radio channel emulator designed to test terrestrial, satellite and tactical communication systems and devices. It enables testing of any existing radio interface, including LTE, LTE-Advanced, WCDMA, HSPA+, GSM, TD-SCDMA, EV-DO / CDMA2000, TETRA, IS-54, WiMAX and Wi-Fi, and known future wireless system air interfaces. EB PropSim F8 offers flexibility and reliability for system and network level testing, especially in systems requiring excellent RF signal fidelity for higher order modulations and wider bandwidths up to 125 MHz with MIMO. EB PropSim F8 is equipped with up to 8 RF interface channels and up to 64 fading channels.

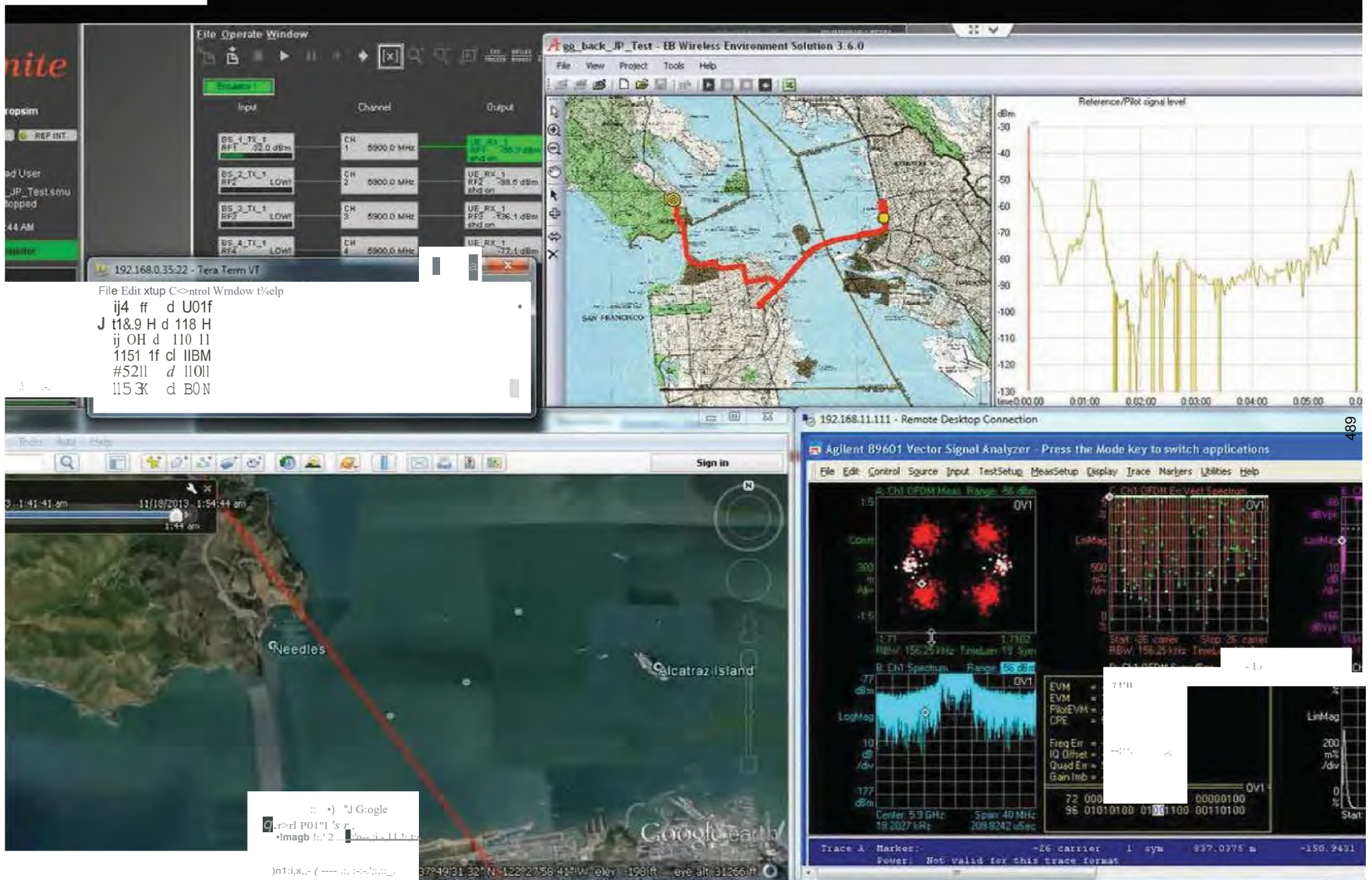
Product Features of the EB PropSim F8:

- Testing of terrestrial, satellite and tactical communication systems and devices
- Optimize air interface performance of IEEE 802.11ac products
- Evaluate LTE-A product performance up to 100 MHz bandwidth

A photograph of the EB PropSim F8 hardware unit. It is a black, rectangular device with a green digital display at the top showing the number '81'. Below the display are several rows of ports and connectors, including what appear to be BNC connectors and other RF interfaces.

013 8.02.45 AM





System Setup



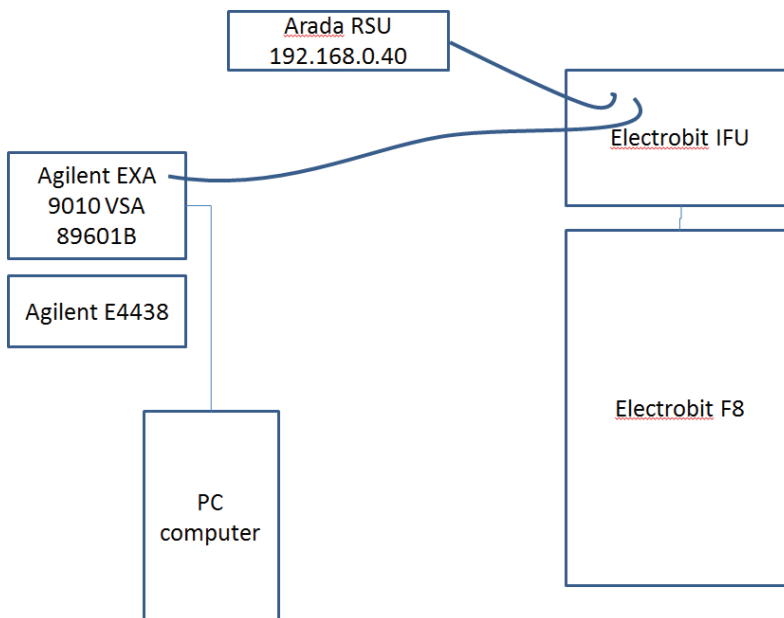
The Elektrobit Propsim F8 has multiple N-connector rf inputs, GPIB, DVI, USB and Ethernet. The power switch is in the upper left corner.

Ensure the 120V power cable is connected to the unit, connect a monitor, keyboard and mouse to the EB F8 Propsim unit ("the F8")

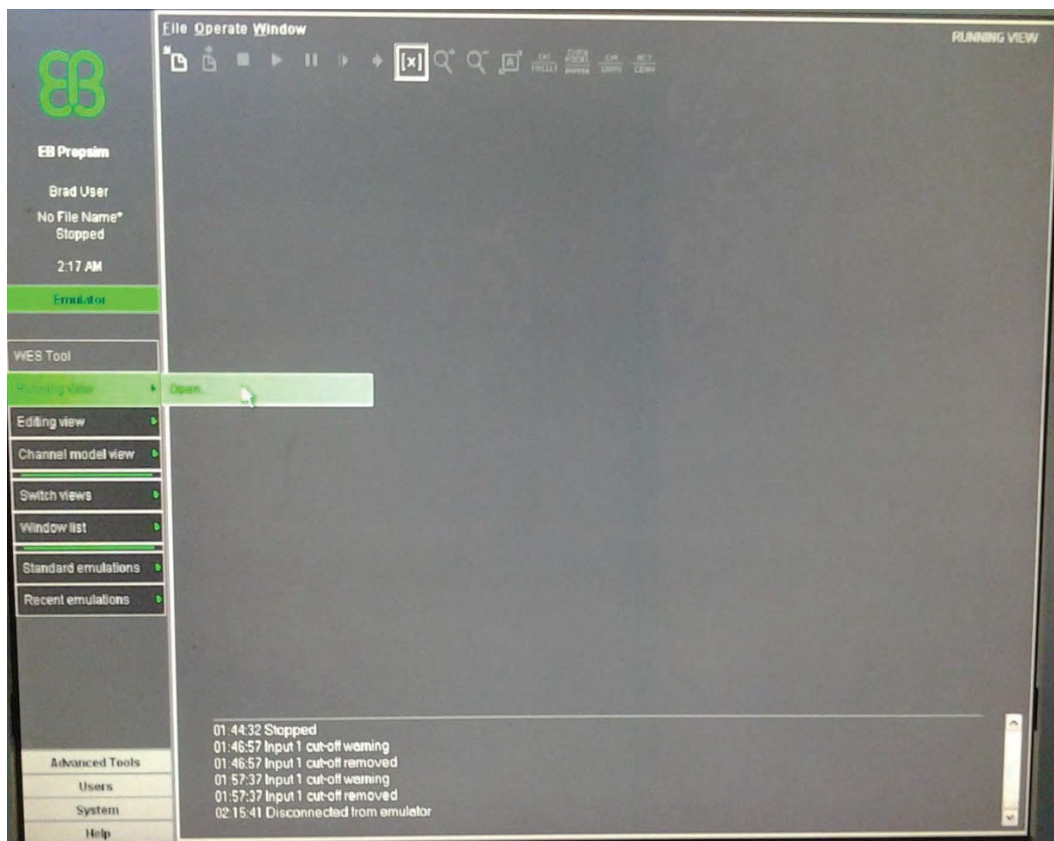
Power on the F8 and wait until the main screen appears, this takes up to 5 minutes.
Connect the Arada RSU unit to its power over Ethernet PoE and connect the network to the PoE.
Connect the antenna output directly into the P1 port on the EB IFU box. Connect P3 into the Agilent EXA. (Warning: use an attenuator at the input of the IFU as needed to prevent possible overload)



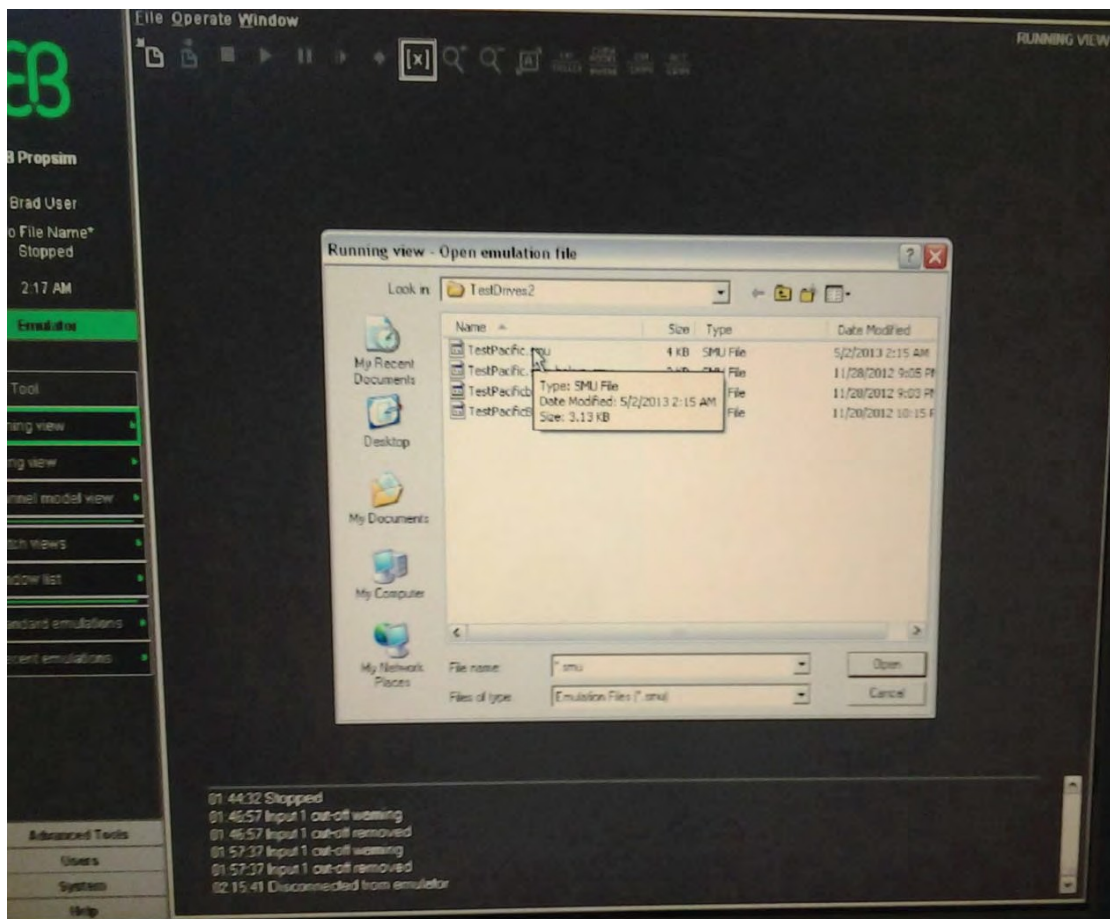
Note:
Connections are on Port 1 and Port 3 of the IFU



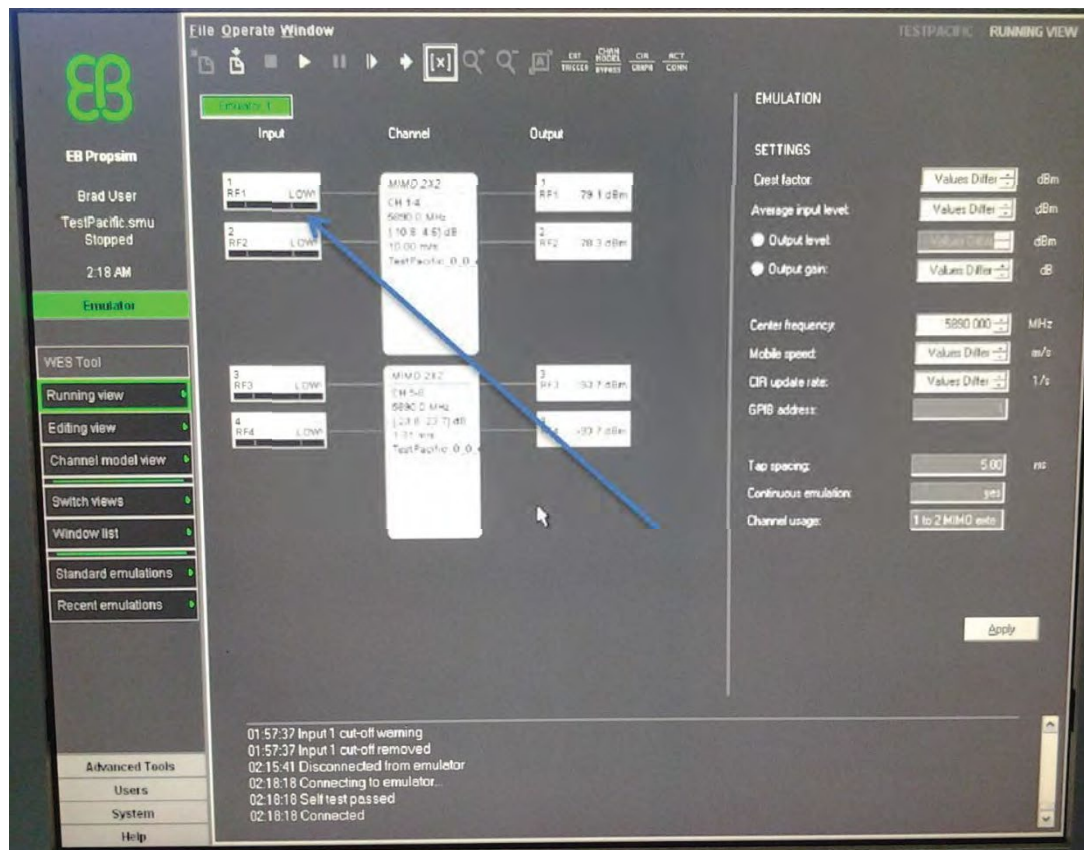
The PC computer runs a remote session of the 89601B



Above: at the startup screen click on Running View then Open



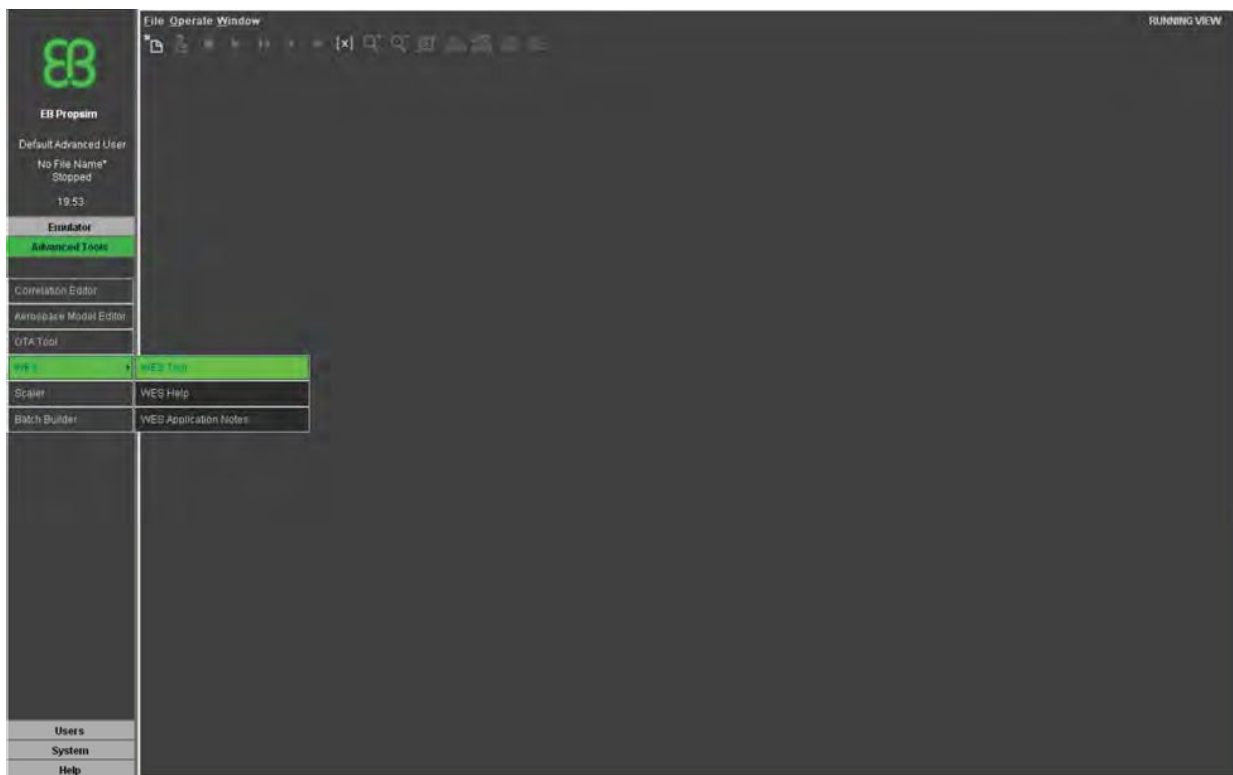
Above: clicking on open brings up a file open dialog. Note this file used 5/2/2013 where the others have a time stamp in 2012. Click on TestPacfic.smu and open it.



Above: opening the TestPacific.smu file shows this in "Running View". Note there is no signal

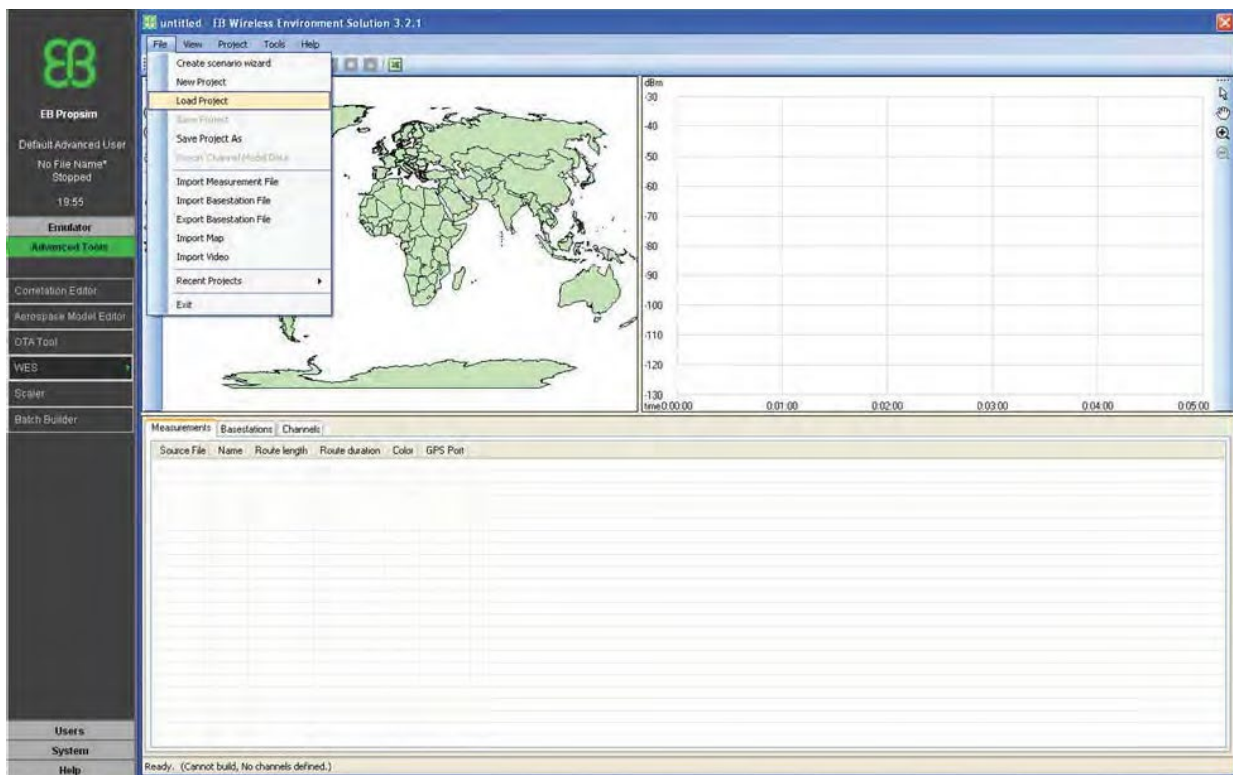
Open an existing project file to playback the San Diego Simulation

Step 1 Open existing file in WES



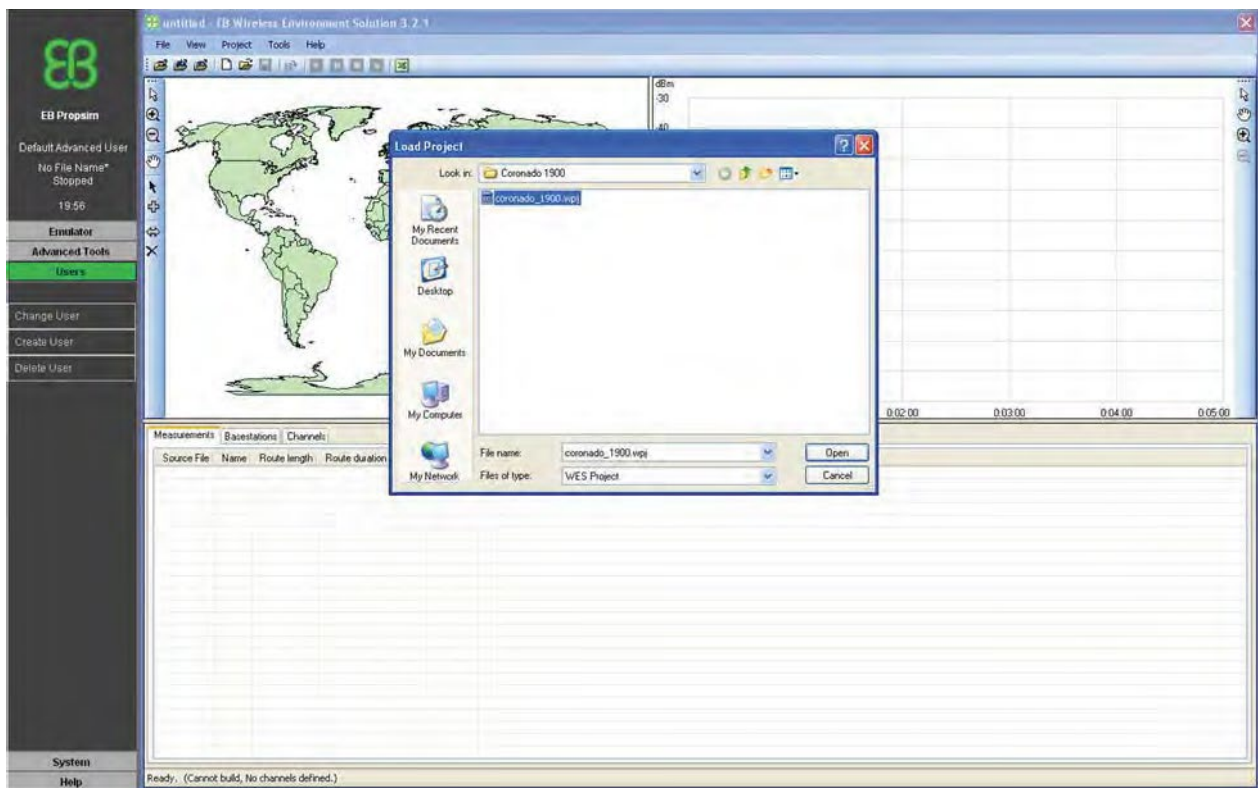
Above: this is the menu to open to begin a simulation, the WES Tool

Step 2 Load Project



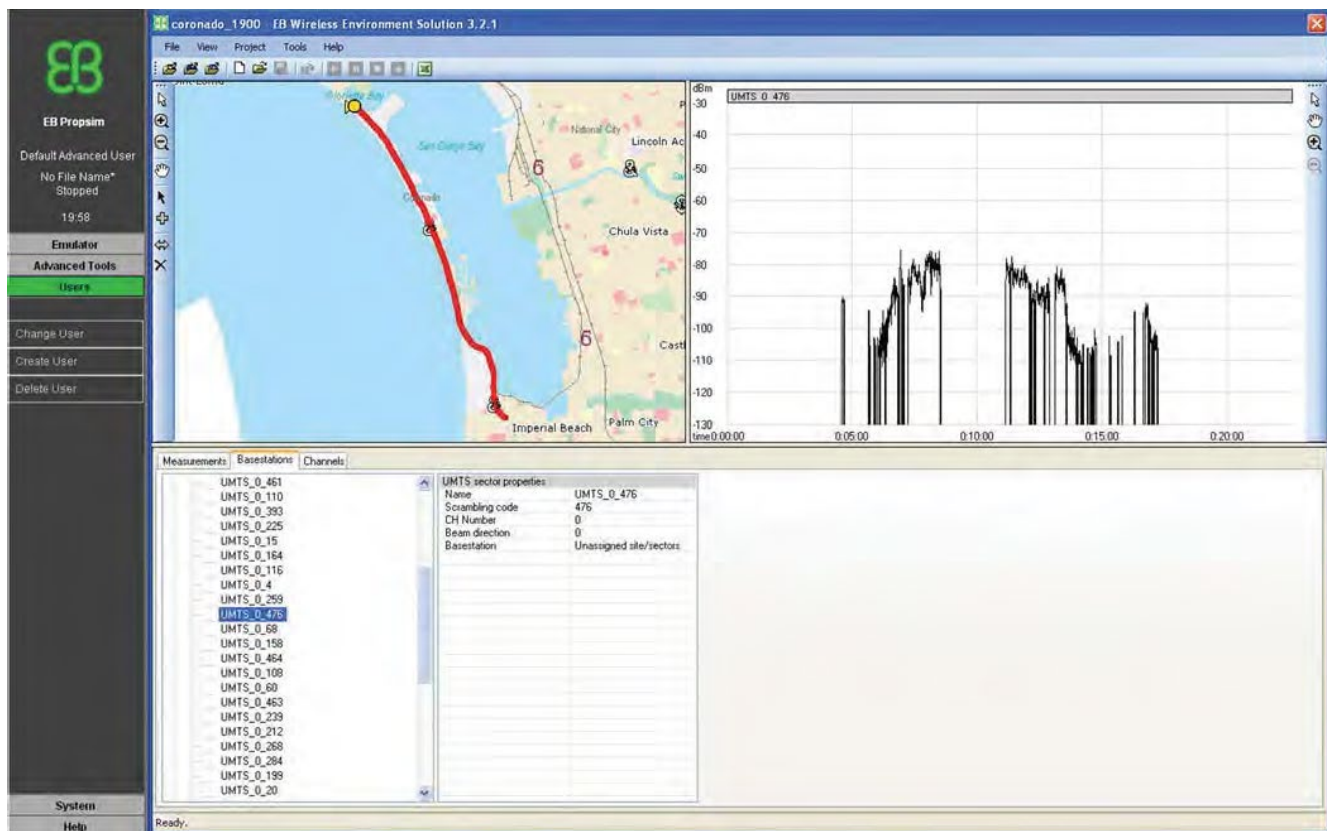
Above: click on the menu items shown, load project

Step 3: Look for *.wpj

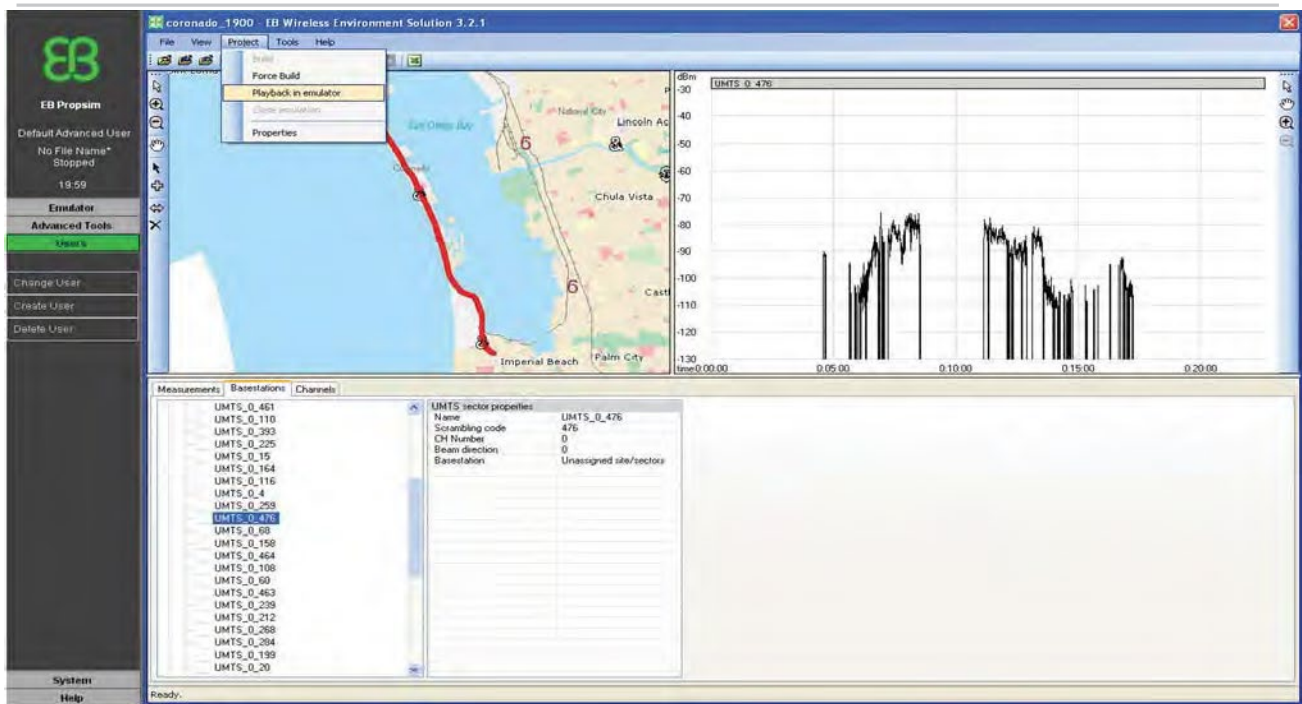


Above: locate the applicable file

Step 4 wait a few seconds, this display appears:



Step 5 goto Project -> play back in emulator

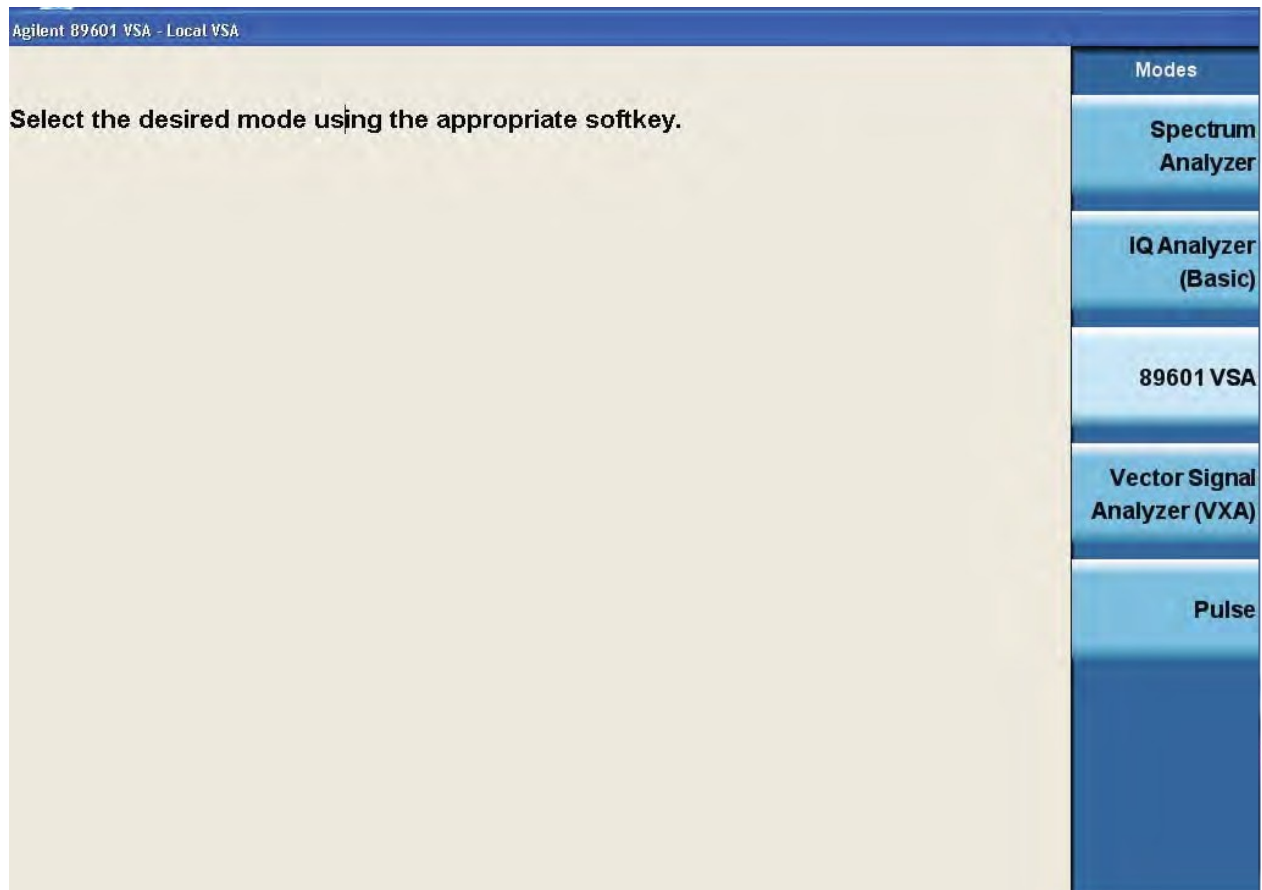


Step 6 wait and this screen opens:

Measurement on the Agilent EXA

Ensure that the Agilent machine is powered on (The button is located at the front at the lower left side..
Wait until the self-test is finished. This takes approximately three minutes.

Open a remote Desktop connection. The IP address for the Agilent is 192.168.111.11. The user name is 'Instrument' and the password is 'measure4u'.



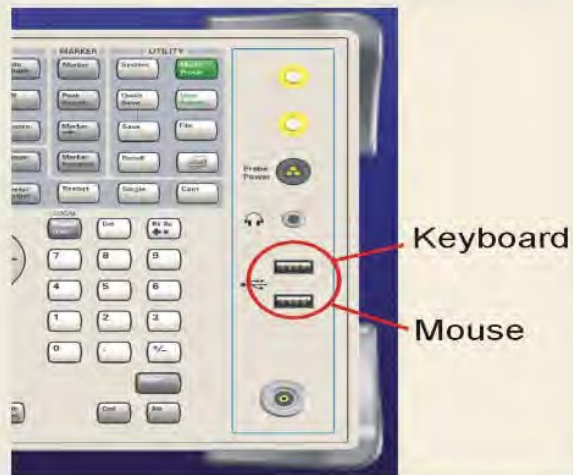
Above: The initial screen of the Agilent EXA Signal Analyzer. Click on the 89601 VSA.

Important Notes:

- The 89601 Vector Signal Analyzer (VSA) is a Windows® application. Operation with a mouse and keyboard installed is recommended.
- When the 89601 VSA is selected, access to the hardkeys and softkeys will be limited. For Hardkey/Softkey information, see the *Agilent 89600 "Measurement Hardware, Agilent MXA-MXA Embedded"* help topic.
- For 89601 VSA software with MXA information, see the *Agilent 89600 "Measurement Hardware, Agilent MXA - About MXA with 89600-Series Software"* help topic.

Press the **Start** softkey to begin 89601 VSA operation.

Press the **Mode** hardkey to switch to another application.



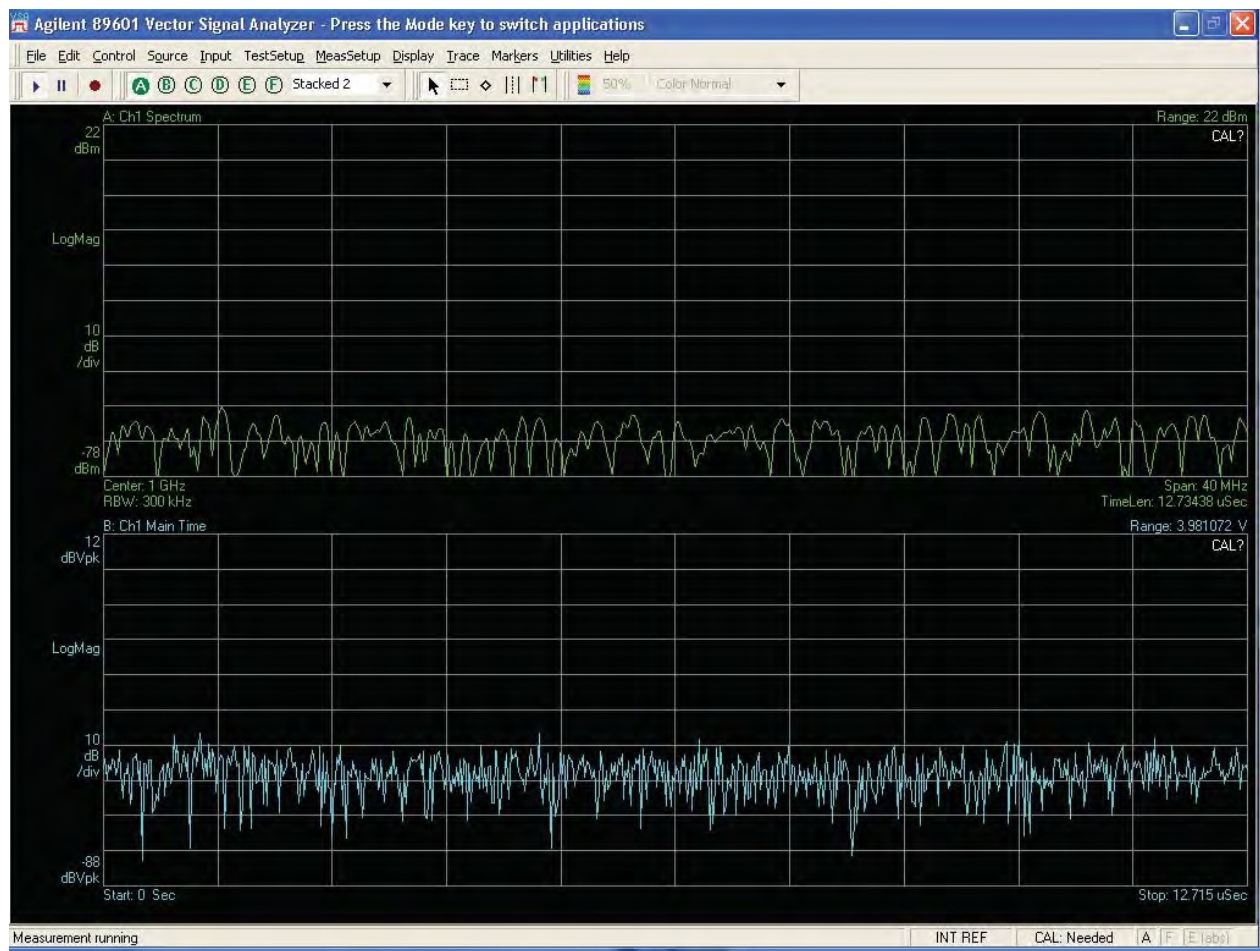
MSG

STATUS

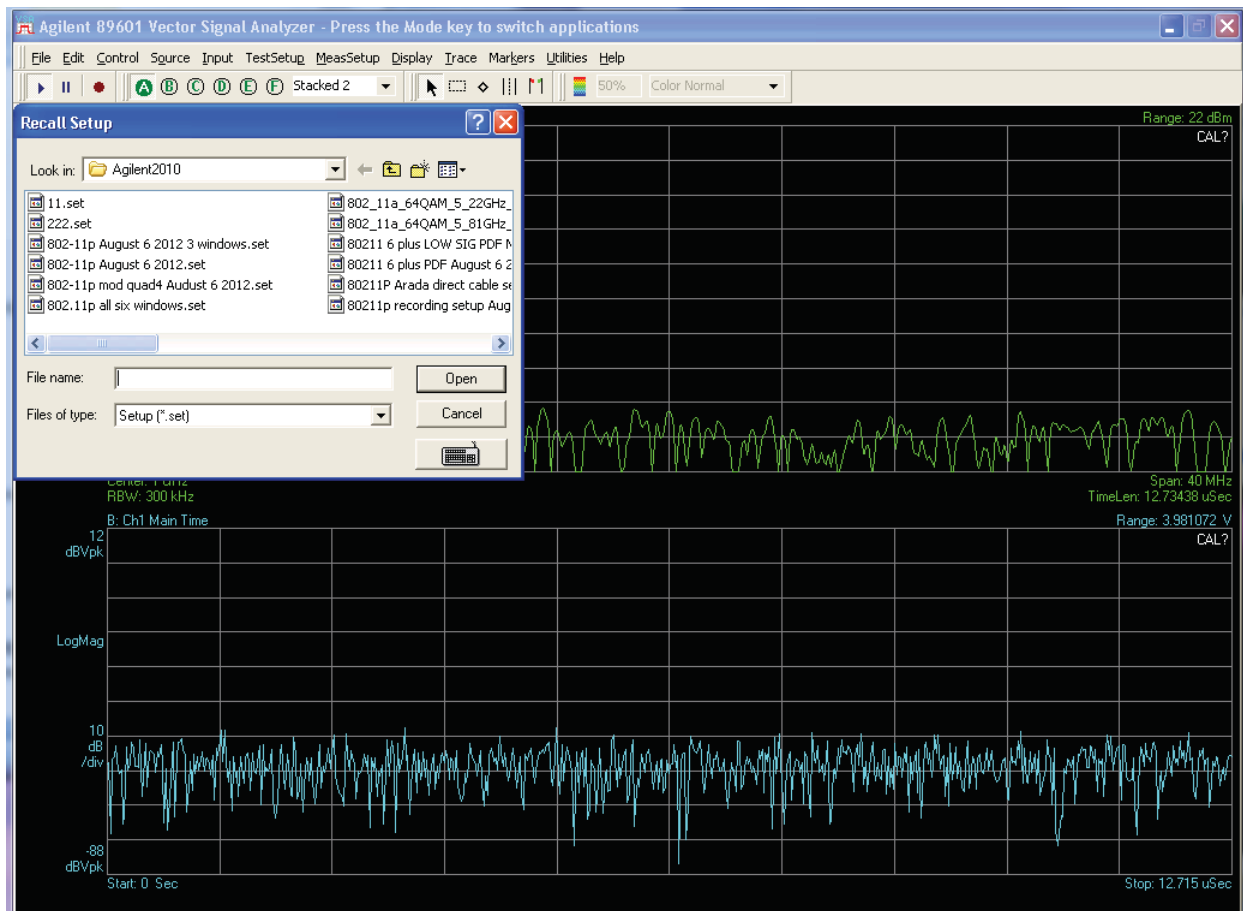
89601 VSA

Start 89601A
(Rev 11.21)**Start 89601B**
(Rev 15.01)

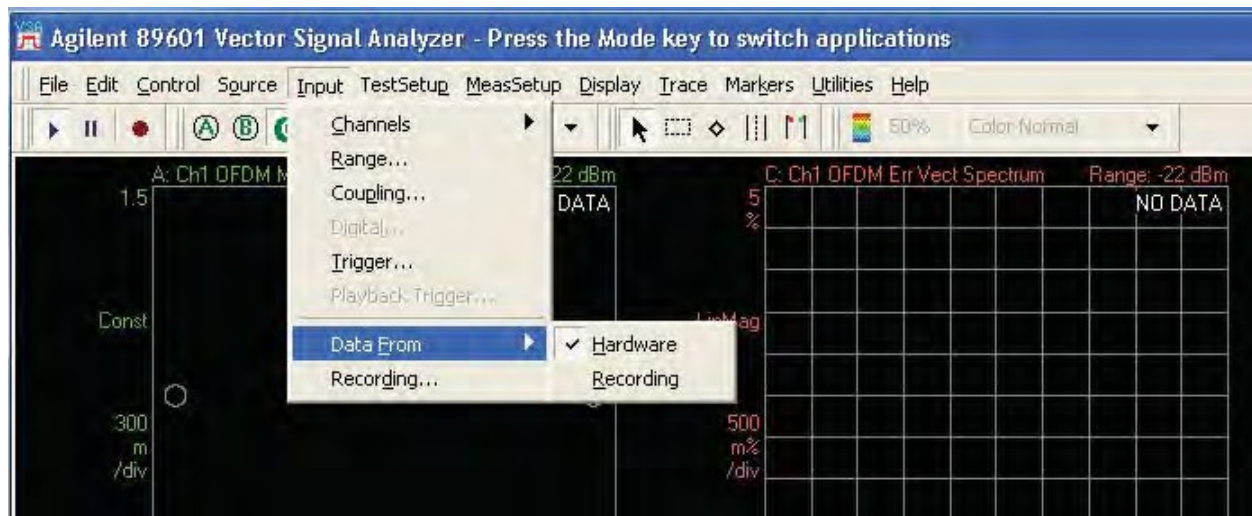
Above: Click on 'Start 89601 A'



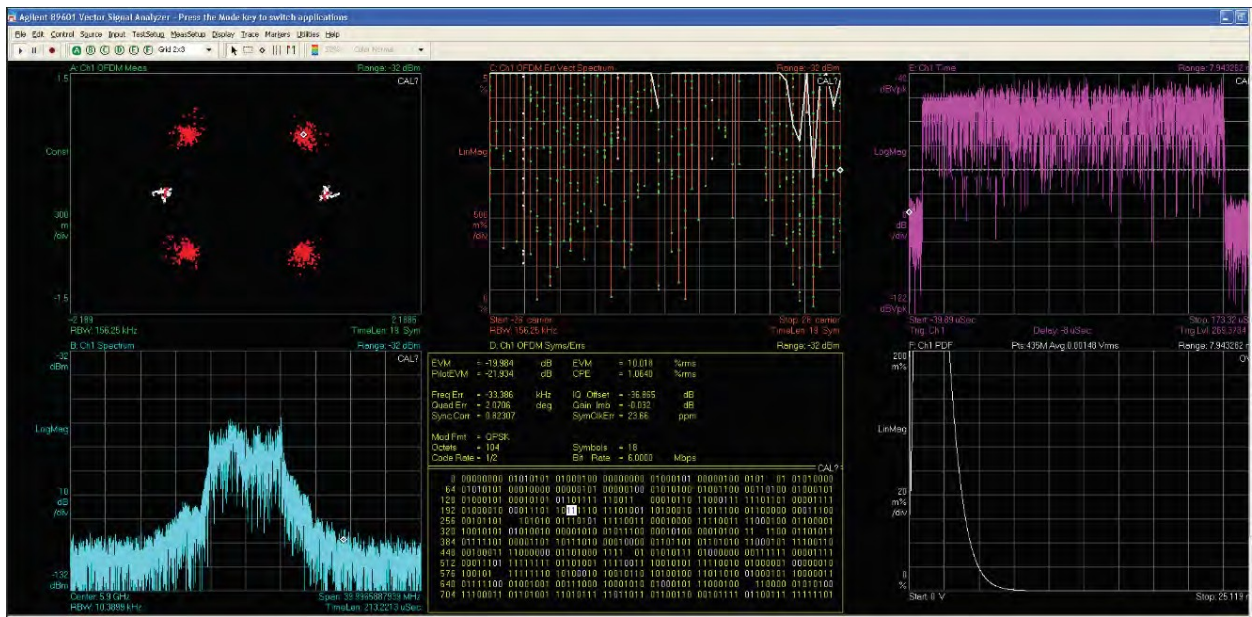
Above: The main screen of the VSA. Open a setup file by clicking on file recall setup.



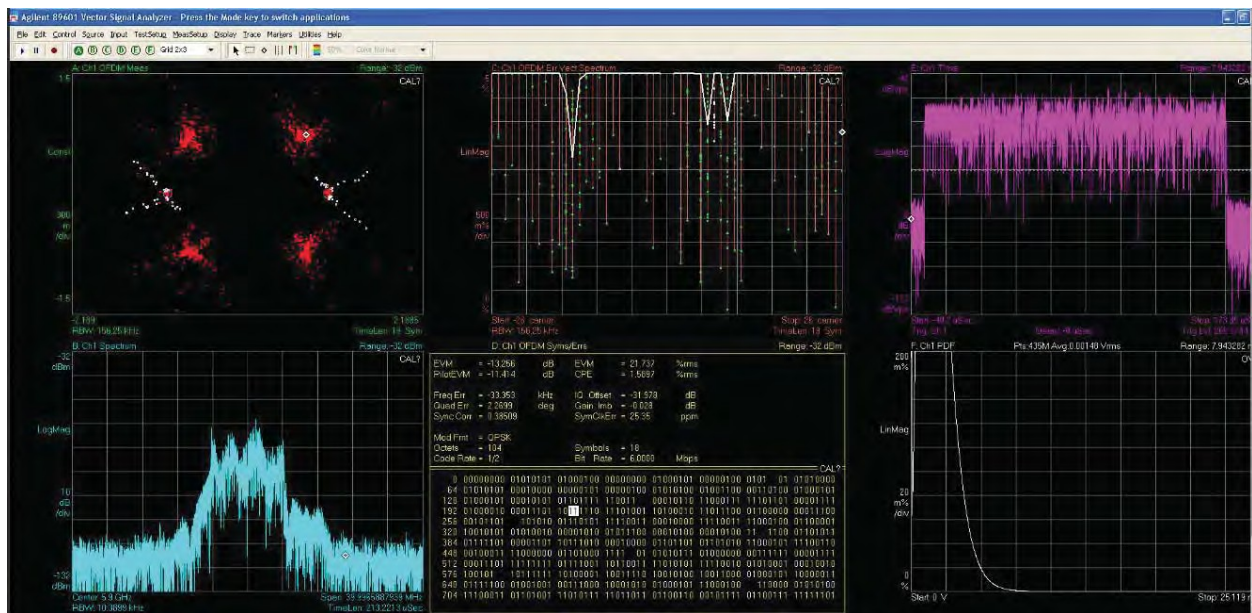
Above: Select the appropriate set up file and click open. Use the June demo file.

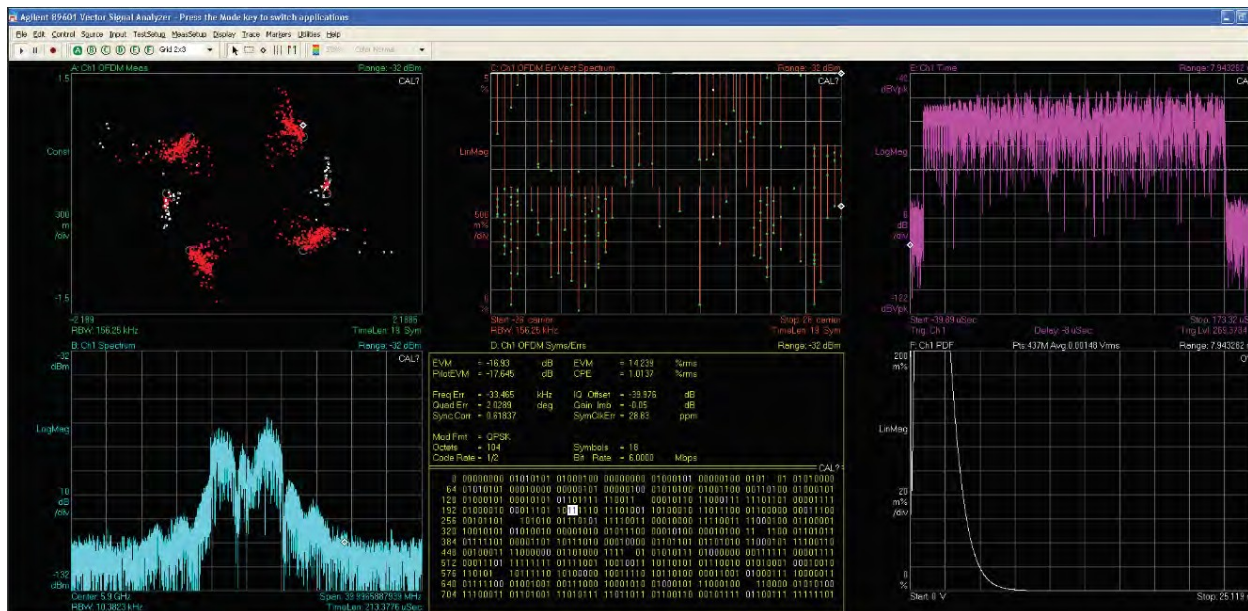
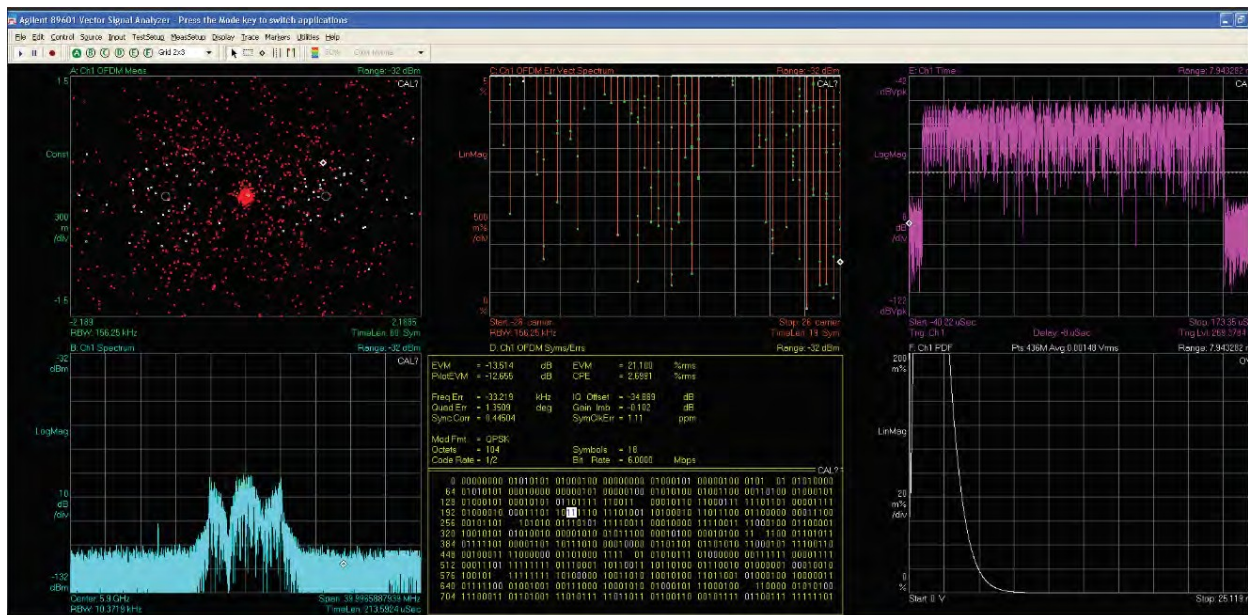


Make sure that the Input is coming from the hardware for real-time measurement. Use recording to play back a recording.



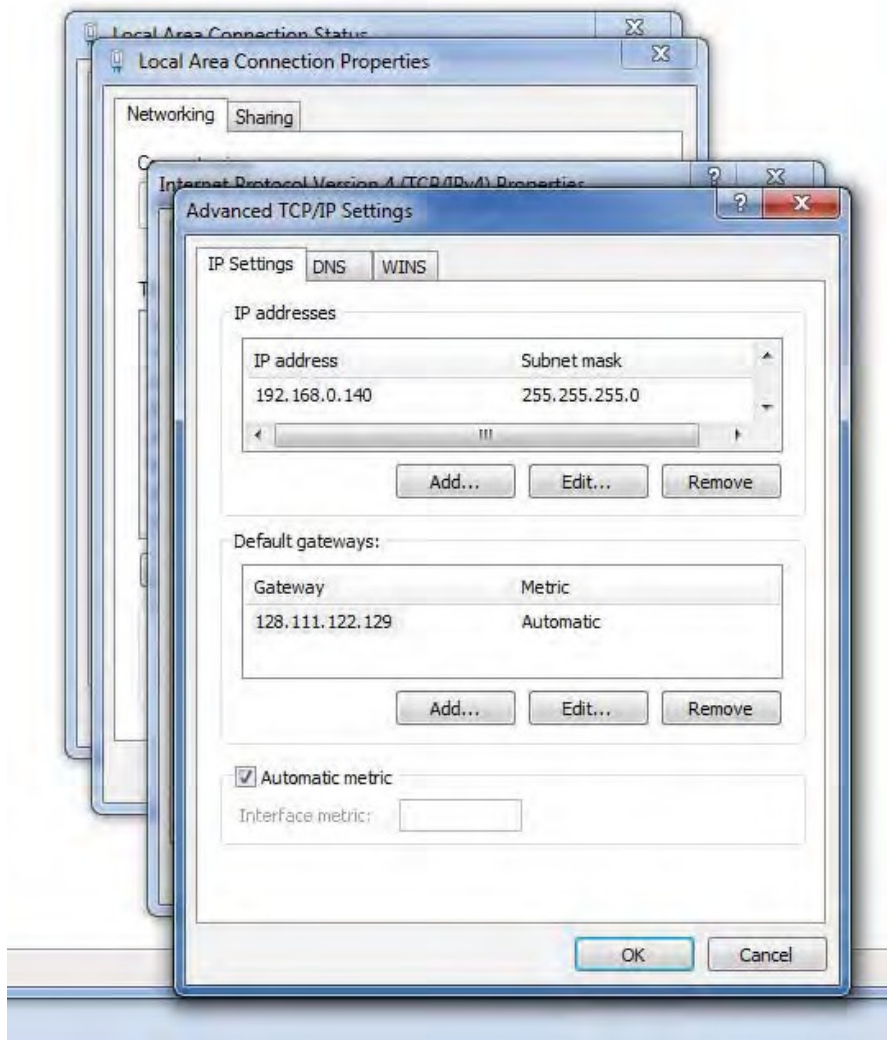
Above: Note the pattern gets distorted as the emulator plays back





Setup of the Arada for the radio source

Our Arada system has an IP set to 192.168.0.40 . To make use of this local IP, set the Host PC computer such that it has an IP on this 192.168.0 network. Open a control panel window→Network and Internet→Network and sharing Center the network settings→Change Adapter settings→right click on Local Area connection→Properties→ In TCP/IP v4 advanced settings add an IP address (if one is not already assigned) using the same last number as the main static IP.



For example if the PC's address is 128.111.122.140 then add an IP of 192.168.0.**140** . Now the Arada can be accessed without having to change the main IP of the PC. See Appendix: *Network Settings* for a detailed description.



Connect to the Arada using Tera Term with an SSH connection. In the Start menu, click on Tera Term. Enter the connection information as follows:



Above: this is the initial screen from Tera Term. Enter the address, CHANGE the Service to SSH. TCP port will change to 22 when you click SSH.

- Type the IP address of the Arada being used
- Click the Telnet radio button and click OK (user= root, pwd=password)
- If the Arada radio does not log in then repower the unit by disconnecting and reconnecting the 12V power cable.

The root directory should be active. Stop the running transmit processes by entering the CLI menu and sending the command 'apphalt'. This stops the default transmission so we can send specific data:



```
File Edit Setup Control Window Help
root@Arada01ED04 /root/#
root@Arada01ED04 /root/# ps
PID    USER    TIME    COMMAND
1      root     0:00    init
2      root     0:00    [kthreadd]
3      root     0:00    [ksoftirqd/0]
4      root     0:00    [events/0]
5      root     0:00    [khelper]
15     root     0:00    [kblockd/0]
21     root     0:00    [ksuspend_usbd]
27     root     0:00    [khubd]
50     root     0:00    [pdflush]
51     root     0:00    [pdflush]
52     root     0:00    [kswapd0]
53     root     0:00    [aio/0]
89     root     0:01    [mtdblockd]
138    root     0:00    [scsi_eh_0]
139    root     0:00    [usb-storage]
155    root     0:00    [krfcommd]
204    root     0:00    [jffs2_gcd_mtd4]
234    root     0:00    /usr/bin/watchdog
238    root     0:00    /usr/bin/reset_detect
300    root     0:00    [NewQueue]
301    root     0:00    [UDPQueue]
302    root     0:00    [VSAQueue]
303    root     0:00    [ome_udp_server]
359    root     0:00    /usr/sbin/configd
370    root     0:00    /sbin/syslogd -S -D -O /var/log/messages -s 64 -b 2 -t 2340
384    root     0:00    /usr/sbin/dropbear
392    root     0:00    /usr/sbin/telnetd
399    nobody   0:00    /usr/local/sbin/dnsmasq -N -h -i brwifi
591    root     0:00    /usr/sbin/nmbd -s /etc/smb.conf -D
618    nobody   0:08    /usr/local/sbin/gpsd /dev/ttyS0
620    root     0:01    /usr/local/bin/gpsc 1
623    root     0:00    /usr/local/bin/gpstime 15
645    root     0:00    /sbin/udev -d
661    root     0:00    /bin/sh /usr/local/bin/asmrecovery.sh
768    root     0:00    /usr/local/bin/usbd -l /tmp/usb/ -x ModelDeploymentPktCaptur
785    root     0:00    /usr/local/bin/getwsstxrncdec -o NORXALL -w User -u 2 -x
787    root     0:00    /usr/local/bin/getwsstxrncdec -o NORXALL -w User -u 2 -x
790    root     0:00    /usr/local/bin/getwsstxrncdec -o TXRXUDP -w User -u 2 -B
794    root     0:00    /usr/local/bin/getwsstxrncdec -o NOTXRX -y 35 -a 1 -s 176
797    root     0:00    /usr/local/bin/getwsstxrncdec -o TXRXUDP -w User -u 2 -B
808    root     0:00    /usr/local/bin/capture_app 0000
833    root     0:00    /usr/local/bin/auto_off_load -c /var/log/offload.conf
846    root     0:00    /usr/local/bin/hbrtc
847    root     0:00    /usr/local/bin/control_apps
2731   root     0:01    /usr/sbin/dropbear
2736   root     0:00    -sh
2854   root     0:00    sleep 1
2855   root     0:00    ps
root@Arada01ED04 /root/# cli
Arada01ED04#apphalt
getwsstxrncdec Successfully Terminated (Pid = 797)
Please wait while terminating getwsstxrncdec (Pid = 794)
getwsstxrncdec Successfully Terminated (Pid = 794)
Please wait while terminating getwsstxrncdec (Pid = 790)
getwsstxrncdec Successfully Terminated (Pid = 790)
Please wait while terminating getwsstxrncdec (Pid = 787)
getwsstxrncdec Successfully Terminated (Pid = 787)
Please wait while terminating Asm.bin (Pid = 785)
Asm.bin Successfully Terminated (Pid = 785)
Please wait while terminating capture_app (Pid = 808)
capture_app Successfully Terminated (Pid = 808)
Please wait while terminating usbd (Pid = 768)
usbd Successfully Terminated (Pid = 768)
Please wait while terminating auto_off_load (Pid = 833)
auto_off_load Successfully Terminated (Pid = 833)
Arada01ED04#
```

script. In this case we want to change the setting so at the command line:

- type 'cli' (a different prompt should appear)
- type 'apphalt'
- type exit

Now the Arada radio should be ready to be set to a specific channel, power and xmit type.

d. `getwbsstxrxcdec -s 180 -t BSM -o norx -a1 -r6 -j3`

Note: Arada Locomate user manual page 3-16:

1. Continuous Channel mode

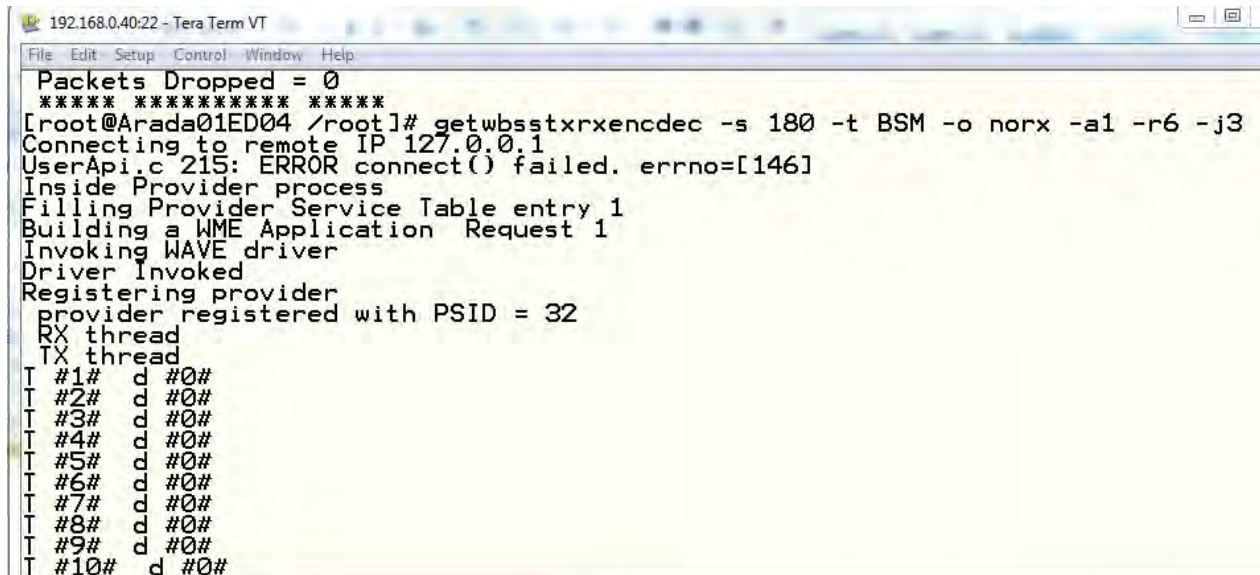
1.1 BSM –Basic safety Message

- Provider

`getwbsstxrxcdec -s 172 -t BSM -o norx -a 0 -e sign`

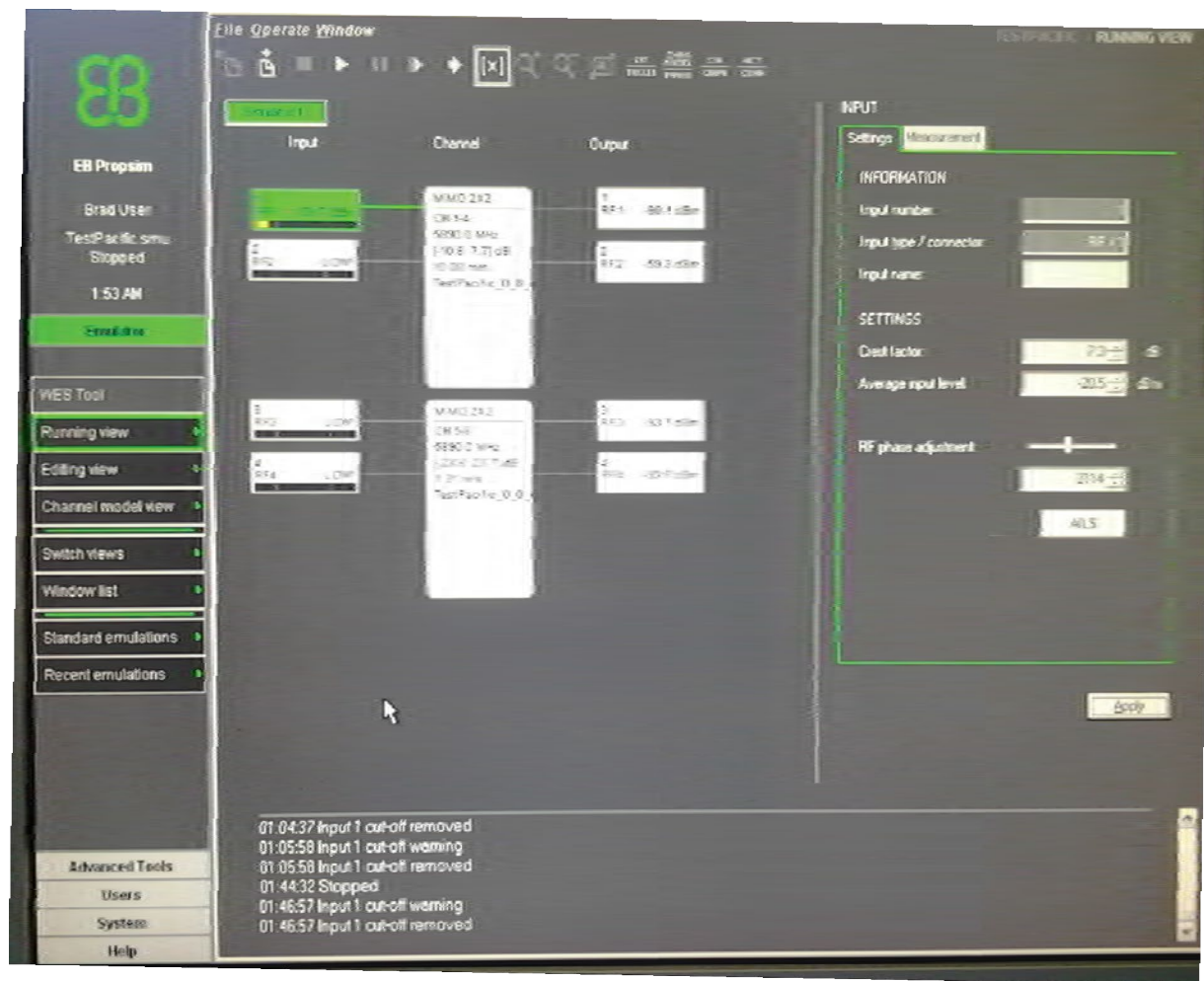
- Registers and Starts a provider
- Starts continuous channel at service channel 172
- Transmits the BSM which is encoded in DER on service channel 172

We modified the command line to add the data rate and output power level. We omit ‘-e sign’ and simply transmit the BSM on channel 180 at the rate of 6 Mbps, command of 3dBm has an effective output of about 1dBm



```
192.168.0.40:22 - Tera Term VT
File Edit Setup Control Window Help
Packets Dropped = 0
*****
[root@Arada01ED04 /root]# getwbsstxrxcdec -s 180 -t BSM -o norx -a1 -r6 -j3
Connecting to remote IP 127.0.0.1
UserApi.c 215: ERROR connect() failed. errno=[146]
Inside Provider process
Filling Provider Service Table entry 1
Building a WME Application Request 1
Invoking WAVE driver
Driver Invoked
Registering provider
provider registered with PSID = 32
RX thread
TX thread
T #1# d #0#
T #2# d #0#
T #3# d #0#
T #4# d #0#
T #5# d #0#
T #6# d #0#
T #7# d #0#
T #8# d #0#
T #9# d #0#
T #10# d #0#
```

Above: expected output of entering the command. There are errors encountered in the text but there should be packets counting quickly.



Above: with the signal from the Arada running note the reading of 54.7dBm on the input. We want the signal to be showing up as yellow or green

Appendix

Logging in to the EB/Anite website for files or upgrade information is done by following this link: <http://www.elektrobit.com/ebprosimextranet> username is 800189 and password is QNDBZ

Anite

Login to Anite Propsim Extranet

For more information on Propsim Extranet, please contact your account manager or visit our website at www.anite.com.
Please see Anite's website for more details.

Username

password

-I

U>OIN

[Forgot your password?](#)

Anite

HOME

DOCUMENTS

SOFTWARE DOWNLOADS

NEWSROOM

FAQ

KNOWLEDGE BASE

Welcome UCSE

Latest information on Propsim products

Newsroom section with various product updates and announcements.

Search from the Knowledge Base

Search results section displaying relevant information from the knowledge base.

- Your Configuration
- Service Agreements

Latest news

News section containing various announcements and updates.

Need personal support?

[Go to Support Request Form](#)

File management

File management section with links for file uploads and downloads.



Fig. 4 EB Propsim F8 configuration list updated April 8, 2013



Creating a new MiMO template

Create a new Emulation file in the EB. Close any existing emulation. (refer to appendix 1 email from JP)

Please make 2x2 bi di emulation, that is

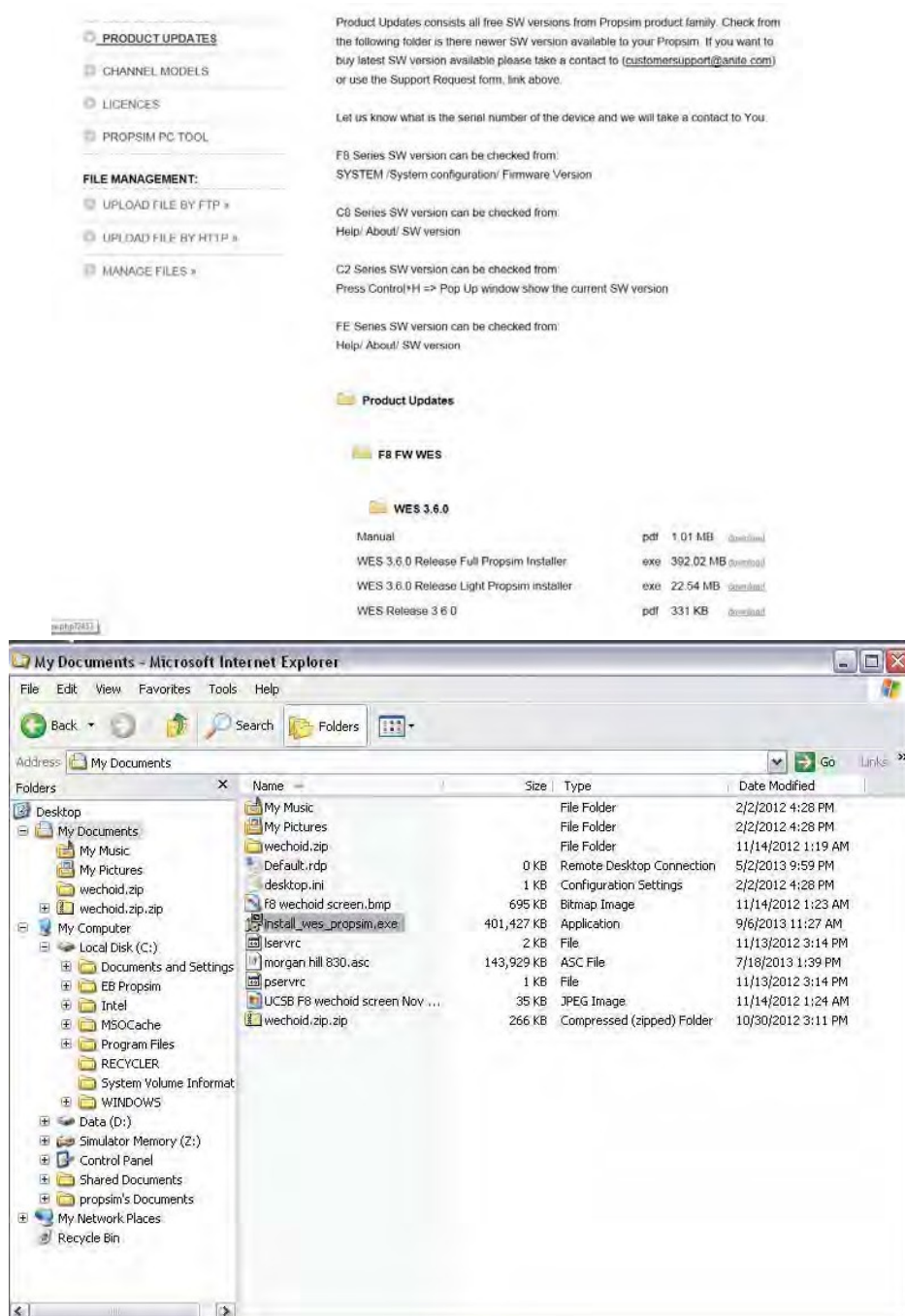
Go to emulation editor(where is it) -> select MiMO Template, input 2 and 2, go again to MIMO template, input 2 and 2 into menu. Click the channel model, go to channel modeling tab (down right hand side), select constant model from the ready made library. Save emulation and compile the

emulation by pressing the 4 squares in the main menu. Go to running view, open the emulation You just did and run it

In this case the file was named PacificTest when the WES tool is run. Describe the connection to the filename for the shapefile this is the one used by the test pacific program emulation that was sent to us. When the WES tool is run this runs, behold:

Installing the WES update:

If this file(s) is not already present in the PropSim F8, download it here. In the Software Downloads section under Product updates, goto PropSim F8. The file we want is WES 3.6.0 Release Full PropSim Installer. To download, use Internet Explorer Browser as download issues have been reported with non-ie browsers. Once setup file is downloaded transfer the file to the EB. The set up file is stored in My Documents. Open the setup file and follow the installation instructions. Two different installers will appear as shown below.





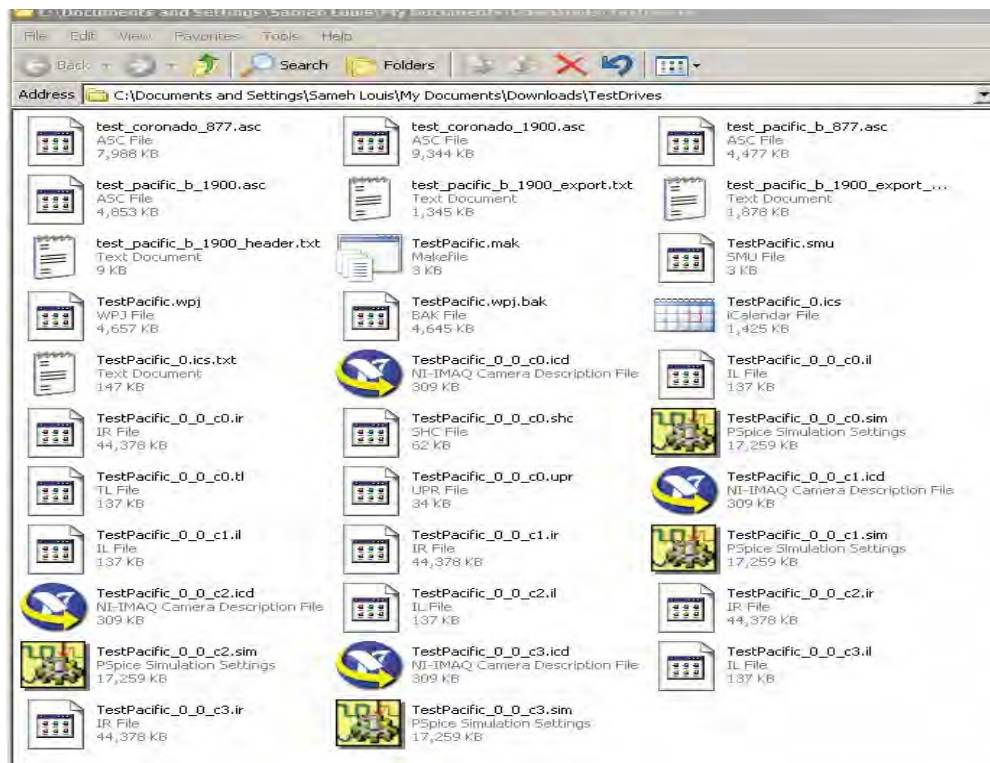


Fig. 5 Download the file TestDrives and extract. TestDrives contains these folders

Initial load of SD Simulation test software into EB

Extract the file in the PC instead of in the EB. Load this folder onto a USB Memory (such as a flash memory stick), then upload to the EB unit. Insert the flash stick into the EB's spare USB port, then using the file manager, copy the file onto the EB's local hard drive. When the WES program is run it will ask for this file.

First Responder Support Systems Testbed (FiRST)

Dr. Rick Churh¹, PI

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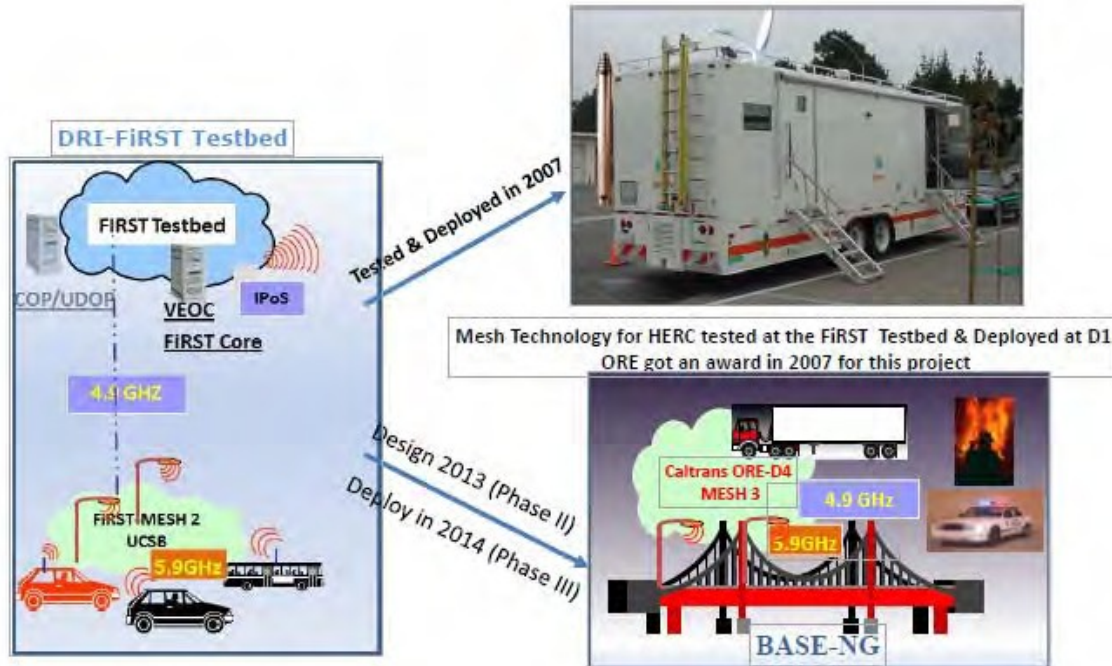
2. Office of Communication Systems Research

California Department of Transportation, FiRST Testbed



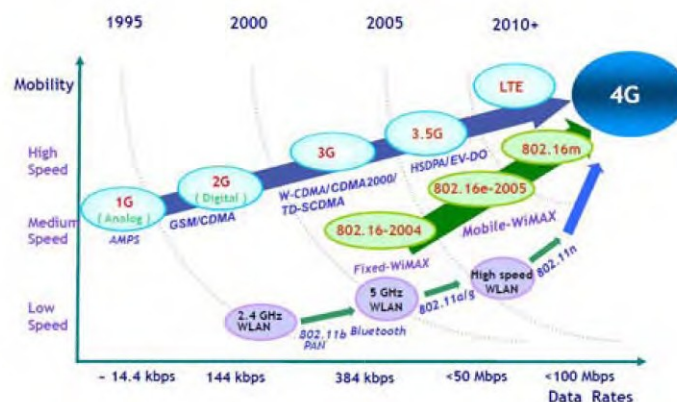


Integration of Cellular (e.g. LTE) and DSRC for ITS/PS Applications



Spectrum allocation and Interoperability were once the main obstacles for both ITS (Intelligent Transportation Systems) and Public Safety radio services. Licensed Frequency spectrum has been available for both ITS (75 MHz at 5.9 GHz), and PS (50 MHz at 4.9 GHz) for the almost 15 years. However, we still don't have the seamless service continuity when users move between different network services. Interoperability has been the focus of current federal initiatives (e.g. first net) to address the PS intra-agency communication. Similarly, in the commercial "connected vehicles" environment, DSRC standards have been developed for vehicle-to-vehicle active safety applications.

Wireless Technology Evolution





The intent of this brief study is to explore the feasibility of integrating heterogeneous wideband networks (e.g. DSRC and PS), and cellular wide area services (e.g. LTE) to address the current gap of agency-to-citizens communications. The emerging machine-to-machine and the Internet-of-Things will drive the future evolution of seamless services for everyone.

Operational & Technical Challenges in Public Safety Domain

Table 1. Public Safety Applications

Database checks	Public safety officers must often retrieve data from the headquarters to support their work. For example, in a chemical plant fire, public safety officers may need the building plans, the location of specific assets (e.g. water) or the most dangerous areas (e.g. deposit of inflammable liquids).
Verification of biometric data	Public Safety officers may check the biometric data of potential criminals (e.g., fingerprints) during their patrolling duty. The biometric data could be transmitted to the headquarters or to a control center to be compared against biometric archives. Then, the response could be sent back to the PS officers. This would be a positive method of identification during field interrogation stops if identification documents (e.g., I.D. card) are missing.
Wireless video surveillance	A fixed or mobile sensor can record and distribute data in video-streaming format, which is then collected and distributed to public safety responders in the area or back to the Headquarters.
Automatic number plate recognition	A camera captures license plates and transmits the image to headquarters to verify that the vehicles have not been stolen or the owner is a crime offender.
Documents scan	During patrolling activities, public safety officers can verify an identification document (e.g. I.D. card or driving license) in a more efficient way. Document scan is also useful in border security operations where people, who cross the borders, may have documents in bad condition or falsified.
Location/Tracking for Automatic Vehicle/Officer Location. Situation Awareness	The public safety officer has a Global Navigation Satellite System GNSS (e.g., GPS) position localizer on the handheld terminal or the vehicular terminal. The positions are sent periodically to the headquarters so that the command center knows the location of the public safety officers and they can organize and execute the operations in a more efficient way.
Transmission of Building/Floor plans	In case of an emergency crisis or a natural disaster, Public Safety responders may have the need to access the layout of the buildings where people are trapped. Building or floor plans can be requested to the headquarters and transmitted to the public safety responders.
Remote emergency medical service	Through transmission of video and data, medical personnel may intervene or support the rescue team in the field.
Sensor networks	Sensors networks could be deployed in a specific area and transmit images or data to the public safety responders operating in the area or to the command centre at the headquarters. This application does not include video-surveillance, which is previously described.
Monitoring of Public Safety officer	Vital signs of Public Safety officers could be monitored in real-time to verify their health condition. This is particularly important for firefighters and officers involved in search and rescue operations.





PS organizations must operate in a difficult environment and in various operational scenarios, which are characterized by a number of significant challenges:

- **Interoperability.** Interoperability barriers among the communication systems of various PS organizations are still present at the local and national level.
- **Broadband Connectivity:** Table 1 provides examples of current and future PS applications that are driving the need for broadband connectivity to transmit images or video. The wireless communication technologies currently deployed (e.g. APCO25) provide only limited data capacity (e.g., 28.8Kbits). Using the DSRC/WAVE in the 4.9 GHz in addition to the ITS 5.9 GHz band is a challenging task. Both the frequency spectrum allocation and the hardware/software technologies are available to support the desired applications. However, the deployment of these new technologies may be inhibited the limited budget of the involved jurisdictions. Current federal initiatives such as the FirstNet at 700 MHz may be a more practical approach as they provided the required fund and the implementation standards (LTE).
- **Challenging operational environment:** PS infrastructures may be destroyed or degraded as a consequence of the crisis. For example an earthquake, flooding or tsunami can destroy the physical network infrastructure or disrupt the supply chain used in humanitarian logistics. Even if the PS infrastructure is not destroyed, it can be overloaded by the increase of traffic due to panic calls as in the 9/11 event.
- **Equipment lifecycle:** Evolving technologies and standards may cause the existing wireless equipment to become obsolete. Due to the different market sizes (200:1 ratio), the equipment lifecycle in the PS domain is usually less dynamic than the commercial domain.

It is hoped that the FirstNet initiative will address these PS challenges.

Public Safety Spectrum & Architecture

Frequency Band (MHz)	MHz[Approximate]	Usage
25-50	6.3	Narrowband Voice
150-174	3.6	Narrowband Voice
220-222	.1	Narrowband Voice
450-470 ⁸	3.7	Narrowband Voice
809-815/854-860 ⁹	3.5	Narrowband Voice
806-809/851-854 ¹⁰	6	Narrowband Voice
758-763/788-793 ¹¹	10	Wide Area Broadband
763-768/793-798 ¹²	10	Wide Area Broadband
768-769/798-799 ¹³	2	Guard
769-775/799-805	12	Narrowband Voice ¹⁴
4940-4990	50	Short range Broadband
Total	107.2	

In 2002, the FCC allocated the 4.9 GHz (4940-4990 MHz) band for public safety use, adopting service rules in 2003 to encourage agencies to benefit from high-speed applications like real-time video, data downloads, and short-range wireless networking at emergency incidents. Those rules allowed utilities and other commercial entities to use the spectrum to provide public safety services if they were authorized by traditional public safety licensees. In 2009, the FCC modified



Issues that it still to be addressed are:

- Whether to establish formal coordination requirements in the 4.9 GHz band
- Whether the 700 MHz Regional Planning Committees (RPCs) could administer a database registration process
- Whether expanding eligibility to critical infrastructure entities and commercial users would promote more effective and efficient use of the band
- Whether eligibility for commercial users should be on a secondary basis subject to a shutdown feature to allow public safety priority access
- Whether the First Responder Network Authority (FirstNet) is or should be eligible for a 4.9 GHz band license
- Technical approaches to increase spectrum efficiency, usage, and throughput in the 4.9 GHz band

LTE – Long Term Revolution

The First complete LTE specifications 2008 became available in 2008. LTE is specified at the following layers:

Physical Layer:

- Can support portable speeds over 100 MPH
- MIMO (Multiple Input Multiple Output) technology
- Bandwidth up to 20 MHz
- High order modulation (64QAM)

Media Access:

- DL: OFDM
- UP: SC-FDMA

Network Architecture:

- All IP end-to-end
- Flatter architecture

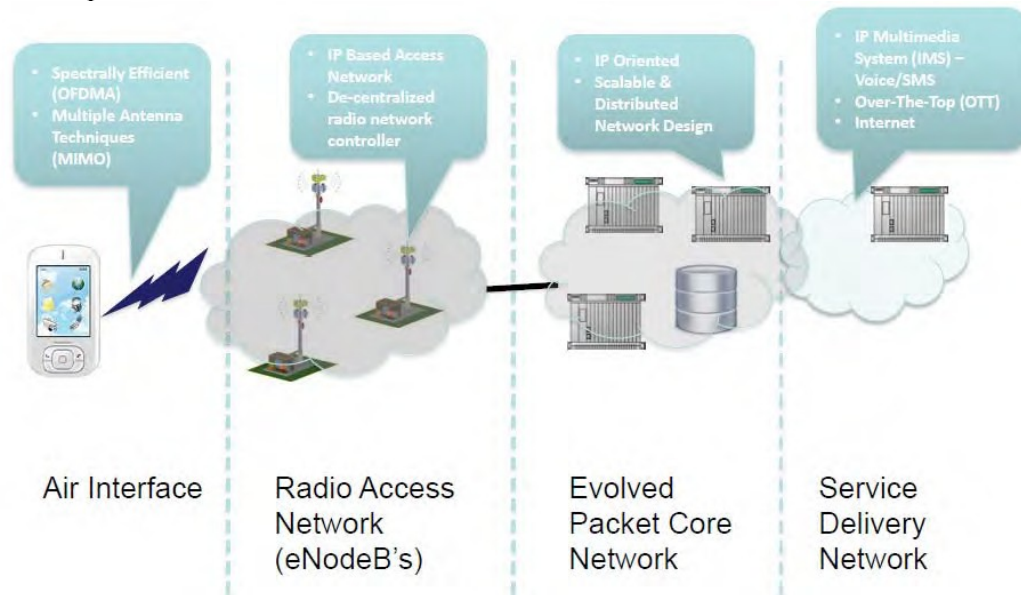
The table below reflects the LTE potential data rates for different frequency bandwidths.

Modulation and Coding	Bits per Symbol	MIMO Usage	5 MHz	10 MHz	15 MHz	20 MHz
64 QAM 1/1	24	4x4 MIMO	80.3	161.9	243.5	325.1
64 QAM 1/1	12	2x2 MIMO	42.5	85.7	128.9	172.1
64 QAM 3/4	9	2x2 MIMO	31.9	64.3	96.7	129.1



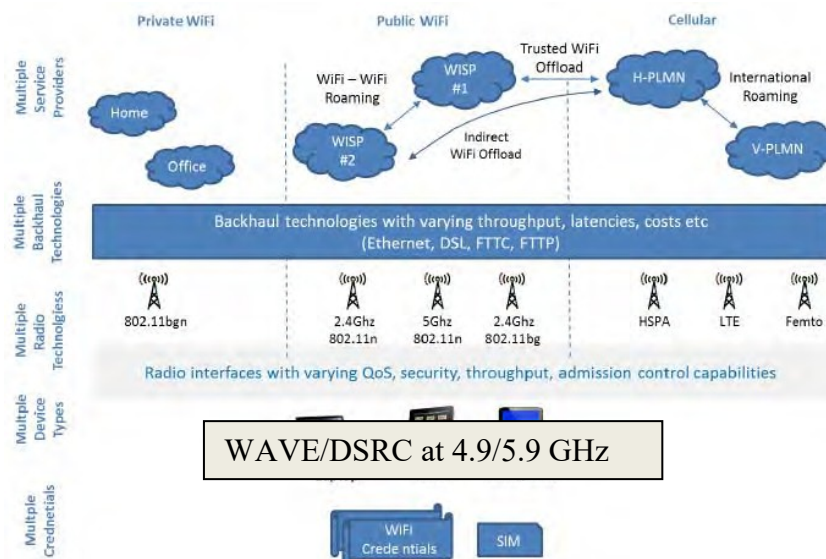
Additionally LTE technologies promise the following:

- An end-to-end all-IP significantly higher capacity
- Peak data rate up to 300 Mbps
- Round-trip delay <10ms
- Call setup latency < 300ms
- QoS Support
- Deployable in existing 3G frequency bands already auctioned or allocated (FirstNet) spectra.



LTE Network Architecture

Integration of Cellular (e.g. LTE) and DSRC for ITS/PS Applications



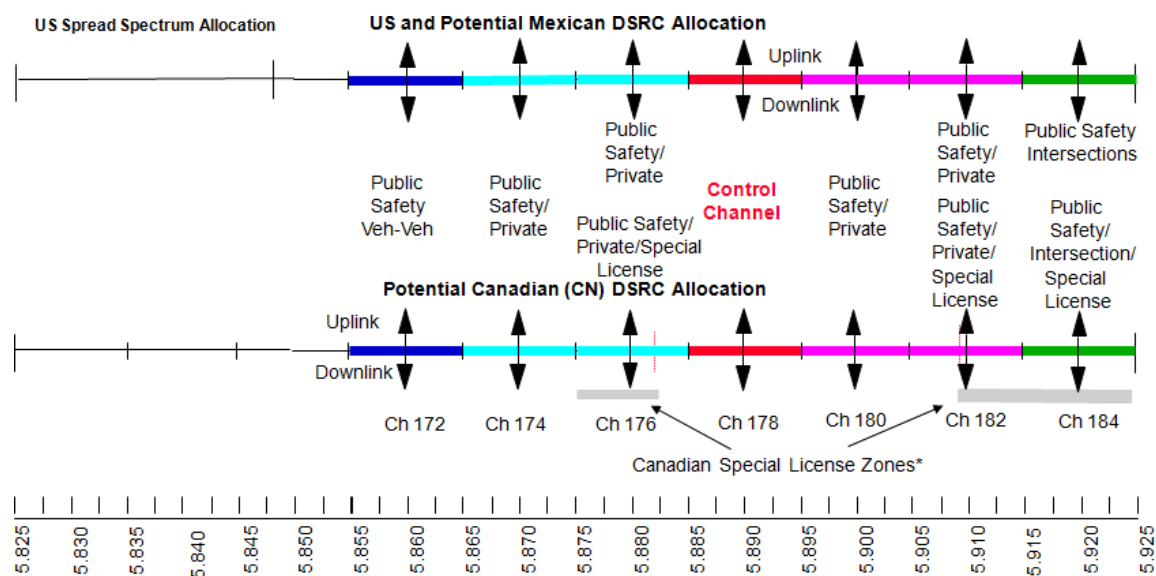


The specific technology used by a 3GPP cell impacts the decision of whether DSRC or LTE should be used. Specifically, if DSRC is available, the device may be configured to prefer DSRC to LTE, whereas if the availability of DSRC is limited to specific locations (e.g. Toll), then LTE may be preferred. It is envisioned that in the near future the mobile device (smart phone) will support DSRC services, and may replace the DSRC OBU (on board unit), especially for aftermarket installation. Using the information available in the mobile device about the cell features and policies that consider such parameters enables the mobile device to perform more intelligent decisions.

IEEE Standards for Wireless Access in Vehicle Environments (DSRC-WAVE)

Development History

In February 2011, the IEEE published the (IEEE P802.11p, IEEE 1609.3 and IEEE 1609.4). This international standard was the result of more than 10 years and partnerships with tens of public private entities.



These international standards were pioneered in 1997 by Caltrans' DRI (NTRP, then), where test data at TCFI (UCSB) proved the inadequacy of narrow band communication for DSRC applications (wireless access in vehicle environments). In 1999, Caltrans formed alliance with the OFDM Forum to develop and demonstrate the first DSRC prototype at 5.9GHz. We competed against the Japanese' narrow-band Standard and Motorola propriety technology, and field tests proved that our approach had better performance for both vehicle-to-vehicle and infrastructure-to-vehicle applications.

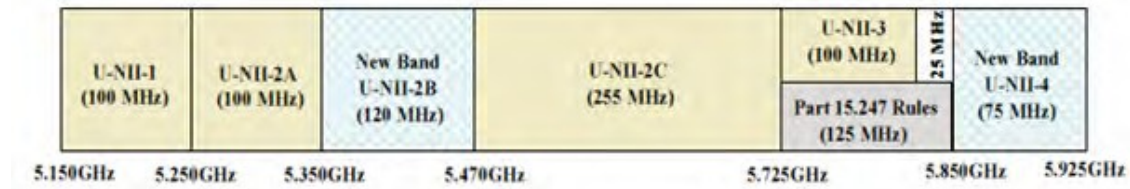
Caltrans led more than 14 public agencies and PATH, and convinced other private entities to support our proposal. Two electronic chip manufacturers demonstrated the feasibility of using COT parts for the new standard. In 2001, our proposal entitled "802.11a-RA" for was accepted as the basis of the North American standard for DSRC.



The standard attracted electronics and vehicle manufacturers and emerged as an international standard. It took the team 15 years to refine and publish these standards.

On December 17, 2003 the Commission adopted a Report and Order establishing licensing and service rules for the Dedicated Short Range Communications (DSRC) Service in the Intelligent Transportation Systems (ITS) Radio Service in the 5.850-5.925 GHz band (5.9 GHz band). The DSRC Service involves vehicle-to-vehicle and vehicle-to-infrastructure communications, helping to protect the safety of the traveling public. It can save lives by warning drivers of an impending dangerous condition or event in time to take corrective or evasive actions. The band is also eligible for use by non-public safety entities for commercial or private DSRC operations.

UNII

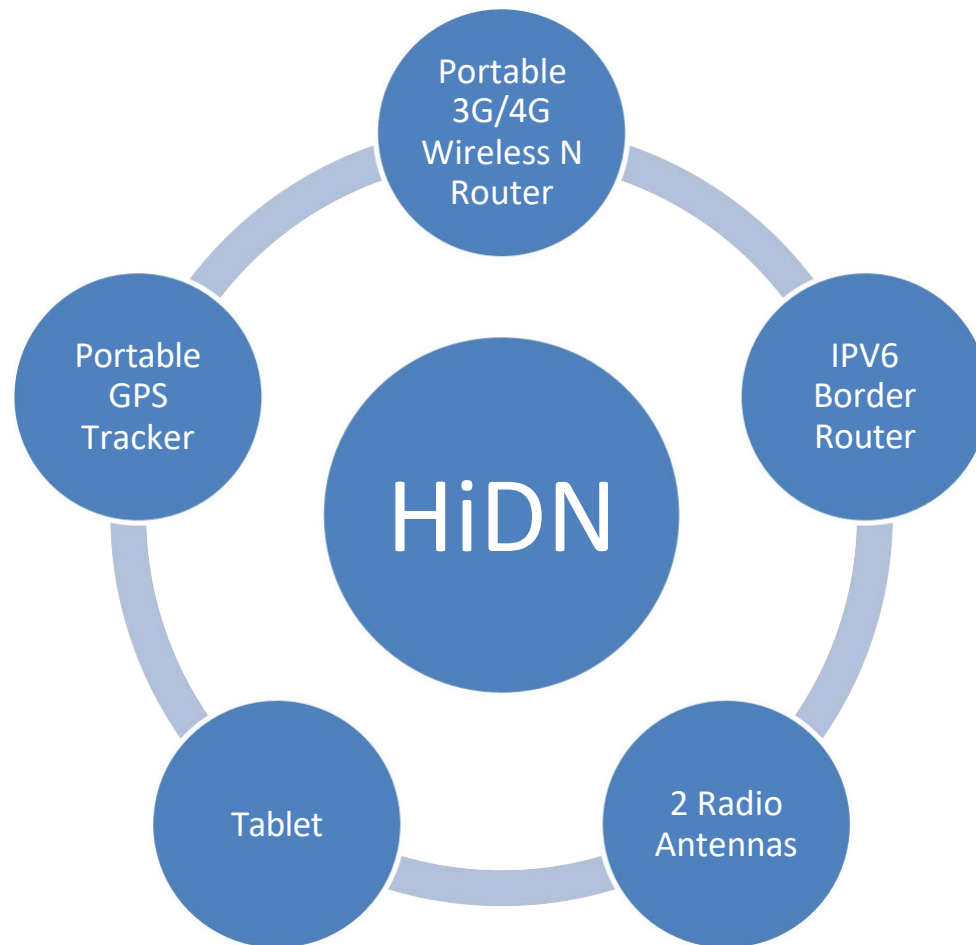


The FCC issued an NPRM on February 20, 2013, proposing an additional 195 megahertz of spectrum in the 5.35-5.47 GHz (UNII-2B) and 5.85-5.925 GHz (UNII-4) bands for UNII use and enhanced use of 5 GHz spectrum already designated for UNII use. At a Congressional hearing in November 2013, representatives from the auto industry acknowledged that there is room in the 5.9 GHz Band for DSRC and unlicensed operations to share the band and agreed to actively engage with the technology community to identify harmful interference mitigation solutions in the 5.9 GHz Band.

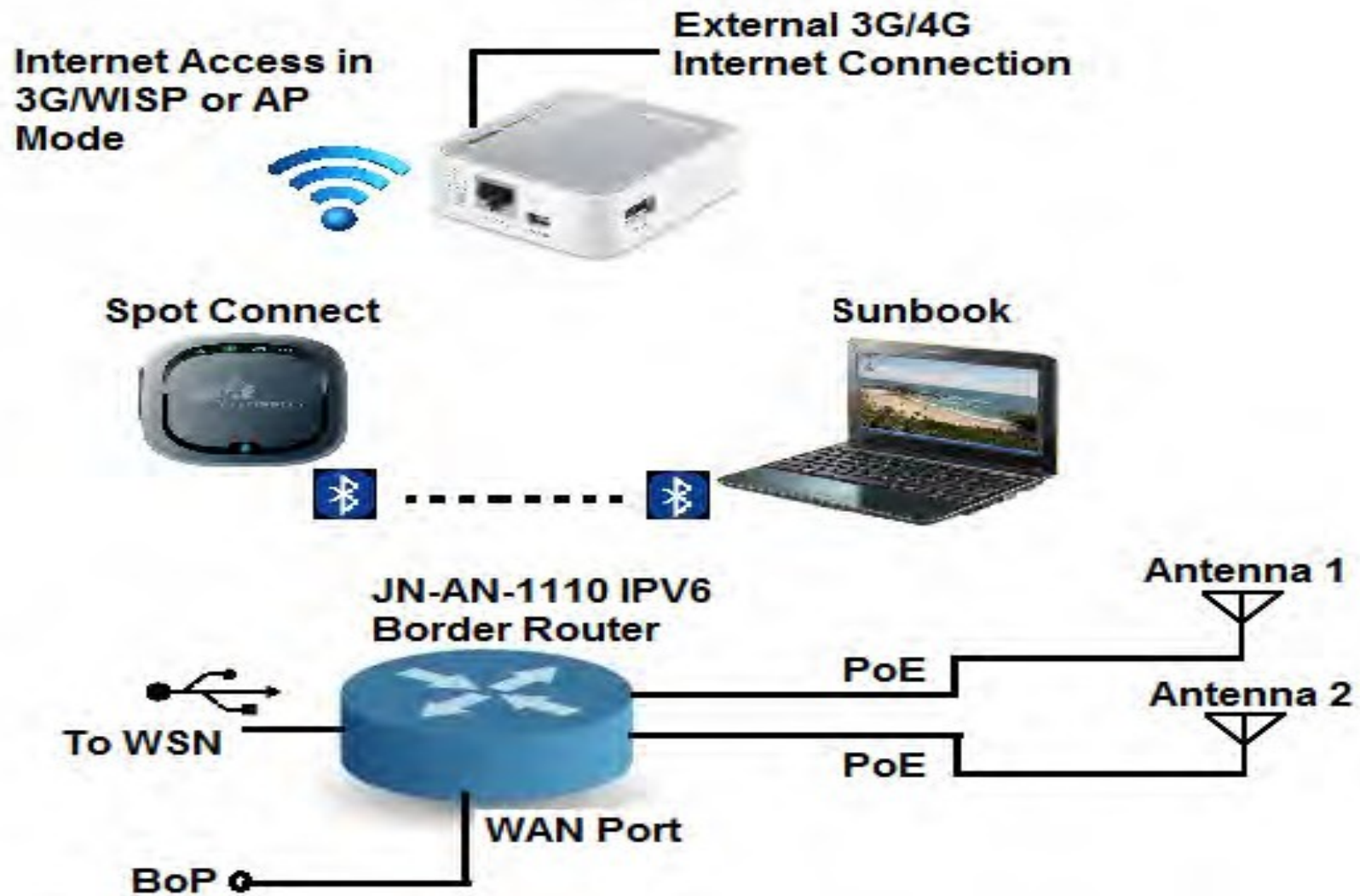
DEMO2: Interoperable Emergency Communications

- Interoperable Emergency Communications
 - Wireless Channel Emulation
 - Tx Signals (BPSK, QPSK, 16QAM, 64QAM)
 - Rx Signals (BPSK, QPSK, 16QAM, 64QAM) through the GG channel
 - Repeat for QPSK at 5 MHz, same GG channel segment
 - How to set the EB for a specific Run?
 - Antenna Patterns
 - How to set the RFX Antenna ?

HiDN Station Basic Configuration



HiDN Block Diagram



Device Names

- 3G Portable router: **TP-LINK TL-MR3020**
- 4.9-5.9 GHz radios
- Two **RF Antennas**
- Tablet or **laptop**
- Portable GPS Device: **SPOT Connect**

Portable router: TP-LINK TL-MR3020

- Important Features:
 - Shares a 3G/4G mobile connection, compatible with 120+ LTE/HSPA+/UMTS/EVDO 3G/4G USB modems
 - Wireless N speed up to 150Mbps
 - Three working modes: 3G/4G Router, Travel Router (AP), WISP Client Router
 - 3G/4G and WAN failover guarantees an "always-online" Internet connection.

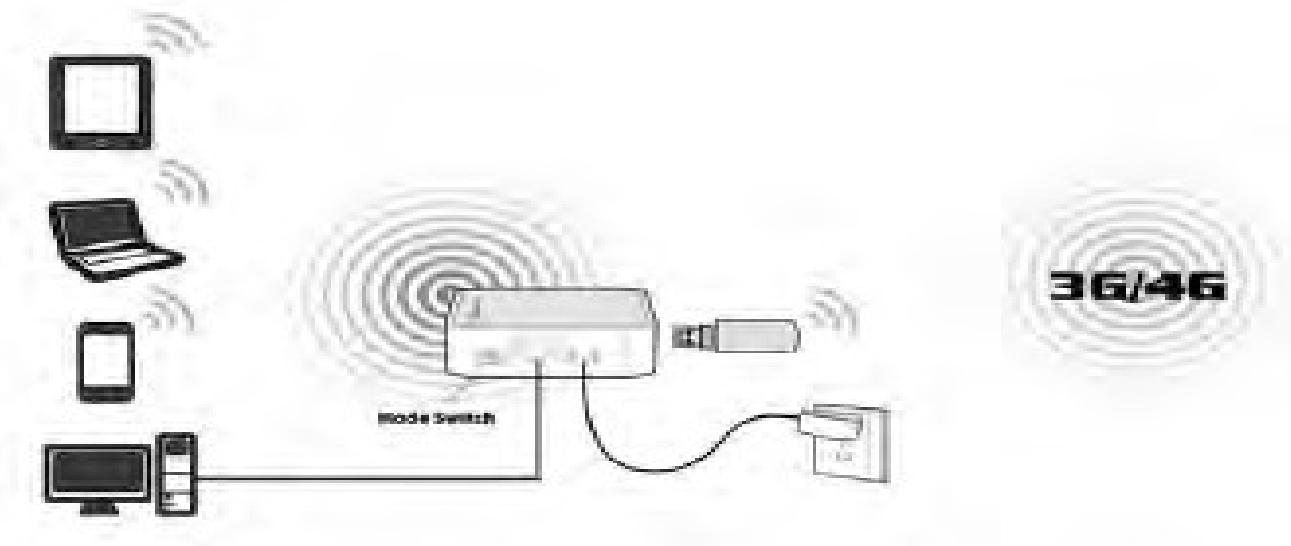
The General Working



TP LINK - MODES

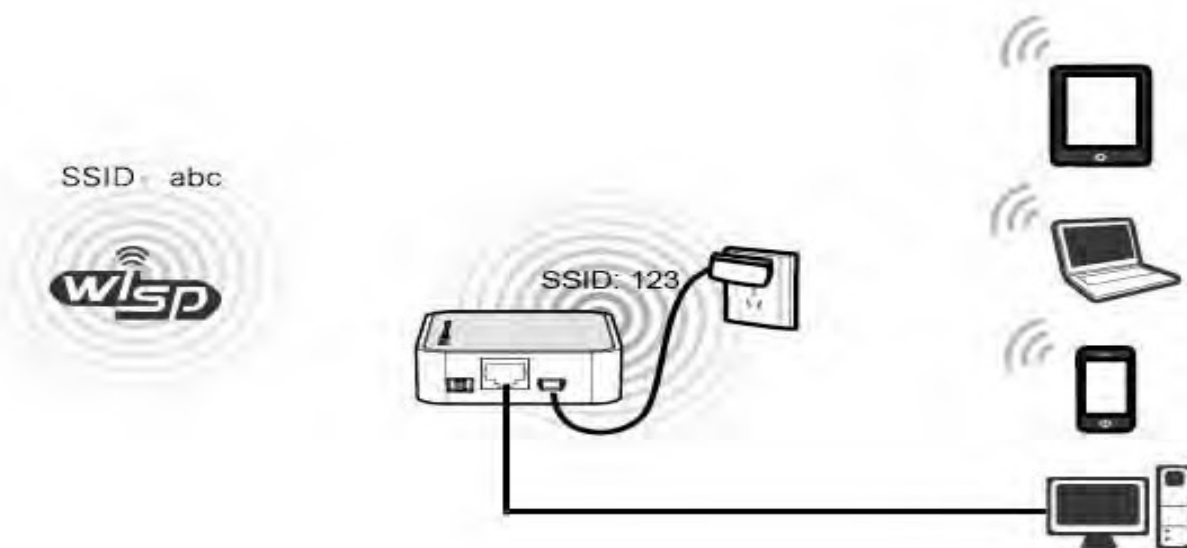
(A) 3G/4G Router Mode:

Operation - with a 3G/4G modem/card, it joins a 3G/4G network as well as act as a wireless central hub to broadcast its SSID. Using this other devices can join Internet.



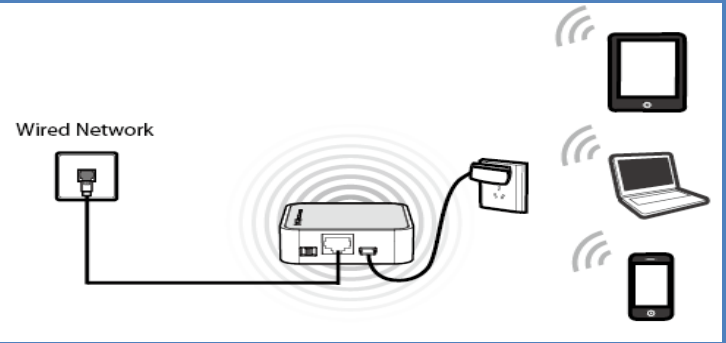
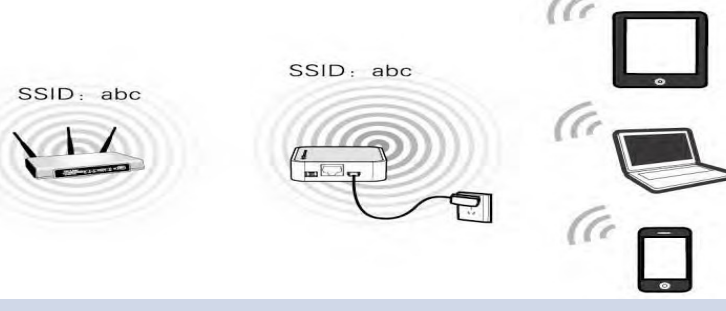

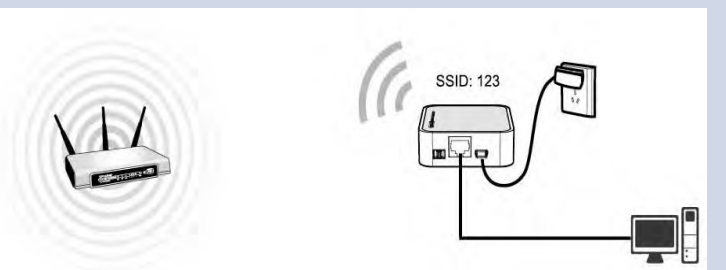
(B) WISP Mode:

- **Operation** - The Router will act as a wireless card to connect with WISP as well as a wireless central hub to broadcast its SSID for user wireless LAN clients, and the other wireless devices can connect to the Router for Internet connection.



(C) AP Mode

Operation - In AP mode, the Router will act as a wireless access point supporting four further modes, Access Point mode, Repeater mode, Bridge with AP mode and Client mode. These are shown in the table in the next slide.

Access Point (AP) Mode	Router will act as a wireless central hub for user's wireless LAN clients, giving a wireless extension for user's current wired network.	 <p>The diagram shows a router connected to a 'Wired Network' (represented by a wall outlet and a network switch). The router is also connected to a power source. It is emitting wireless signals (represented by concentric circles) to three wireless devices: a tablet, a laptop, and a smartphone.</p>
Repeater Mode	the Router can extend the coverage of another wireless Access Point or Router.	 <p>The diagram shows two wireless routers. The first router, labeled 'SSID: abc', is emitting signals. The second router, also labeled 'SSID: abc', is connected to the first via a power cable and is also emitting signals to a tablet, a laptop, and a smartphone.</p>
Bridge with AP Mode	Router can wirelessly connect two remote LANs together.	 <p>The diagram shows two wireless routers. The first router, labeled 'SSID: abc', is emitting signals. The second router, labeled 'SSID: 123', is connected to the first via a power cable and is also emitting signals to a tablet, a laptop, and a smartphone.</p>
Client Mode	the Router will act as a wireless card to connect with wireless network.	 <p>The diagram shows a wireless router connected to a desktop computer. The router is emitting signals and is labeled 'SSID: 123'. It is connected to a power source.</p>

TP Link: Few Facts

- Default IP Address: 192.168.0.254
- Default Subnet: 255.255.255.0
- SSID: TP-LINK_POCKET_3020_xxxxxx.
(xxxxxx is the last six characters of the router's MAC address.)
- Credentials: User name and Password - admin


Installing TP-Link

(A) In 3G/4G Mode:

A.1 PC Configuration

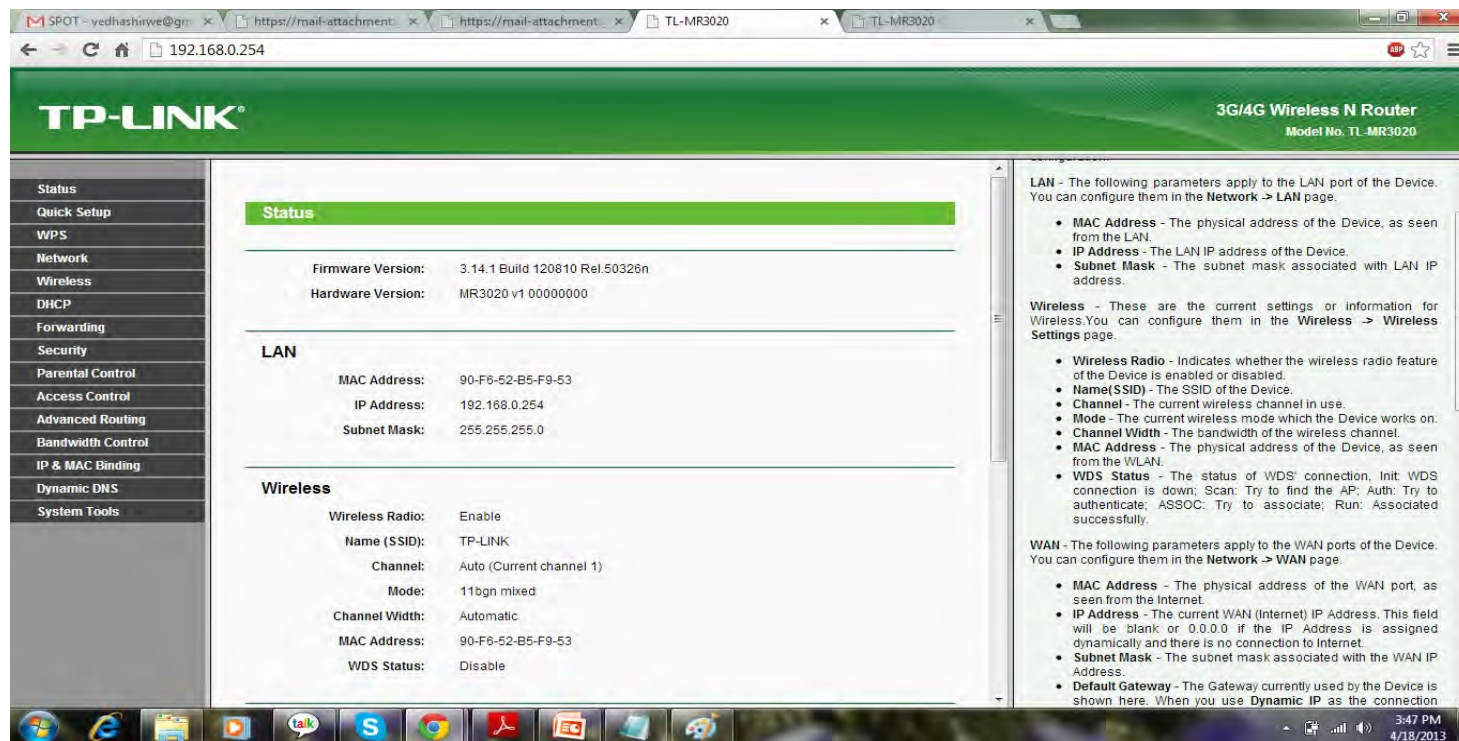
1. For Windows7 machines, follow the path, Start → Settings → Control Panel → View network status and tasks → Manage network connection. Right click Wireless Network Connection, and select Properties.
2. Select Internet Protocol Version 4 (TCP/IPv4).
3. Select “Obtain an IP address automatically” and “Obtain DNS server address automatically”. Click OK to finish the settings.

A.2 Connect to Network

1. Select the icon  at the bottom right corner of your machine.
2. Refresh the Network list and wait for TP Link device to appear.
3. If you get 'Connected' Message after clicking 'Connect', you are now on the wireless network.

A.3 Router Configuration

1. Open your Web Browser and type <http://192.168.0.254>
2. In the login window which appears, enter the default user name and password.
3. You should see following screen



4. Refer 3G/4G section on the status tab. It must say 'Identifies' for 3G/4G USB Modem and '100%' for the Signal strength.

3G/4G	
3G/4G USB Modem:	Identified
Signal Strength:	100%
IP Address:	10.185.139.127
Subnet Mask:	255.255.255.0
Default Gateway:	10.185.139.1
DNS Server:	198.224.174.135 , 198.224.173.135
Online Time:	0 day(s) 00:04:45
<div>Disconnect</div> Connected.	

5. Go to Quick setup tab and click Next.
6. Choose Internet Access type and click Next
7. Select your ISP (Verizon in this case) .
8. You can change Network name and password(by using WPA). Current password is mentioned on the next slide.

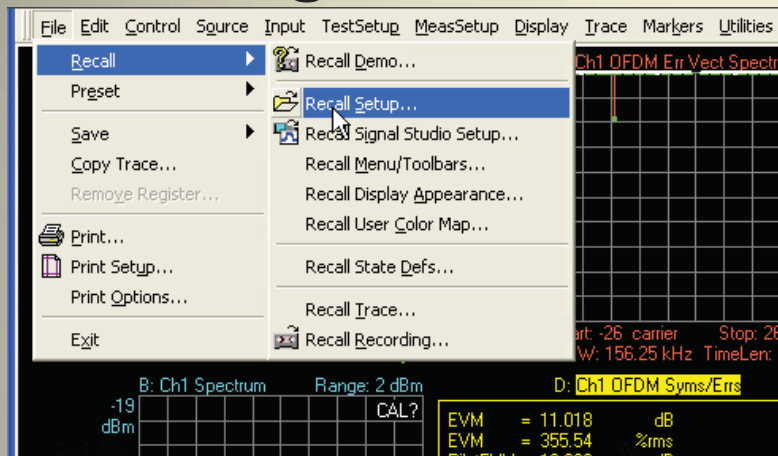
TP-LINK

- TP Link is the SSID of the already configured Wireless Network. I have configured it in 3G/4G Mode.
- Its WPA Password is FiRST.

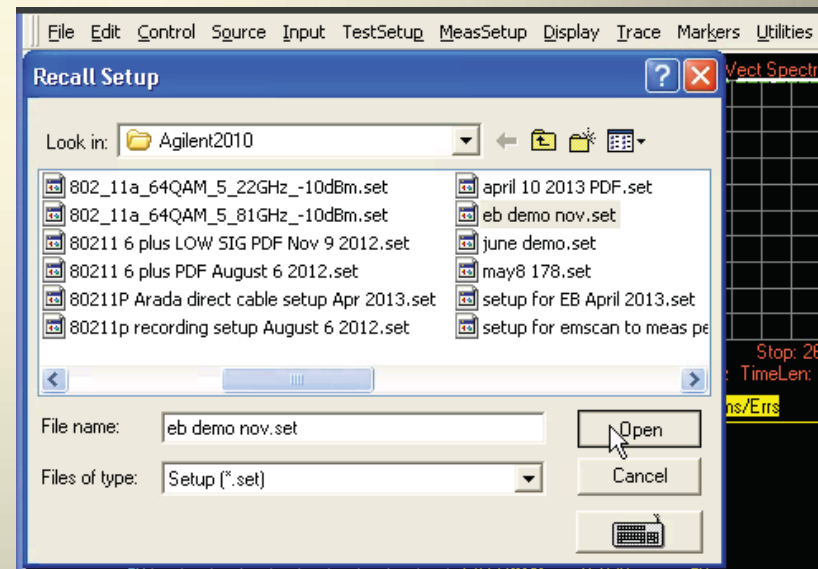
Agilent N9010 VSA

How to setup for these measurements

- In the Agilent click on File, Recall, Recall Setup

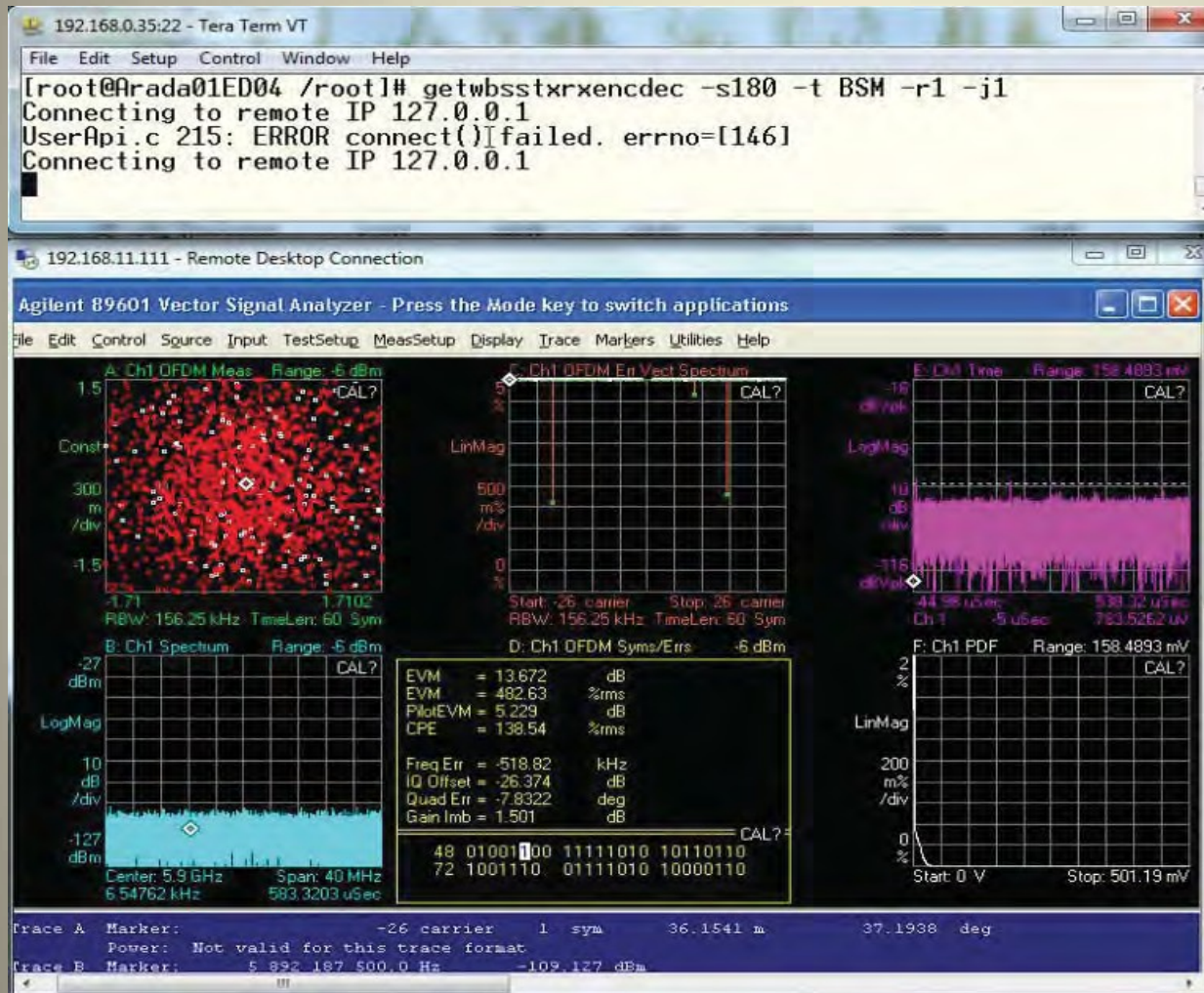


Select the file eb demo nov.set and click on Open. This loads all of the Agilent settings automatically for this set of measurements.



Set Trigger and Level for the Agilent

- Setting for direct connection from the Arada at 1dBm. When the signal comes from the EB it will be -50dBm, adjust these 2 values as needed



Arada at 1dBm:

Ch 1 Spectrum: 2dBm

Ch 1 Trigger: 2mV

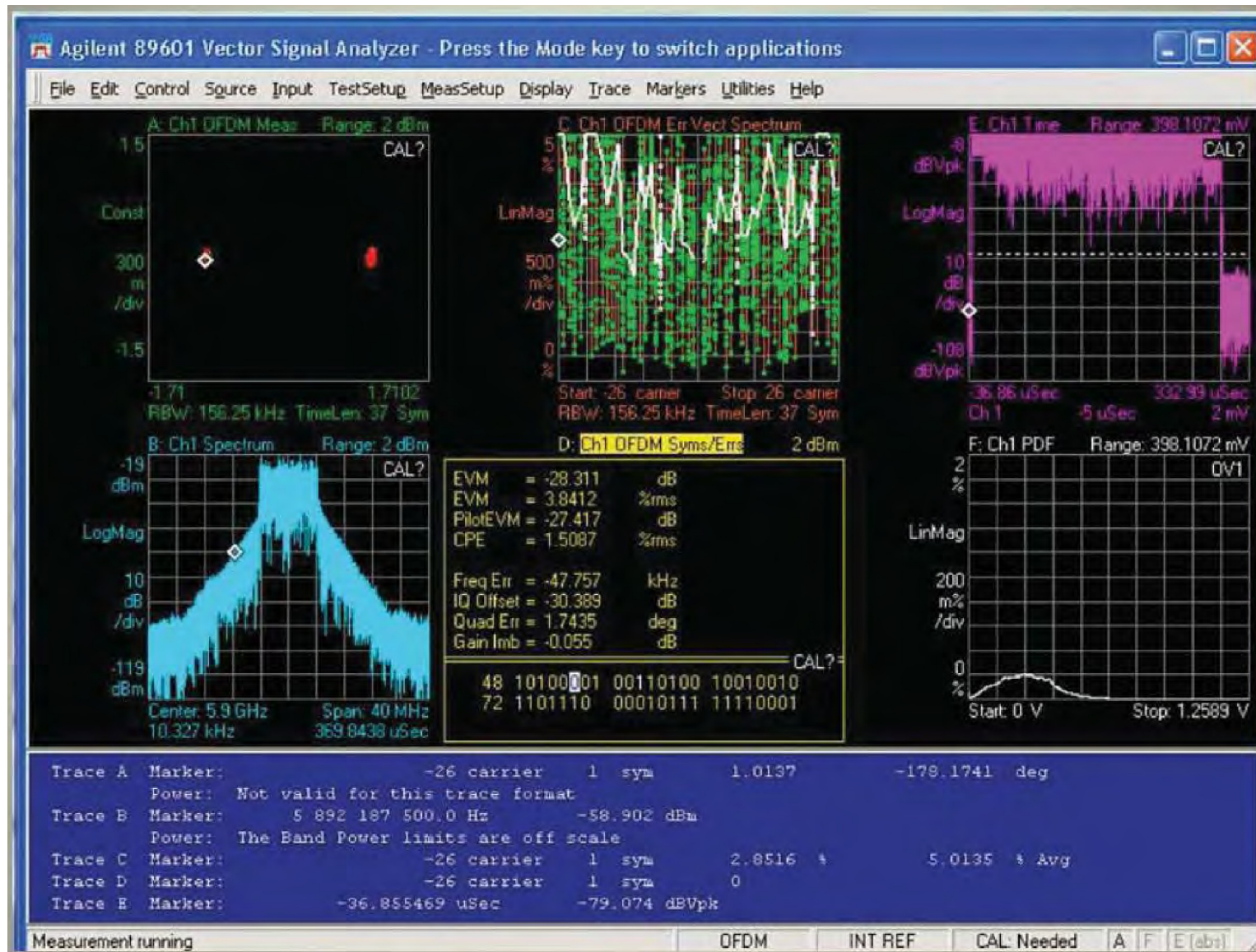
EB at -50dBm:

Ch 1 Spectrum: -50dBm

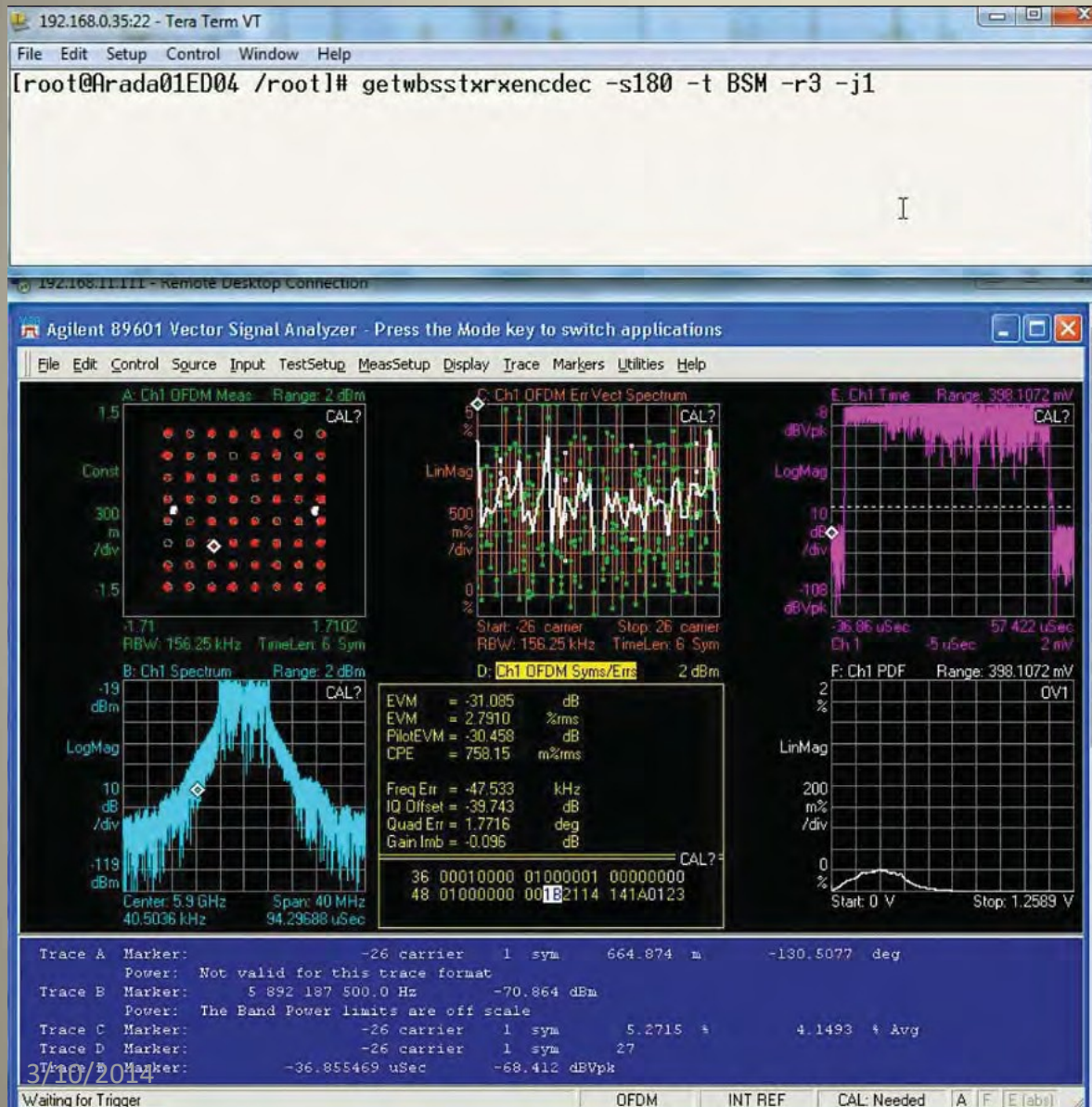
Ch 1 Trigger: 780uV

NOTE: Clicking on the value, the mouse wheel will adjust the setting

TX Signals, BPSK

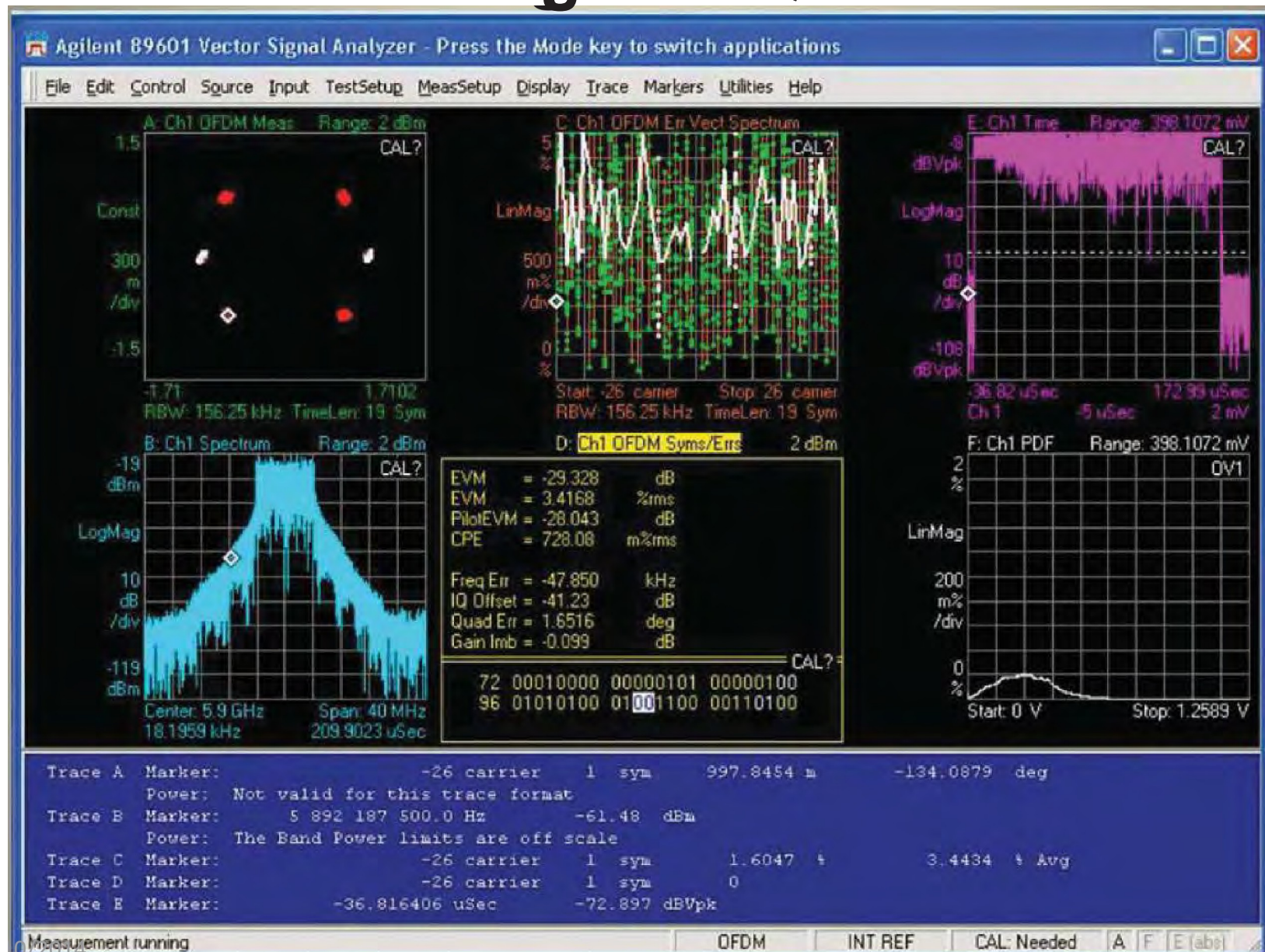


Direct TX output BPSK

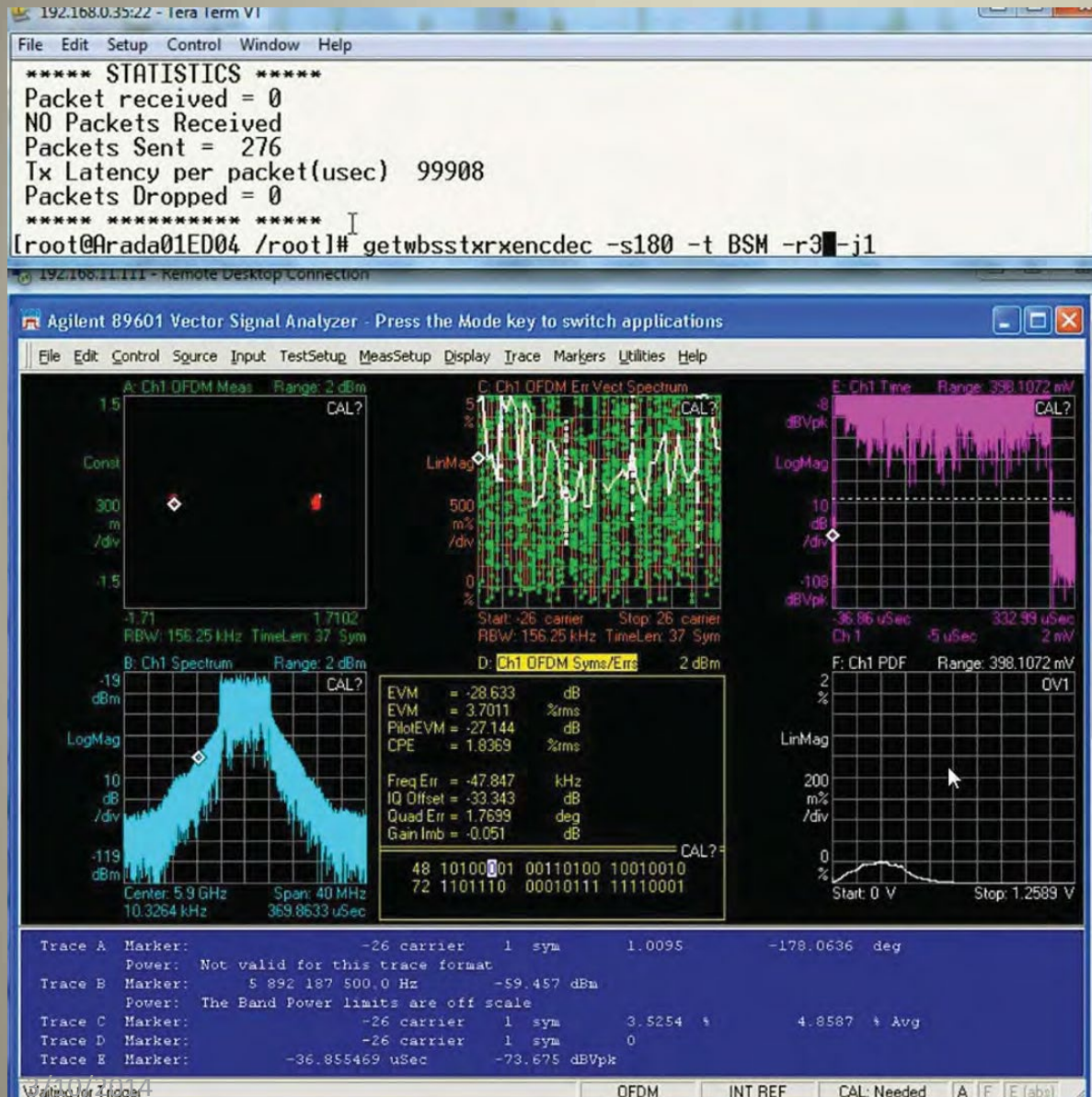


The Arada is programmed to Service channel 180, type BSM, rate of 3Mbps and 1dBm. The OFDM measurement will detect the change from 64QAM to BPSK and 2 dots will appear instead of the 8 x 8 pattern.

TX Signal Is QPSK



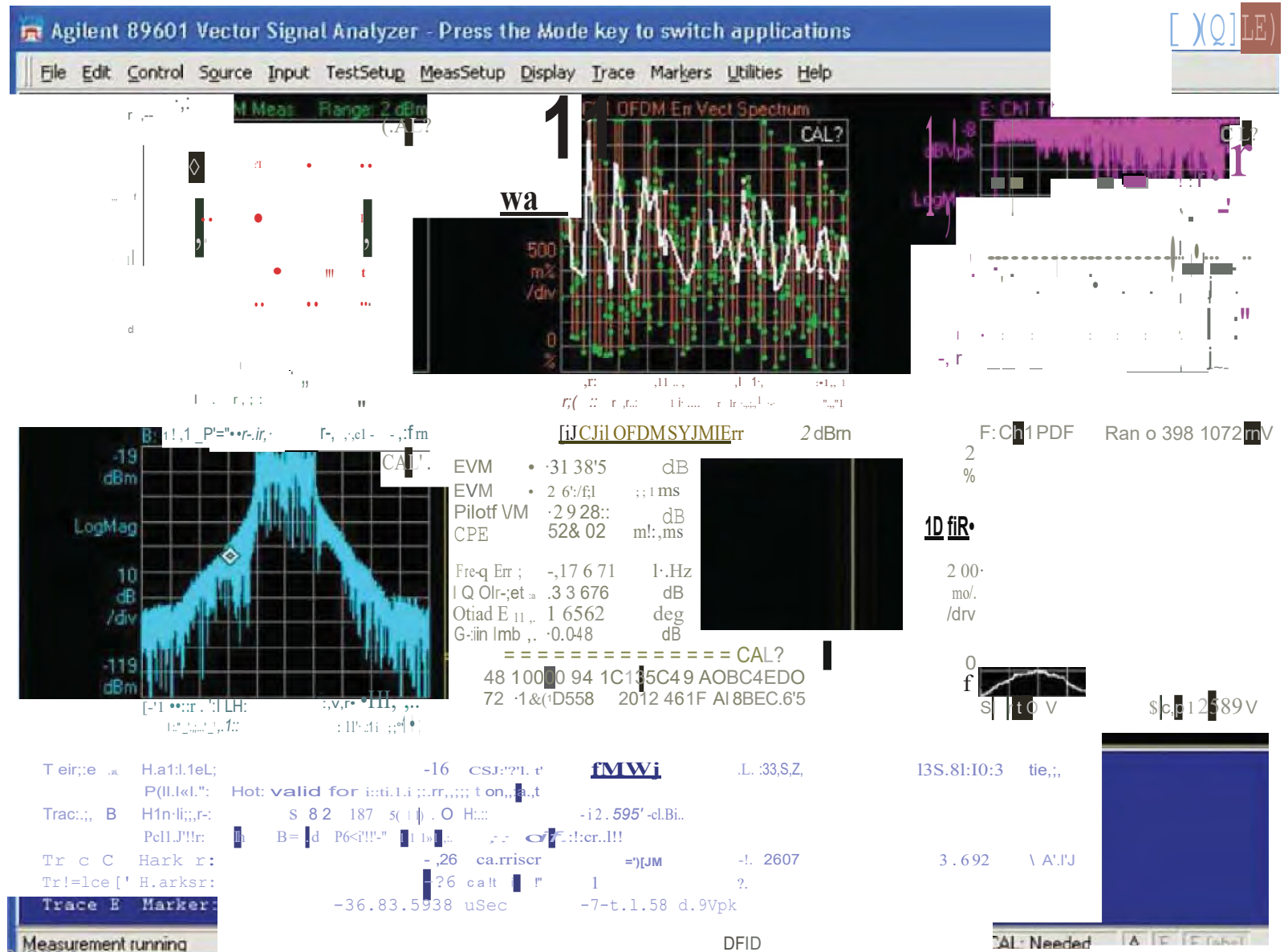
Direct TX output QPSK



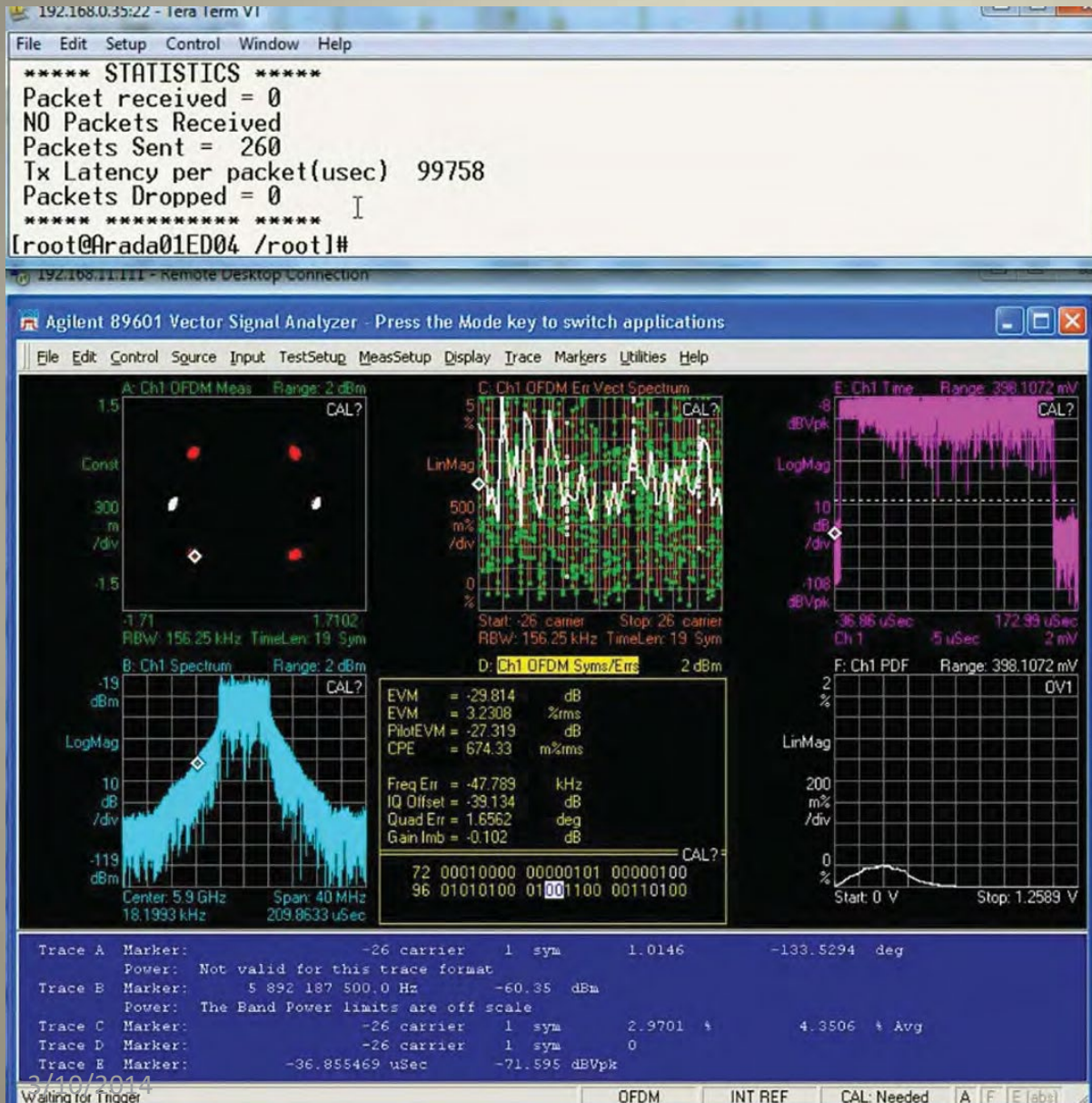
The Arada is programmed to Service channel 180, type BSM, rate of 6Mbps and 1dBm

The OFDM measurement will detect the change from BPSK to QPSK and 4 dots will appear with 2 index markers instead of the 2.

TX Signals 16QAM



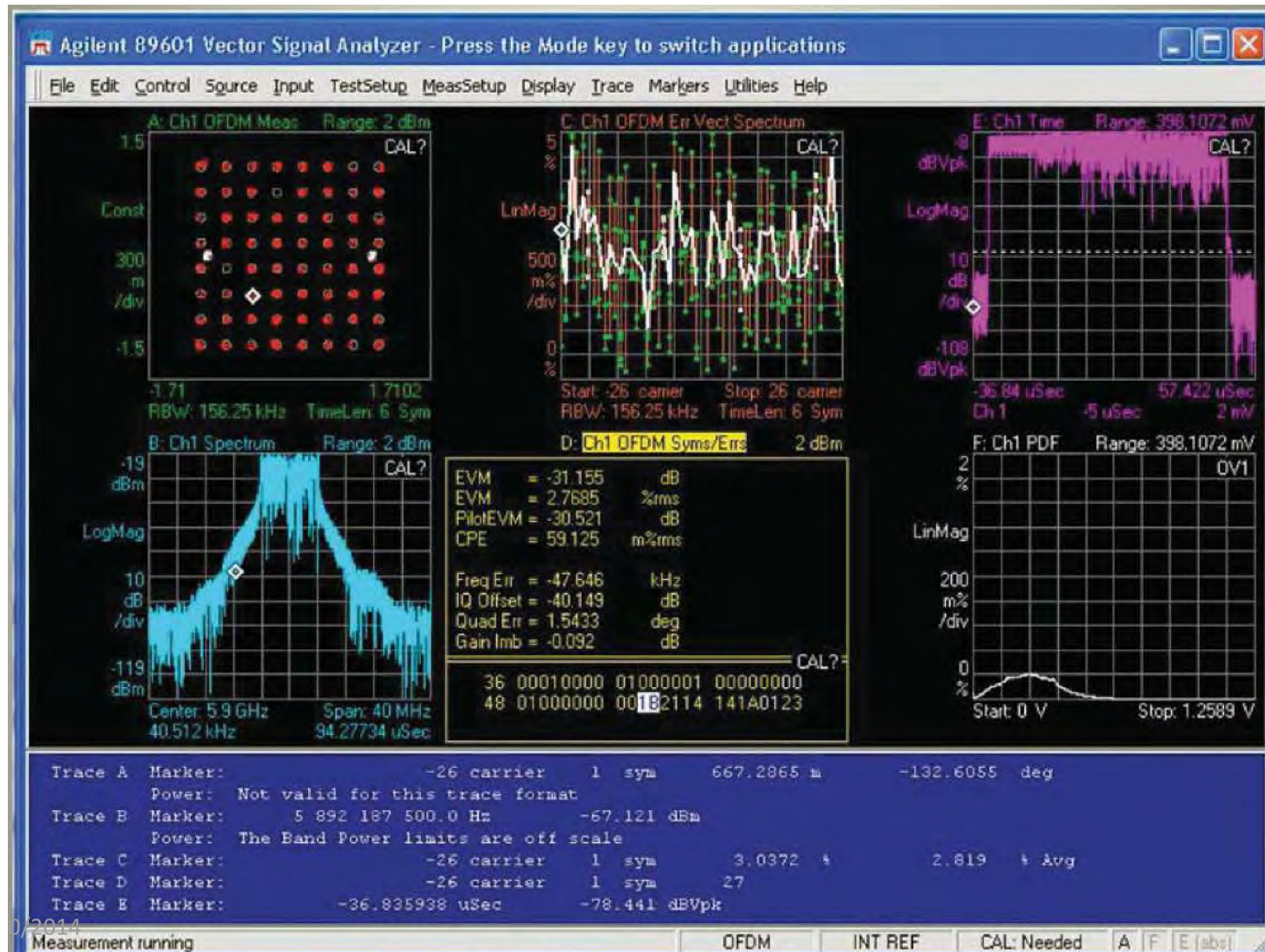
Direct TX output 16QAM



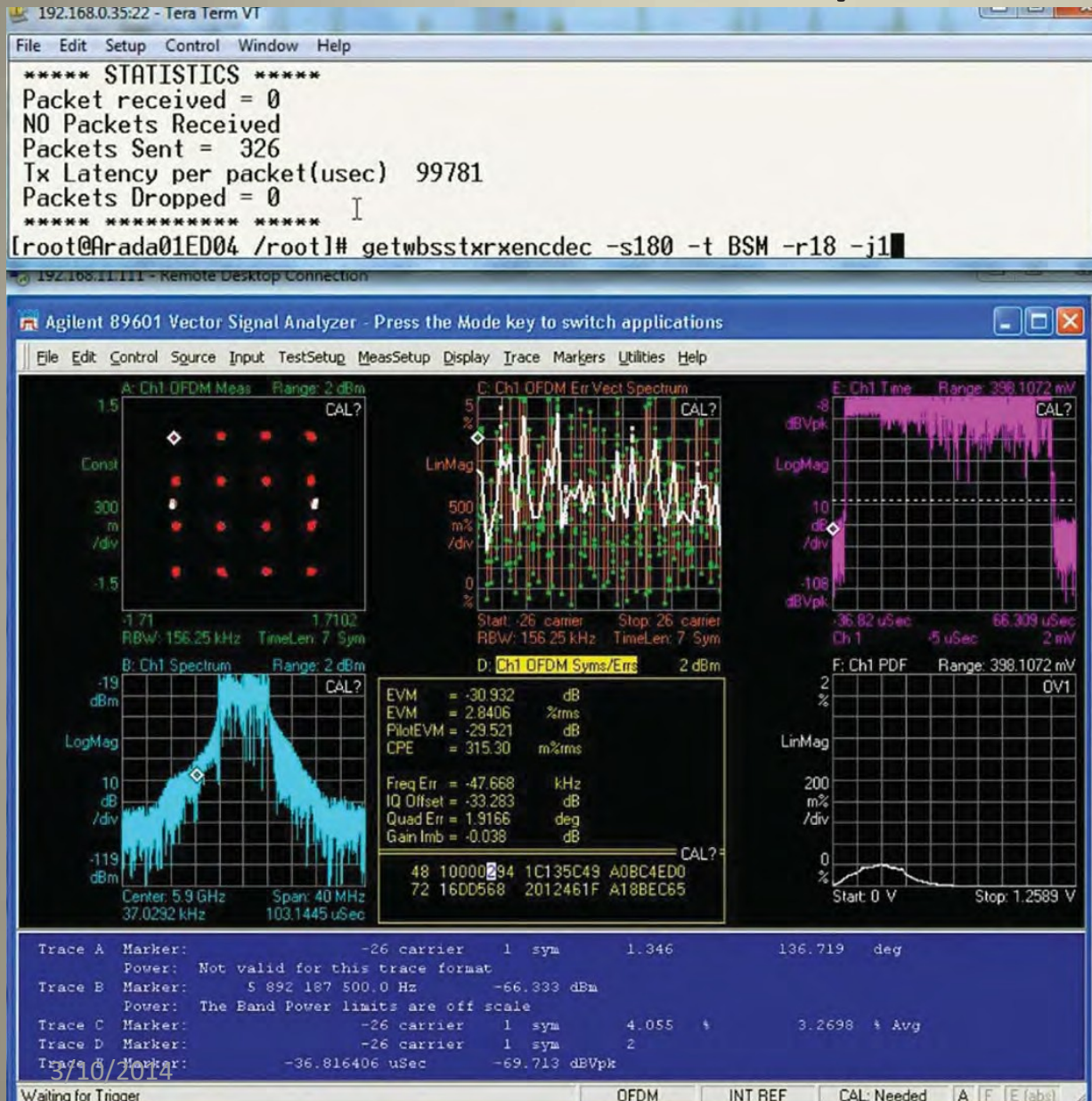
The Arada is programmed to Service channel 180, type BSM, rate of 18 MBps and 1dBm.

The OFDM measurement will detect the change from QPSK to 16QAM and 16 plus 2 dots will appear instead of the 6.

TX Signals 64QAM



Direct TX output 64QAM



The Arada is programmed to Service channel 180, type BSM, rate of 24 MBps and 1dBm. The OFDM measurement will detect the change from 16QAM to 64QAM and 64 plus 2 dots will appear instead of the 16.



**First Responder Support Systems Testbed (FiRST)
Contract # 65A0257
Cross-Cutting Cooperative Systems**

**TRACK IV – FiRST Baseline Enhancement and Maintenance
Wireless Sensor Networks for Cooperative Work Zone Safety
Final Report**

**Principal Investigator: Dr. Richard Church
Co-Principal Investigator: Dr. John Shynk
University of California Santa Barbara**

Contract Manager: Ramez Gerges, Ph.D., P.E.

Wireless Sensor Networks for Cooperative Work Zone Safety: Safety at work zones remains a serious concern for Caltrans. This research was in response to the loss of Caltrans workers on Highway 96 and other work zone fatalities. As we move into the “connected vehicles” environment, new challenges and opportunities are emerging. A cooperative system approach that integrates sensors and wireless communications and employ new localization algorithms will offer a new design for safer work zones in urban and rural areas.

This project provides the basis of innovative solutions to reduce Caltrans’ worker injuries and fatalities in work zones. Localization methods are critical to cooperative algorithms for sub-meter localization, we describe their use for two scenarios. The first scenario involves smart cones that are located along the work zone area, to directly detect dangerous events and alert Caltrans’ workers in work zones. In the second scenario, the nodes are vehicles traveling at high speeds on highways. It is assumed that vehicles can communicate with other vehicles and the infrastructure within the emerging “connected vehicles” environment. We address this class of localization algorithms that are able to fuse the data coming from neighboring vehicles and refine their own position estimates within a specific lane, and without the need for a dense fixed nodes along the roadside. In addition to the theoretical treatment, this report includes

FiRST Baseline Enhancement & Maintenance

ScreenCapture_1-7-2014 3:04:47 PM

The screenshot displays the FiRST software interface, which is used for traffic incident detection and response. The interface is divided into several functional areas:

- Communication and Display:** This panel on the left contains various settings and data. It includes a table for 'SAS-1' data:

SAS-ID	Displ Sens	Scale
SAS0001	24.00	0.45

 Below this is a 'Detector' section with 'Max Det Sensitivity' set to 2.0 and 'Min Det Sensitivity' set to 15.75. There is also a 'Lanes or Zones' table:

	5	4	3	2	1
Center	179	113	105	67	41
Size	3	11	7	19	31
Sens	0.00	4.00	4.00	3.00	3.00
Spd Cal	0	17	11	11	10
Occ Cal	0.60	0.40	0.50	0.50	0.55
- Detector:** This window shows a live video feed of a road with lane markings. It includes a 'Display Relays' section and a 'Stop' button.
- Real Time TAI Mode:** This window shows the 'Real Time TAI Mode Started...' status and a 'Lane Finder Reset < 120 Sec' button.
- Network Socket Connection:** This window shows the connection status to a remote host. It includes a 'Socket is Connected to Remote Host' message and a 'Keep This Window Open To Maintain Network' warning.
- Last 10 of 9457 Unreviewed Events:** This window displays a list of events. The first event is:

UID	Start Time	Event Name	Canidid's Name(s)	Canidid's Priority
101111	Tue Jan 14 10:50:05	East Gate	W1.1	100
- Main Video Feed:** The central window shows a live video feed of a road with a car. It includes a '100 Pixels' scale bar.
- Right Sidebar:** This area contains a list of camera feeds and their properties. The list includes:
 - mph (41)
 - mph (42)
 - mph (43)
 - mph (45)
 - mph (48)
 - mph (26)
 - mph (26)
 - mph (29)
 - mph (31)
 - 63144
 - 034pc21f1
 - 0347-afdc43b4c086
 - 14db07
 - mph (32)
 - mph (34)
 - mph (34)



Cooperative High-Accuracy Localization Algorithms for Low- and High-Mobility Nodes

A Final Report Submitted to
Division of Research, Innovation, and System Information
California Department of Transportation
Sacramento, CA 95814
from
Department of Electrical and Computer Engineering
University of California
Santa Barbara, CA 93106-9560

I. EXECUTIVE SUMMARY

As the transportation infrastructure ages, there is an increasing need for the maintenance and rehabilitation of the road network, which means there will be more work zones. Safety at work zones remains a serious concern for Caltrans, and research is lacking in addressing methods to directly detect dangerous events and alert Caltrans' workers in work zones. As we move into the "connected vehicles" environment, new challenges and opportunities are emerging. Workers' safety is not limited to urbanized areas; the recent loss of Caltrans workers on Highway 96 due to a landslide is a reminder of this class of hazards. A cooperative system approach that integrates sensors and wireless communications and employ new localization algorithms will offer a new design for safer work zones in urban and rural areas. There has been a surge of interest in using wireless technologies for both transportation and public safety. Recently, the FCC issued a new notice of proposed rule-making (NPRM 13-49) for wireless broadband spectrum. The US Department of Transportation is starting a new DSRC initiative focused on vehicle-to-infrastructure communication, and the US Department of Commerce is moving forward with the FirstNet wireless broadband initiative for public safety. Those challenges and opportunities require a trained workforce. The virtual wireless lab, and the modeling and testing infrastructure at the First Responder Support Systems Testbed (FiRST) has been leveraged to address these new opportunities.

II. INTRODUCTION

This project provides innovative solutions to reduce Caltrans' worker injuries and fatalities in work zones. The proposed architecture integrates wireless sensor networks (WSN) for reliable incident detection and alerting of workers via a heterogeneous wireless communications networks. In addition to the WSN, both DSRC (5.9 GHz) and public safety radios (PS-4.9 GHz) can be used to communicate with the emerging "connected vehicles" environment and CHP/EMS vehicles. The architecture employs the FirstNet (700 MHz-D Block) for wide-area public safety communications. A critical element for detecting hazards and alerting Caltrans workers is the use of high-accuracy localization algorithms. Two different localization subsystems were investigated to improve the safety of highway workers, as well as the driving public as they approach work-zone lanes in both urban and rural settings.

The first subsystem consists of a wireless sensor network of smart cones which includes a centralized master node, and are used in work zones to control traffic flow and protect construction and maintenance workers. The second subsystem performs localization of vehicles at normal highway speeds using cooperative techniques only between "connected vehicles" that form an ad hoc network, and without any fixed road-side nodes. Different sensors can be used for different hazard conditions and work environments. One sensor class detects car intrusion on urban work zones. The other class of sensors can be used to monitor and detect when hill-slopes are primed for sliding and provide early indications of rapid, catastrophic movement. Both sensor classes employ the same WSN platform and cooperative systems architecture, and Caltrans workers would receive real time alerts using Personal Safety Networked Sensors (PSNS).

Caltrans funded the development of the FiRST Testbed into a unique research facility ready to offer solutions for the above mission critical areas according to the published DRISI wireless research roadmap. The return on investment (ROI) in the FiRST Testbed materialized in realizing answers and deployable solutions to the above mission critical areas. Short term ROI is realized in deploying the PSNS and to save the lives of Caltrans workers. A long-term ROI will be achieved from developing an excellent workforce and maintaining a Caltrans competitive research advantage at the national level. This project leverages the simulation, lab, and field infrastructure at the FiRST Testbed to provide deployable solutions in order to save Caltrans workers' lives, improve safety, and increase mobility of the transportation network.

III. OVERVIEW OF LOCALIZATION APPROACHES

There has been much research in wireless communications over the last several years directed toward localization techniques that improve upon conventional methods based on the Global Positioning System (GPS). Most of these techniques involve some form of *cooperation* or collaboration among nodes, where they exchange position estimates with their neighbors in order to improve these

estimates. Since GPS signals provide a location accuracy of only 7 m for 97% of the time, other more sophisticated methods and signal processing techniques are needed to bring localization into the sub-meter range. Differential GPS (DGPS) and Network Real-Time Kinematic (NRTK) positioning can improve upon the location accuracy of GPS [1], but they mainly compensate only for ionospheric and tropospheric distortions. They do not correct for multipath distortion, which can be a significant channel impairment, especially in urban environments and for high-mobility nodes [2].

When there is significant multipath propagation, the received signal is a mixture of line-of-sight (LOS) and non-LOS (NLOS) waveforms which are necessarily delayed [3], [4]. As a result, the composite received signal has distortion and its power can vary over time, resulting in fading and even loss of signal for extended periods. Moreover, the additive noise of NLOS signals is no longer Gaussian; it is sometimes modeled as the sum of Gaussian and exponential random processes, resulting in an exponentially modified Gaussian distribution. This is important because adaptive algorithms such as the Kalman filter (KF) require a Gaussian noise model for accurate estimation. As a result, other techniques are required such as particle filtering (PF) [5].

In this report, we describe cooperative algorithms for sub-meter localization of nodes for two highway scenarios. The first scenario involves smart cones that are located along the highway where there is maintenance or construction work. The cones can communicate with each other, and there is a central node called a smart drum that collects the data from all smart cones, which can be fused and relayed to personnel within the cone zone. From this information, it is possible to construct a virtual map of the work area, which is updated when a cone is moved or accidentally displaced by a worker. The main purpose of this cone arrangement is to alert personnel of a potential problem if there is a sudden change to the virtual map caused by vehicles moving into closed lanes and hitting one or more of the smart cones.

In the second scenario, the nodes are vehicles traveling at high speeds on highways, which often tend to move in clusters so that neighbors can be designated within some radius extending from the center of a cluster. It is assumed that most of the vehicles are capable of estimating their own positions, and that information can be regularly broadcast to their neighbors [6]. The localization algorithms are able to fuse all the data coming from their neighbors, in order to refine their position estimates, and without the need for fixed nodes along the roadside. From these position estimates, it should be possible to detect when vehicles change lanes, even when the highway has significant curvature.

IV. REVIEW OF PREVIOUS WORK

A. Signal Propagation Models (References [10] and [11])

Reference [10], “Experimental Characterization of DSRC Signal Strength Drops,” describes a model for predicting null points for Dedicated Short-Range Communications (DSRC) on the basis of two-

wave ground reflections. Null points due to destructive interference were estimated within a range of ± 7 m, demonstrating a high accuracy of prediction and an improvement over existing analytical models and experimental data found in the literature. The model for the received power LOS distance depends on the transmitted power, the receive antenna gain, the wavelength, and a system loss factor. The NLOS path is more complicated, as it depends on the relative permittivity and the reflection coefficients for vertical and horizontal polarizations. The test equipment and parameters were as follows: (i) wireless safety unit (WSU) with integrated 802.11p-based wireless access in vehicular environments (WAVE) radio chip, (ii) omni-directional DSRC antenna, (iii) GPS receiver and antenna, (iv) wireless short messages (WSMs) sent with a 100 ms period, (v) 16 dBm transmit power, and (vi) 6 Mbps data rate. The following quantities were measured: vehicle position, speed, acceleration, heading, time stamp, and the receive signal strength indication (RSSI) obtained from the WSU. In an example experiment, the model derived a null point at 82.2 m, whereas experimentally it was observed at 78 m (outgoing) and 90 m (incoming). A packet success ratio (PSR) higher than 70% was found within distances less than 310 m. High errors in the model before the null point are probably due to multiple reflections from the vehicle itself. The results of paper [10] can be exploited to implement accurate signal propagation models for algorithm development and computer simulations.

Reference [11], “Use of RSSI and Time-of-Flight Wireless Signal Characteristics for Location Tracking,” attempted to determine the correlation between the error from time-of-flight (TOF) measurements and the error from RSSI methods. Any relationship between the two was expected to help associate probabilities in distance estimation for use in particle filtering (PF), but they discovered no such relationship. A particle filter was implemented to obtain upper and lower bounds for various simulated scenarios. Noise samples in the input and measurement were varied, and the maximum noise level from which it can recover and the number of particles were studied. It was found that the number of particles had no bearing on how long the algorithm took to stabilize. However, the final error after stabilization decreased with an increase in the number of particles. The following were observed: (i) RSSI showed a sharp decline for small distance variations and then was roughly linear. (ii) A high variation was found in the distance errors for RSSI, with spikes probably due to Rayleigh fading effects. (iii) The TOF computation overestimated the distance, and the magnitude of error did not vary as much as the error itself. The results in paper [11] are useful for our signal models in order to incorporate RSSI and TOF in the position estimation algorithms.

B. Vehicle Localization (References [7], [8], [9], [4], [1], and [5])

Reference [7], “Peer-to-Peer Cooperative Positioning, Part I: GNSS-Aided Acquisition,” describes sharing Global Navigation Satellite System (GNSS) aiding quantities like Doppler, satellite carrier-to-noise (C/N) ratio, and secondary code delay to facilitate improved and faster localization. The approach is similar to assisted GNSS but does not require additional infrastructure, and can be useful

in environments with adversely affected availability. This unstructured peer-to-peer (P2P) approach is also highly scalable and robust in heterogeneous time-varying networks, without a control or data fusion center or P2P ranging. Vehicles are assumed to be equipped with P2P networking capabilities and GPS. In a centralized cooperative approach, data are collected from all receivers, and then enhanced data are returned to all receivers. Mean acquisition time (MAT) simulations were conducted, for light indoor and open sky conditions, and pedestrian and vehicular mobility. The results show that the performance of the P2P approach is equivalent to assisted GNSS, but offers the advantages mentioned above. In order to combine the information coming from different peers, the following methods of weighting were proposed: (i) uniform weights, (ii) weights related to the aiding quality, (iii) weights related to the distance, and (iv) a closest peer approach.

Reference [8], “Peer-to-Peer Cooperative Positioning, Part II: GNSS- Hybrid Devices with GNSS and Terrestrial Ranging Capability,” is a continuation of the previous paper that develops a hybrid system capable of fusing GNSS positioning and a local ranging system to obtain the best localization information. Again, it is assumed that every node (vehicle or pedestrian) has the capability of GNSS localization and has a short-distance ranging system. It is suggested that fully decentralized versions of these algorithms can be developed with each node having capabilities of fusing data on its own. The different information sources are merged using estimation algorithms such as the KF, PF, or a least-squares (LS) estimator. Using previous knowledge of the transmitted power, environmental variables, and received signal strength, the distance is estimated by inverting a path loss model, though it turns out that the accuracy achieved using this method is generally not acceptable. The intra-node TOF distance is estimated by taking into account the speed of light and measuring the time difference between the transmitted and received signal. Several estimation algorithms were considered: (i) LS, which is simple to implement, (ii) extended KF (EKF), due to the nonlinear model, (iii) unscented KF (UKF), which can perform better than the EKF, (iv) PF, which was initialized by a simple KF, and (v) sum-product algorithm over a wireless network (SPAWN), of which a hybrid version is proposed in the paper. Particle filtering provided the best performance, and the system had the following advantages: (i) dramatic improvement in localization in areas without GPS, (ii) no data fusion is required, and (iii) nodes with a priori positioning are not needed. Papers [7] and [8] are mostly tutorial in nature, but they include several approaches which were for our two mobility scenarios, such as PF and signal information such as RSSI and TOF.

Reference [9], “Performance Assessment of Cooperative Positioning Techniques,” presents an overview of the performance of cooperative positioning (CP) algorithms. Novel CP schemes for various communication architectures were investigated via a performance analysis for centralized and distributed approaches. In the centralized approach, ten users could interact and exchange information moving over an area of $100 \times 100 \text{ m}^2$ according to a random walk mobility model. WiFi hotspots were placed in such a way that two of them could be accessed on average, and P2P interaction between

users was realized by a short-range communication system. In the distributed approach, intricate ranging and distributed positioning procedures were based on two CP protocol transactions and time-of-arrival (TOA) estimation in low data-rate impulse-radio ultra-wideband (IR-UWB) networks. These CP approaches are expected to adequately cover emerging short-range applications requiring P2P communications, through mesh networking and precise indoor location. It was shown that the proposed CP schemes can significantly improve the accuracy of positioning information in different scenarios. Specifically, the availability in a WiFi scenario can be increased by centralized CP techniques. Our work also involves collaborative wireless communications between nodes (vehicles and smart cones), as well as fixed locations such as roadside nodes.

Reference [4], “Improvements in Terrain-Based Road Vehicle Localization by Initializing an Unscented Kalman Filter Using Particle Filters,” develops an algorithm to initialize a UKF using a PF for applications with initial non-Gaussian probability density functions (pdfs). The method was applied to estimating the position of a vehicle along a one-mile test track and a 7 km span of a highway using terrain-based localization where the pitch response of the vehicle was compared to a pre-measured pitch map for the road. Data were collected using DGPS, and the UKF operated until a desired threshold of performance was achieved. The UKF vehicle positioning algorithm was shown to be capable of localizing a vehicles longitudinal position with sub-meter accuracy and with a significant reduction in computations compared to PF. We also used PF for position estimation, but instead can be initialized by an EKF or UKF, not vice versa as in this paper. For the high-mobility scenario, we believe that PF will yield better performance than a UKF, though with a greater complexity that depends on the number of particles needed. Other papers suggest that PF offers more accurate results than any of the KF-based approaches.

Reference [1], “Hybrid Cooperative Positioning Based on Distributed Belief Propagation,” proposes a novel cooperative positioning algorithm that fuses information from satellites and terrestrial wireless systems, and is suitable for GPS-challenged scenarios. The proposed message-passing algorithm is SPAWN mentioned above in Reference [8]. The mathematical formulation is as follows: (i) Mobility is modeled as a Markov process, which is independent of that in other nodes. (ii) The measurement likelihood depends only on the current state and can be split into two factors, since range and pseudo-range measurements are independent. (iii) Pseudo-range measurement noise samples are independent across nodes but with known variances. (iv) Range measurement noise samples are also independent, but with symmetric link variances that are known by node pairs. The resulting SPAWN algorithm combines terrestrial ranging from neighboring peers and pseudo-ranging from visible satellites, and provides an estimate of a posteriori distributions of a nodes position. Simulation results show the superior performance of SPAWN compared to competing algorithms, such as LS and the KFs. Our work also improve GPS localization performance using cooperative techniques among vehicles. A Markov model can be used to give probabilistic estimates of vehicle lane positions.

Reference [5], “Distributed High Accuracy Peer-to-Peer Localization in Mobile Multipath Environments,” focuses on multipath interference which is prevalent in cities and urban canyon environments, and is a challenge for high-accuracy localization of fast-moving vehicles. Multipath tends to dominate the received signal, which is no longer Gaussian in nature. This paper proposes a P2P architecture where nodes collaborate with each other to refine their position estimates. It assumes that each vehicle is equipped with a sensor capable of receiving TOAs from surrounding vehicles and anchor nodes. Each measurement is modeled as an LOS signal with Gaussian noise or an NLOS signal with Gaussian plus exponential noise. Each vehicle is assumed to be equipped with an accelerometer and a magnetometer. A graphical model was implemented where each vehicle and anchor is treated as a node, and hidden nodes and vehicle positions are estimated using a PF. At every time instant, each vehicle receives estimated locations from its neighbors and its own location using a particle filter. Simulations demonstrate that the PF accurately estimates vehicle locations in high NLOS environments, and there is an improvement in localization performance if more anchor nodes are added to the model.

C. Lane Position (References [2] and [3])

Reference [2], “Co-operative Lane Level Positioning Using Markov Localization,” proposes using inter-vehicle cooperative communication systems to improve road traffic efficiency and safety in multipath environments, without the need for complicated processing algorithms or high-accuracy sensors. It is assumed that most vehicles are equipped with GPS receivers, and they can communicate with each other by sending information regarding position via an ad hoc network. Using the available position data, a Markov chain model is used to find the lane positions of the vehicles and determine when lane changes occur. Each vehicle has a conditional probability for each of the possible lanes, and these are adapted over time using sequential prediction and correction steps. In simulations conducted to validate the algorithm, GPS data were collected from each vehicle, and the performance was improved using a PF fused with a Butterworth filter to remove noise. The results show that this simple localization method works well compared to other methods which use more complex processing techniques or expensive sensors.

Reference [3], “Real-Time Experiment in Markov-Based Lane Position Estimation Using Wireless Ad-Hoc Network,” is a continuation of the previous paper that focuses on the low-pass Butterworth filter and PF for GPS noise rejection. The vehicle localization software included the following threads: (i) Server thread for sending GPS data to other vehicles. (ii) Client thread for receiving GPS data from other vehicles. (iii) GPS thread for reading GPS measurements from sensors. (iv) Filters for rejecting receiver measurement noise. (v) A localization algorithm for lane position estimation using the Markov model. The GPS data were processed by the particle and Butterworth filters to reject noise and reduce errors due to ionospheric effects, a lack of visible satellites, and multipath. The

PF compensates for the delay introduced by the Butterworth filter used to remove high frequencies. Simulations show that the Markov localization algorithm with filtering works well even without prior knowledge of the initial lane positions, and by using low-cost GPS receivers instead of more expensive sensors. A similar Markov model can be incorporated in our receiver algorithms in order to estimate vehicle lane positions.

V. COOPERATIVE LOCALIZATION USING SMART CONES

A. Introduction

In this section, we describe a high-accuracy localization algorithm that improves the safety of roadway workers. The proposed system consists of a wireless sensor network (WSN) of smart cones that includes a centralized master node and several sensor nodes. The master cone maps the topology of all sensor cones placed along the periphery of a work zone, with the goal of providing decimeter location accuracy. The low-mobility smart cone network can detect vehicles that intrude on a work zone, alert construction workers of impending danger, and notify high-mobility vehicles approaching the work zone. The master cone creates a work zone topology by estimating angles and distances relative to the sensor cones using radio interferometric measurements (RIM) and received signal strength indication (RSSI) measurements. Computer simulations characterize the performance that can be achieved for realistic environment conditions.

The recent increase in worker fatalities and injuries in roadway construction and maintenance zones across California is a serious concern for the California Department of Transportation (Caltrans). In order to offer an improved level of safety as well as mobility services in work zones, we describe a high-accuracy localization algorithm in this paper. Currently a work zone is protected from vehicle intrusion by warning approaching vehicles using traffic signs placed well ahead of the construction area. Cones are placed close to the impacted lane(s) in order to reduce the driving space within the construction zone. However, at high speeds there have been cases where drivers miss these warnings and intrude on the work zone by hitting the cones. There are other indirect ways of alerting drivers, for example by broadcasting information on a changeable message sign (CMS). Most of the research addressing work-zone safety is vehicle-centric [15], [16], [17], requiring that vehicles give more space to workers, and the algorithms do not directly alert workers to give them time to avoid injuries. The approach in this paper is work-zone-centric with a focus on worker safety, and is achieved by alerting them to dangerous situations.

We describe a cooperative algorithm for sub-meter localization of nodes in a WSN [13] that involves *smart cones* located along the roadway where there is maintenance or construction work. A master cone collects data from all surrounding sensor cones and communicates it to personnel through a work zone station. From this information, it is possible to construct a virtual map of the work area that is continuously updated. If there are any changes to this map, for example caused by an intruding

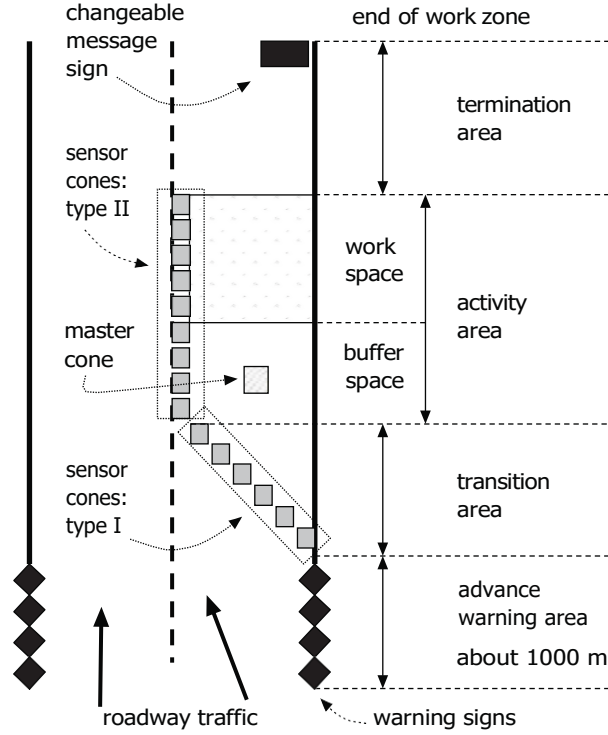


Fig. 1. Work zone and smart cone placement.

vehicle or when a cone is accidentally displaced by a worker, alert signals are transmitted.

We use a radio interferometric technique (RIM) for determining bearings from the master node to several sensor nodes at unknown positions in the network. By grouping various network nodes for RIM, a virtual antenna array is formed from which phase differences between two received signals can be used to estimate their angle of arrival (AOA) [18]. To obtain distances between the master and sensor cones, we use RSSI measurements [11]. In computer simulations, path loss models for various scenarios are based on measurement results carried out within WINNER [19]. Together, these distances and AOAs allow the network topology to be created from which vehicle intrusions can be detected.

B. Work Zone Layout and Smart Cones

A typical work zone layout is depicted in Figure 1, which consists of an advance warning area, transition area, activity area, and termination area [20]. This temporary traffic control zone includes the entire section of roadway between the first advance warning sign and the last traffic control device, where traffic returns to normal flow and conditions. In the advance warning area, drivers are informed about the construction zone, and in the transition area, traffic flow is channelized to a new

path. The activity area is where construction takes place, and it consists of two distinct sub-areas: the buffer space and work space. The termination area allows vehicles to return to normal conditions, and there may be a CMS at the end of the workzone.

There are three types of smart cones in the network: one master cone, several type I sensor cones, and several type II sensor cones. The master cone is located within the buffer space of the activity area where there are no workers, type I sensor cones are located in the transition area, and type II sensor cones are located all along the activity area up to the termination area. The master cone has three important functions: (i) accurately estimate its own position, (ii) estimate the spatial configuration of all sensor cones in the work zone, and (iii) create a topology of sensor cones in order to detect any sudden changes and to receive interrupts due to vehicle intrusions. The three types of cones are equipped as follows.

Master Cone:

- ZigBee[ⓧ] with 3 tags, one for each axis denoted by $\{M_x, M_y, M_z\}$ [18] as shown in Figure 2. This is used to estimate the phase differences and signal strengths of the transmitted signals from the sensor cones.
- Inertial measurement unit (IMU) with accelerometer and optional gyroscope and magnetometer. This is used to obtain the orientation of the master cone with respect to the horizontal plane.
- Global Positioning System (GPS) with NTRIP (networked transport of RTCM via internet protocol) and DGPS (differential GPS) support, which allows the master cone to estimate its position with sub-meter accuracy. (RTCM is the Radio Technical Commission for Maritime Services.) The accuracy of standard GPS is only about 10 meters (m), but this can be improved by using phase correction with NTRIP data and offset correction using DGPS data.

Sensor Cone Type I:

- ZigBee[ⓧ] with one tag denoted by R . This is used to provide the measured phase and signal strength of signals transmitted to the master cone.
- IMU accelerometer with optional gyroscope and magnetometer, which can generate an interrupt. This is used for motion detection when there is an unexpected collision due to vehicle intrusion. The interrupt notifies the master cone to generate an alert.

Sensor Cone Type II:

- ZigBee[ⓧ] only, with one tag denoted by R . This cone is similar to type I, but without an IMU for cost effectiveness.

C. Radio Interferometric Measurements (RIM)

In order to determine the AOAs of the transmitted radio frequency (RF) signals between the various cones, several measurements are collected. From RIM, the goal is to estimate the time differences of arrival (TDOAs) between the individual tags $\{M_x, M_y, M_z\}$ that form a virtual antenna array. These

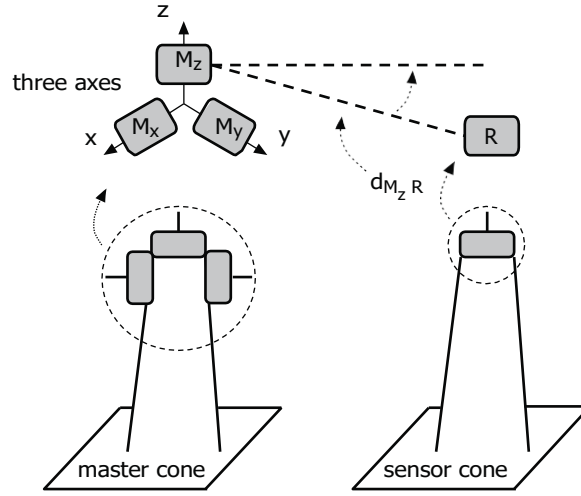


Fig. 2. Cone structures and antenna orientations.

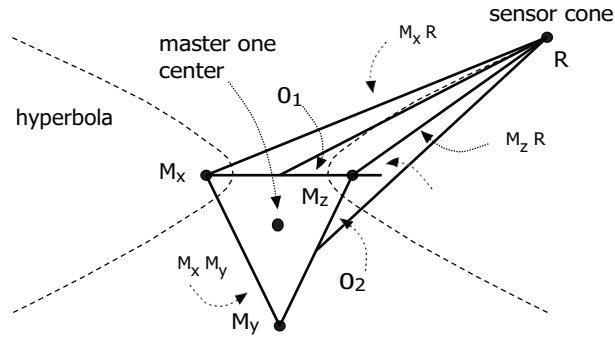


Fig. 3. Angles and distances based on a hyperbola. The three tags of the master cone are equally spaced: $d_{M_x M_y} = d_{M_x M_z} = d_{M_y M_z} = \sqrt{3} d$. The distance between the center of the master cone and sensor cone R is denoted by d_{RSSI} because it is estimated using RSSI.

angles along with the distance measurements provided by RSSI allow the network to detect changes in the cone topology. The measurements are obtained using the following sequence of events (see Figure 3 for the three angles):

- M_z and M_x transmit, M_y and R receive, θ_1 is estimated.
- M_z and M_y transmit, M_x and R receive, θ_2 is estimated.
- β is estimated by averaging θ_1 and θ_2 .

These are repeated as part of the localization algorithm described in a subsequent section.

D. Time Difference of Arrival (TDOA)

TDOA defines a hyperbolic relationship between the transmitter and a receiver as shown in Figure 3 [18]. Various distances are defined; for example, the distance between M_x and R is $d_{M_x R}$, and the distance between the center of the master cone and R is d_{RSSI} . These distances and the angles between M_x , M_z , and R define a hyperbola that intersects R , with an asymptote that passes through the midpoint of the line between M_x and R . Observe in the figure that M_x and M_z are located at the foci of the hyperbola. We are interested in angles θ_1 and θ_2 , as determined by the line from R to the midpoint between M_x and M_z , and likewise to the midpoint between M_y and M_z . From these results, the AOA β between the master cone and a sensor cone is estimated as the average of θ_1 and θ_2 .

The phase differences between tags on the master cone and a sensor cone are defined as follows:

$$\Delta\phi_1 = \phi_R - \phi_{M_x}, \quad \Delta\phi_2 = \phi_R - \phi_{M_y}, \quad (1)$$

where ϕ_R is the receiver phase at the sensor node, and likewise for the other phases. Two methods for estimating these are as follows:

- Beat frequency between two high-frequency carriers.
- Using ZigBee[®] sensor nodes at 2.4 GHz with special firmware.

For the latter case, the transmitter from a tag of one cone sweeps between 2.4 and 2.483 GHz, and the receiver of another tag (either on the master cone or a sensor cone) measures the phase of the incoming frequencies. The transmitter and receiver roles are then reversed and the phase is measured again.

From distance measurements, we have for the first phase difference with RF or beat frequency wavelength λ [18]:

$$\Delta\phi_1 = (2\pi/\lambda)(d_{M_x R} - d_{M_z R}). \quad (2)$$

Rearranging this expression gives

$$d_{M_x R} - d_{M_z R} = \Delta\phi_1 \lambda / 2\pi, \quad (3)$$

from which the desired angle is

$$\theta_1 = \tan^{-1} \frac{d^2 - (d_{M_x R} - d_{M_z R})^2}{(d_{M_x R} + d_{M_z R})^2}, \quad (4)$$

where d is the distance between any two tags on the master cone (see the caption of Figure 3). Although θ_1 has been written in terms of distances between the cones, we find they are not needed because the measurement $\Delta\phi_1$ is available and d is fixed and known. Substituting (3) yields

$$\theta_1 = \tan^{-1} \frac{4\pi^2 d^2 - \Delta\phi_1^2 \lambda^2}{\Delta\phi_1^2 \lambda^2}. \quad (5)$$

Likewise for the other phase:

$$d_{M_y R} - d_{M_z R} = \Delta\varphi_2 \lambda / 2\pi, \quad (6)$$

which gives a similar expression for θ_2 :

$$\begin{aligned} \theta_2 &= \tan^{-1} \frac{d^2 - (d_{M_y R} - d_{M_z R})^2}{(d_{M_y R} - d_{M_z R})^2} \\ &= \tan^{-1} \frac{4\pi^2 d^2 - \Delta\varphi_2^2 \lambda^2}{\Delta\varphi_2^2 \lambda^2}. \end{aligned} \quad (7)$$

Combining these results yields the estimated AOA:

$$\beta = (\theta_1 + \theta_2)/2. \quad (8)$$

E. Received Signal Strength Indication (RSSI)

The local received signal power relative to the transmit power is a function of the distance between two cones. From RSSI measurements [11], it is possible to estimate the distances between the master and sensor cones. The RF propagation loss in outdoor environments for line-of-sight (LOS) transmission is modeled as

$$\begin{aligned} L_{\text{LOS}}(d_{\text{RSSI}}) &= \\ &L_{o1} + 10n_1 \log_{10}(d_{\text{RSSI}}) + X_1, \quad d_{\text{RSSI}} < d_b \\ &L_{o2} + 10n_2 \log_{10}(d_{\text{RSSI}}) + X_2, \quad d_{\text{RSSI}} > d_b, \end{aligned} \quad (9)$$

where $n_1 = 2.34$, $n_2 = 3.73$, and $d_b = 6.2$ is the break-point distance. The standard deviations for the additive log-normal noise terms $\{X_1, X_2\}$ are $\sigma_1 = 0.6$ and $\sigma_2 = 0.42$. These parameters were derived from ground plain measurements [21]. $\{L_{o1}, L_{o2}\}$ are generated from the following equations [12]:

$$L_{o1} = 41 + 20 \log_{10}(f/5), \quad (10)$$

$$L_{o2} = 41 + 20 \log_{10}(f/5) - 17.3 \log_{10}(d_b), \quad (11)$$

where f is the carrier frequency. The distance between the center of the master cone and R is then obtained by solving for d_{RSSI} :

$$d_{\text{RSSI}} = \begin{cases} 10^{[(L_{\text{LOS}} - L_{o1})/10n_1]}, & d_{\text{RSSI}} < d_b \\ 10^{[(L_{\text{LOS}} - L_{o2})/10n_2]}, & d_{\text{RSSI}} > d_b. \end{cases} \quad (12)$$

When there is multipath propagation, the following non-LOS (NLOS) expression should be used [12]:

$$L_{\text{NLOS}} = L_{\text{LOS}}(d_A) + 20 - 12.5n_3 + 10n_3 \log_{10}(d_B), \quad (13)$$

where $n_3 = \max(2.8 - 0.0024d_A, 1.84)$, and $\{d_A, d_B\}$ are the transmitter and receiver distances, respectively, to the closest obstruction causing the multipath. The distance d_{RSSI} is again obtained

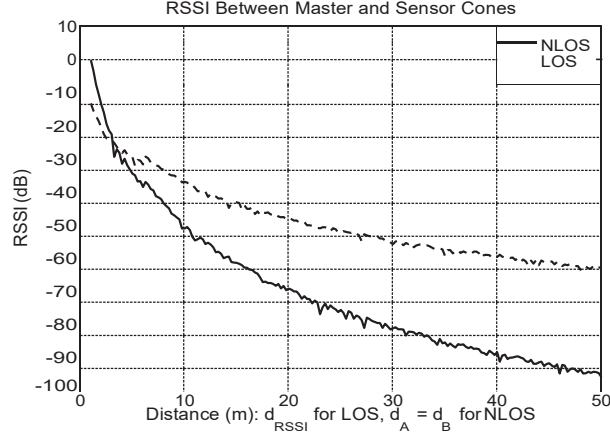


Fig. 4. RSSI versus distance for LOS and NLOS.

by (12), but with L_{NLOS} in place of L_{LOS} . Since (12) is used for both kinds of signals, because in practice we cannot distinguish between LOS and NLOS measurements, the accuracy of d_{RSSI} will be degraded with an increase in the percentage of NLOS measurements.

F. Localization Algorithm

The localization algorithm for each of the sensor cones consists of the following steps performed nominally every second, where we have included the time argument t on the estimated quantities:

- For every cone, estimate their positions using current RSSI and AOA measurements. Based on the estimated distance $d_{\text{RSSI}}(t)$ and angle $\beta(t)$, the x and y coordinates are computed using the usual trigonometric formulas:

$$x(t) = d_{\text{RSSI}}(t) \cos(\beta(t)), \quad y(t) = d_{\text{RSSI}}(t) \sin(\beta(t)). \quad (14)$$

- Compare the current cone topology with the most recent topology at the previous time instant $t - 1$ by computing the following differences. Difference in angle estimates:

$$\Delta\beta(t) = |\beta(t) - \beta(t - 1)|. \quad (15)$$

Difference in x - y coordinates:

$$\Delta x(t) = |x(t) - x(t - 1)|, \quad \Delta y(t) = |y(t) - y(t - 1)|. \quad (16)$$

- If any of these differences exceeds a specified threshold, an alarm is triggered, indicating a possible vehicle intrusion.
- If there is an interrupt from any of the type I sensor cones, the construction workers are alerted.
- Repeat this sequence of steps for all cones.

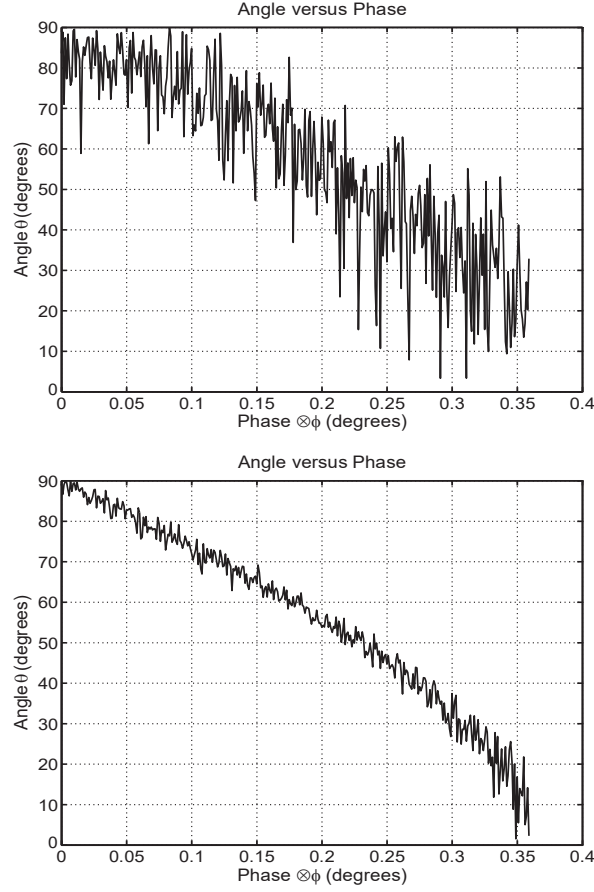


Fig. 5. Angle θ versus phase $\Delta\phi$ for $d_{\text{RSSI}} = 50$ m. (a) $\sigma_\phi = 0.05$. (b) $\sigma_\phi = 0.01$.

G. Computer Simulations

Figure 4 shows example simulations for the LOS and NLOS expressions in (9) and (13). These plots were generated by subtracting L_{LOS} and L_{NLOS} from a transmitted power of 30 dB. The transmission frequency is $f = 5.9$ GHz, and $d_A = d_B$ for the NLOS measurements. Observe that the RSSI measurements for LOS are generally stronger than those for NLOS for a given distance. This means that the estimated distance d_{RSSI} for NLOS measurements will be greater than the actual distance between the master cone and a sensor cone.

Examples of the estimated angle θ from (5) (or (7)) are shown in Figure 5. We have assumed $d_{\text{RSSI}} = 50$ m, and added zero-mean Gaussian noise with variance ϕ to $\Delta\phi$. The topology simulation in Figure 6 assumes a transmitted power of 30 dB, transmission frequency $f = 5.9$ GHz, and distance $d = 0.1$ m between M_x , M_y , and M_z . The master cone is located at coordinates (0, 0), and the sensor cone at (10, 5), corresponding to a distance of 11.18 m. The standard deviation of the Gaussian phase noise is $\phi = 0.01$. Figure 6 shows position estimates of the sensor cone for 100 sets of LOS measurements, demonstrating sub-meter accuracy.

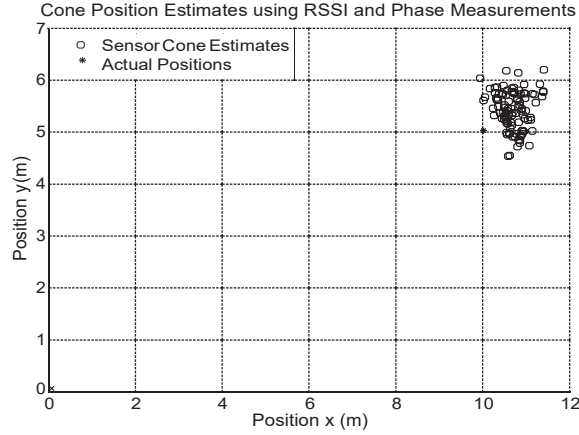


Fig. 6. Topology of master cone and sensor cone. The master cone is located at the origin (0, 0) and the sensor cone at (10, 5).

H. BeagleBoard-xM Hardware

The BeagleBoard-xM will be placed on the master cone and is used for data collection. A properly configured BeagleBoard-xM allows the user to run standalone Simulink models, which are capable of collecting live input data. This will be helpful in the work zone because the master cone receives updated information on location status from sensors placed on each of the two secondary smart cones in order to conclude whether or not any of the smart cones has been displaced. In order to improve performance, cameras with virtual line detection capacity can be used near a work zone. Two cameras create two virtual lines, which in turn are used to calculate the speed and direction of a vehicle when it is close to a work zone. A combination of this approach and the smart cones would make the alert system more accurate and would lead to a safer work zone. A Users' Manual is included as an attachment to this report that describes how to implement a fully functioning BeagleBoard on which standalone Simulink models can be run.

I. Summary

In this section, we have proposed a wireless sensor network consisting of smart cones in a roadway work zone that is designed to improve the safety of maintenance and construction workers. A master cone uses angle of arrival (TDOA) and distance (RSSI) measurements to create a topology of several sensor cones along the roadway, from which it is possible to detect intruding vehicles. A work zone station can alert workers about displaced cones and inform them of dangerous situations. This approach can be extended to continuously track workers who are wearing sensor tags. We also initiated development of a hardware module for a real-time implementation. The model can be extended to support the emerging "connected vehicles" environment to achieve sub-meter localization (within a

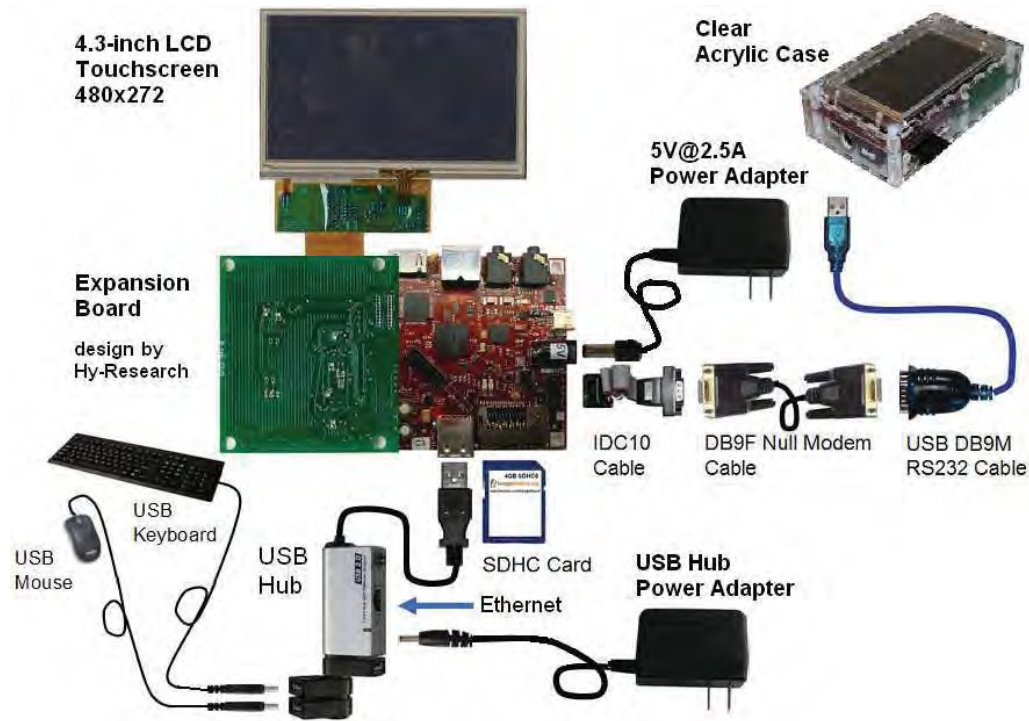


Fig. 7. BeagleBoard connectors and accessories.

lane) of high-mobility vehicles [5], [22]. The work zone station should also be able to alert distant vehicles of upcoming work zone activity and of any incidents.

Finally, we summarize some features of the low-mobility localization.

- Current work zone configurations can be used to develop accurate lane closure models and to implement optimal smart cone layouts.
- Each smart cone will be equipped with an IMU to detect motion and a radio based on wireless access in vehicular environments (WAVE) [13] to communicate position changes to the smart drum, and without a GPS capability. The cooperative algorithms developed for the smart drum will collate all the incoming data in order to construct a virtual map of the work zone. These data include signal strength (RSSI) and time-of-flight (TOF) [10], [11].
- Adaptive beamforming algorithms can provide improved position estimation and a direction-of-arrival (DOA) capability. Time-division multiplexing (TDM) of the smart cone signals is used to assess localization performance when the number of drum antennas is limited.
- Computer simulations of a work zone combined with the high-mobility vehicle models mentioned below are used to evaluate how they operate together. These can be used to refine both sets of

models and both sets of position estimation algorithms.

VI. COOPERATIVE LOCALIZATION AMONG VEHICLES

A. State-Space Mobility Model

In this section, we describe a discrete-time state-space representation that is used to model the mobility of several vehicles. It is a recursive model where positions and velocities in the future depend on previous positions and velocities, as well as vehicle accelerations, and there can be random fluctuations which are modeled by additive noise. This type of state-space model is widely used in engineering to represent the dynamic behavior of parameters of interest, which can be exploited by adaptive algorithms to estimate those parameters.

Assume for simplicity that there are only two vehicles; the extension to any number of independent vehicles is straightforward. The state vector at time instant k is

$$\mathbf{x}(k) \in [p_{1x}(k), p_{1y}(k), v_{1x}(k), v_{1y}(k), p_{2x}(k), p_{2y}(k), v_{2x}(k), v_{2y}(k), \text{offset}_x(k), \text{offset}_y(k)]^T, \quad (17)$$

where $\{p_{nx}(k), p_{ny}(k)\}$ and $\{v_{nx}(k), v_{ny}(k)\}$ are the $\{x, y\}$ positions and velocities, respectively, of the n th vehicle, and $\{\text{offset}_x(k), \text{offset}_y(k)\}$ are the $\{x, y\}$ GPS offsets affecting both vehicles. The goal is to accurately estimate these positions, velocities, and offsets over time using a combination of GPS and receive signal strength indication (RSSI) measurements, as well as accelerations provided by inertial measurement units (IMUs) located in the vehicles. The state vector at the next time instant is generated according to the following recursive state model:

$$\mathbf{x}(k+1) = \mathbf{A}(k)\mathbf{x}(k) + \mathbf{D}(k)\mathbf{u}(k) + \mathbf{B}(k)\mathbf{w}(k), \quad (18)$$

where $\mathbf{A}(k)$ is a state-transition matrix that describes how $\mathbf{x}(k)$ maps to $\mathbf{x}(k+1)$:

$$\mathbf{A}(k) = \begin{bmatrix} 1 & 0 & \Delta t & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 1 & 0 & \Delta t & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 1 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 1 & 0 & \Delta t & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 1 & 0 & \Delta t & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 1 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 1 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 1 \end{bmatrix}. \quad (19)$$

The input vector $\mathbf{u}(k)$ contains the vehicle accelerations in the $\{x, y\}$ directions:

$$\mathbf{u}(k) \in [a_{1x}(k), a_{1y}(k), a_{2x}(k), a_{2y}(k)]^T, \quad (20)$$

which are propagated to $\mathbf{x}(k+1)$ via the following matrix:

$$\mathbf{D}(k) = \Delta t \begin{bmatrix} 0 & 0 & 1 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 1 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 1 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 1 & 0 & 0 \end{bmatrix}^T. \quad (21)$$

Each element of $\mathbf{x}(k)$ is assumed to have independent additive noise, and so $\mathbf{B}(k) = \mathbf{I}$ is the identity matrix and the noise components are defined as follows:

$$\mathbf{w}(k) \mathbf{6} [w_{p1x}(k), w_{p1y}(k), w_{v1x}(k), w_{v1y}(k), w_{p2x}(k), w_{p2y}(k), w_{v2x}(k), w_{v2y}(k), w_{\text{offset}x}(k), w_{\text{offset}y}(k)]^T. \quad (22)$$

The fixed increment Δt is the duration of time from k to $k+1$, and so $\mathbf{A}(k) = \mathbf{A}$ and $\mathbf{D}(k) = \mathbf{D}$ are constant matrices, independent of time. Thus, the state equation in (18) simplifies to

$$\mathbf{x}(k+1) = \mathbf{A}\mathbf{x}(k) + \mathbf{D}\mathbf{u}(k) + \mathbf{w}(k). \quad (23)$$

Ignoring the additive noise, we describe specifically how the positions and velocities change with time according to the model. The first element of $\mathbf{x}(k+1)$ has the update

$$p_{1x}(k+1) = p_{1x}(k) + \Delta t v_{1x}(k), \quad (24)$$

i.e., the new position is the previous position plus the distance traveled, which is the velocity $v_{1x}(k)$ multiplied by the time interval Δt . This change in position is handled easily by the state-space model, where we see the first row in $\mathbf{A}(k)$ of (19) contains 1 and Δt at the appropriate locations to give (24). The third element of $\mathbf{x}(k)$ has the update

$$v_{1x}(k+1) = v_{1x}(k) + \Delta t a_{1x}(k), \quad (25)$$

i.e., the new velocity is the previous velocity plus any change, which is the acceleration $a_{1x}(k)$ multiplied by the time interval Δt . The rows in $\mathbf{A}(k)$ for the velocities contain only 1, and the Δt appears in (21) because it needs to multiply the acceleration contained in $\mathbf{u}(k)$. Similar equations hold in the y direction, and all these results are similar for the second vehicle (and any other vehicle in the general model). The GPS offsets are assumed to be constant in this model; they are included in $\mathbf{x}(k)$ so that they can be estimated by the KF and EKF algorithms described in the next section.

The previous model is a representation of the motion of the vehicles, and (i) it is used to simulate their behavior in **MATLAB** and (ii) its parameters $\{\mathbf{A}, \mathbf{D}\}$, as well as the noise covariance, are embedded in the KF/EKF equations that estimate $\mathbf{x}(k)$ at each time instant. There are two types of measurements for the positions of the vehicles: GPS and RSSI. The RSSI measurements are available more frequently, perhaps 50 samples/s, whereas the GPS measurements are less frequent, on the order of 1 sample/s. They also have different measurement models, which we discuss now.

The GPS measurement model has the following form:

$$y_{\text{GPS}}(k+1) = F_{\text{GPS}}(k+1)x(k+1) + v(k+1), \quad (26)$$

where for two vehicles there are four measurements:

$$y_{\text{GPS}}(k+1) \in [y_1(k+1), y_2(k+1), y_3(k+1), y_4(k+1)]^T. \quad (27)$$

The following measurement matrix indicates how the elements of $x(k+1)$ are combined to generate $y(k+1)$:

$$F_{\text{GPS}}(k+1) = \begin{bmatrix} 1 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 1 & 0 \\ 0 & 1 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 1 \\ 0 & 0 & 0 & 0 & 1 & 0 & 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 0 & 0 & 1 & 0 & 0 & 0 & 1 \end{bmatrix}, \quad (28)$$

which we see is independent of time: $F_{\text{GPS}}(k+1) = F_{\text{GPS}}$. Ignoring the additive noise vector $v(k)$, the first element of $y(k+1)$ is

$$y_1(k+1) = p_{1x}(k+1) + \text{offset}_x(k+1), \quad (29)$$

i.e., it is the position of the first vehicle in the x -direction plus the GPS offset (which affects both vehicles equally). The other elements of $y_{\text{GPS}}(k+1)$ are generated in the same way, and so the measurement vector provides information only about the vehicle positions and not their velocities. The equations for the state-space model and the GPS measurement model are linear. If we assume that the noise vectors $w(k)$ and $v(k)$ are zero-mean Gaussian with covariance matrices $C_{ww}(k)$ and $C_{vv}(k)$, then a standard KF can be used to estimate $x(k)$, as discussed in the next section.

The measurement model based on RSSI is nonlinear as follows:

$$y_{\text{RSSI}}(k+1) = f(x(k+1)) + v(k+1), \quad (30)$$

where $f(\cdot)$ represents the nonlinearity, and $v(k+1)$ is additive Gaussian noise with zero mean and covariance $C_{vv}(k)$ (similar to that for the GPS measurements, but with a different covariance $C_{vv}(k)$). For RSSI measurements, the nonlinearity is typically modeled as [12]

$$f(x(k+1)) = \begin{bmatrix} 22.7 \log_{10}(d_{12}(k+1)) + 41 + 20 \log_{10}(5.9 \times 10^9 / 5 \times 10^9) \\ 22.7 \log_{10}(d_{21}(k+1)) + 41 + 20 \log_{10}(5.9 \times 10^9 / 5 \times 10^9) \end{bmatrix}, \quad (31)$$

and so $y_{\text{RSSI}}(k+1)$ has only two elements (for two vehicles): they are the distances between the vehicles in each direction computed from elements of $x(k+1)$ as follows:

$$d_{12}(k+1) = \sqrt{[x_1(k+1) - x_5(k+1)]^2 + [x_2(k+1) - x_6(k+1)]^2} = f_1(x(k+1)), \quad (32)$$

$$d_{21}(k+1) = \sqrt{[x_5(k+1) - x_1(k+1)]^2 + [x_6(k+1) - x_2(k+1)]^2} = f_2(x(k+1)). \quad (33)$$

The subscripts on $x(k+1)$ in this equation (i.e., $\{1, 2, 5, 6\}$) correspond to the vehicle position elements of $x(k+1)$, and so the nonlinear expression is just the geometric distance equation between

two points. Even though theoretically $f_1(\mathbf{x}(k+1)) = f_2(\mathbf{x}(k+1))$ because we would expect $d_{12}(k+1) = d_{21}(k+1)$, they lead to different components in the EKF equations, and they are corrupted by different noise elements in $\mathbf{v}(k+1)$.

B. KF and EKF State Estimation

In order to incorporate both types of measurements which are collected at different rates, we use a combination of KF and EKF algorithms. Since RSSI measurements are available more frequently, they determine the time interval Δt , and an EKF is used to update the state vector every time instant. When a GPS measurement becomes available, it is used to adjust the state estimate right after the most recent RSSI measurement, and then the new state estimate is used for the next RSSI measurement.

There are two types of state estimates with the following notation:

$$\text{predicted: } \hat{\mathbf{x}}(k+1|k), \quad \text{filtered: } \hat{\mathbf{x}}(k+1|k+1). \quad (34)$$

The first argument is the time instant of the state estimate, and the second argument is the time instant of the most recent measurement vector, either one time step earlier (predicted) or the current time instant (filtered) due to a new measurement (GPS or RSSI). The predicted state estimate uses the state-space model to propagate the previous filtered state estimate from $\hat{\mathbf{x}}(k|k)$ to $\hat{\mathbf{x}}(k+1|k)$ at the next time instant, in order to maintain an accurate estimate in between measurements. When the measurement at time instant $k+1$ is received, the algorithm incorporates that information to generate the new filtered state estimate $\hat{\mathbf{x}}(k+1|k+1)$. The initial filtered state estimate is the mean of the state: $\hat{\mathbf{x}}(0|0) = \boldsymbol{\mu}_{\mathbf{x}}(0)$, which are the anticipated average values of the initial positions, velocities, and GPS offsets.

The prediction stage regardless of the type of previous measurement (GPS or RSSI) is as follows:

$$\hat{\mathbf{x}}(k+1|k) = \mathbf{A}\hat{\mathbf{x}}(k|k) + \mathbf{D}\mathbf{u}(k), \quad (35)$$

where $\hat{\mathbf{x}}(k|k)$ is the most recent filtered state estimate based on measurements up to time instant k , $\{\mathbf{A}, \mathbf{D}\}$ were the previously defined matrices for the state-space model, and $\mathbf{u}(k)$ contains the accelerations that are available from the IMUs. The KF and EKF algorithms require an estimate of the covariance matrix for the state estimation error, which is defined by

$$\tilde{\mathbf{x}}(k+1|k) = \mathbf{x}(k+1) - \hat{\mathbf{x}}(k+1|k). \quad (36)$$

Although $\mathbf{x}(k+1)$ is not available (since we seek an estimate of the state vector), it is possible to recursively compute the covariance matrix $\mathbf{C}_{\mathbf{xx}}(k+1|k) = E[\tilde{\mathbf{x}}(k+1|k)\tilde{\mathbf{x}}(k+1|k)^T]$ as follows:

$$\mathbf{C}_{\mathbf{xx}}(k+1|k) = \mathbf{A}\mathbf{C}_{\mathbf{xx}}(k|k)\mathbf{A}^T + \mathbf{C}_{\mathbf{ww}}(k). \quad (37)$$

The initial value of the state covariance of the state: $\mathbf{C}_{\mathbf{xx}}(0|0) = \mathbf{C}_{\mathbf{xx}}(0)$, which are the initial variances of the positions, velocities, and GPS offsets.

For the filtered stage, we consider GPS measurements first because they are linear and so the standard KF is used. The Kalman gain is computed as follows:

$$\mathbf{G}_{\text{GPS}}(k+1) = \mathbf{C}_{\mathbf{x}\mathbf{x}}(k+1|k)\mathbf{F}_{\text{GPS}}^T(\mathbf{F}_{\text{GPS}}\mathbf{C}_{\mathbf{x}\mathbf{x}}(k+1|k)\mathbf{F}_{\text{GPS}} + \mathbf{C}_{\mathbf{v}\mathbf{v}})^{-1}, \quad (38)$$

where $\mathbf{C}_{\mathbf{x}\mathbf{x}}(k+1|k)$ is given above, and the measurement matrix \mathbf{F}_{GPS} is defined in (28). The measurement error (also called the “innovations”) is the difference between the actual GPS measurements and those estimated by the measurement model:

$$\tilde{\mathbf{y}}_{\text{GPS}}(k+1|k) = \mathbf{y}_{\text{GPS}}(k+1) - \mathbf{F}_{\text{GPS}}\hat{\mathbf{x}}(k+1|k), \quad (39)$$

where $\mathbf{y}_{\text{GPS}}(k+1)$ is defined in (27), and $\hat{\mathbf{x}}(k+1|k)$ contains the estimated GPS measurements. The measurement error is used to generate the filtered state estimate:

$$\hat{\mathbf{x}}(k+1|k+1) = \hat{\mathbf{x}}(k+1|k) + \mathbf{G}_{\text{GPS}}(k+1)\tilde{\mathbf{y}}_{\text{GPS}}(k+1|k). \quad (40)$$

The update for the filtered covariance matrix, which is needed for (37) at the next iteration, is obtained from the predicted covariance matrix as follows:

$$\mathbf{C}_{\mathbf{x}\mathbf{x}}(k+1|k+1) = [\mathbf{I} - \mathbf{G}_{\text{GPS}}(k+1)\mathbf{F}_{\text{GPS}}]\mathbf{C}_{\mathbf{x}\mathbf{x}}(k+1|k). \quad (41)$$

These alternating predicted and filtered estimates are generated as new measurements are collected.

For the RSSI measurements, it is necessary to linearize $f(\cdot)$, after which it is possible to use the standard equations above. However, because of the linearization, the resulting EKF is only an approximation, and so its accuracy may vary depending on the quality of the linear approximation. The particle filtering (PF) approach mentioned in the introduction can be used to provide improved state estimates. The corresponding measurement matrix is (recall that $\mathbf{y}_{\text{RSSI}}(k+1)$ has only two elements for two vehicles)

$$\mathbf{F}_{\text{RSSI}}(k+1) = \begin{bmatrix} (22.7/d_{12})(\partial d_{12}/\partial x_1) & (22.7/d_{21})(\partial d_{21}/\partial x_1) & 0 & 0 \\ (22.7/d_{12})(\partial d_{12}/\partial x_2) & (22.7/d_{21})(\partial d_{21}/\partial x_2) & 0 & 0 \\ 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 \\ (22.7/d_{12})(\partial d_{12}/\partial x_5) & (22.7/d_{21})(\partial d_{21}/\partial x_5) & 0 & 0 \\ 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 \end{bmatrix}^T, \quad (42)$$

where the derivatives are obtained as follows:

$$\frac{\partial d_{12}}{\partial x_1} = \frac{x_1 - x_5}{d_{12}}, \quad \frac{\partial d_{12}}{\partial x_2} = \frac{x_2 - x_6}{d_{12}}, \quad \frac{\partial d_{12}}{\partial x_5} = \frac{-(x_1 - x_5)}{d_{12}}, \quad \frac{\partial d_{12}}{\partial x_6} = \frac{-(x_2 - x_6)}{d_{12}}, \quad (43)$$

$$\frac{\partial d_{21}}{\partial x_1} = \frac{-(x_5 - x_1)}{d_{21}}, \quad \frac{\partial d_{21}}{\partial x_2} = \frac{-(x_6 - x_2)}{d_{21}}, \quad \frac{\partial d_{21}}{\partial x_5} = \frac{x_5 - x_1}{d_{21}}, \quad \frac{\partial d_{21}}{\partial x_6} = \frac{x_6 - x_2}{d_{21}}. \quad (44)$$

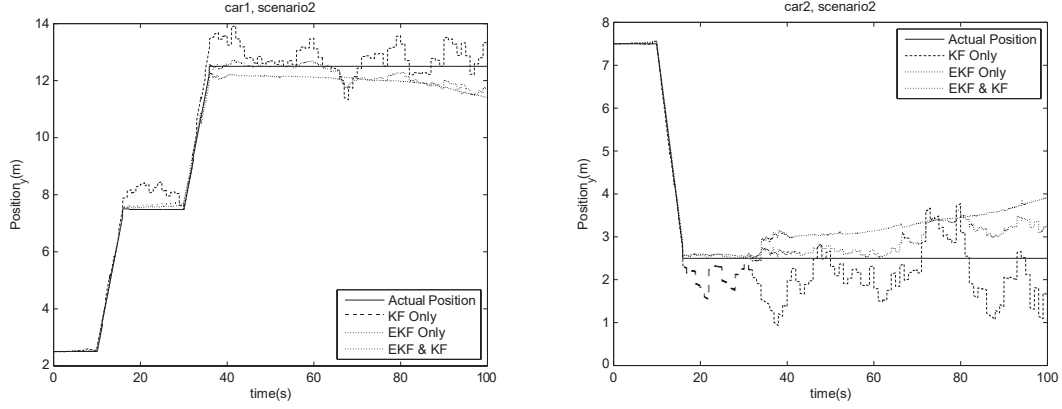


Fig. 8. Example computer simulations of car positions based on GPS and RSSI measurements.

Although we have dropped the argument $k + 1$ on the partial derivatives for notational convenience, the measurement matrix $F_{\text{RSSI}}(k + 1)$ actually depends on time (unlike F_{GPS} which is fixed):

$$F_{\text{RSSI}}(k + 1) = (22.7/d^{12}(k + 1)) \begin{bmatrix} x_1(k + 1) - x_5(k + 1) & -[x_5(k + 1) - x_1(k + 1)] \\ x_2(k + 1) - x_6(k + 1) & -[x_6(k + 1) - x_2(k + 1)] \\ 0 & 0 \\ 0 & 0 \\ -[x_1(k + 1) - x_5(k + 1)] & x_5(k + 1) - x_1(k + 1) \\ -[x_2(k + 1) - x_6(k + 1)] & x_6(k + 1) - x_2(k + 1) \\ 0 & 0 \\ 0 & 0 \\ 0 & 0 \end{bmatrix}^T. \quad (45)$$

When an RSSI measurement is obtained, $F_{\text{RSSI}}(k + 1)$ and $F_{\text{RSSI}}(k + 1)$ are used in place of F_{GPS} and $F_{\text{GPS}}(k + 1)$ in the KF equations above, and the innovations sequence in (39) is replaced by

$$\tilde{y}_{\text{RSSI}}(k + 1|k) = y_{\text{RSSI}}(k + 1) - f(\hat{x}(k + 1|k)), \quad (46)$$

which is based on (30) and $f(\cdot)$. Since the EKF Kalman gain for RSSI measurements is derived from $F_{\text{RSSI}}(k + 1)$, we designate it by $G_{\text{RSSI}}(k + 1)$.

Example computer simulations of the KF and EKF algorithms are presented in Figure 8, where we observe that the combined KF and EKF algorithms provide the best performance. Even better performance is obtained using particle filters, and a Markov chain model can be used to estimate lane changes.

C. Particle Filter

Particle filters are sequential Monte Carlo methods based on point mass (“particle”) representations of probability density functions (pdfs) that can be applied to a state-space model [23]. Similar to the KF and EKF, two models are required in order to analyze and make inferences about a dynamic system: a model describing the evolution of the state vector with time (the system model), and a model relating the noisy measurements to the state (the measurement model). We assume that these models are available in a probabilistic form; in particular, new measurements are represented in the Bayesian form consisting of two stages: prediction and measurement update. The prediction stage uses the system model to predict the state pdf from one measurement time to the next. Since the state is usually subject to unknown disturbances (modeled as random noise), prediction generally translates and spreads the state pdf. The measurement update operation uses the latest measurements to modify the prediction pdf. This is achieved using Bayes theorem, which is an algorithm for updating knowledge about the state given additional information from new data.

Based on the previously described state-space model, the particle filter algorithm has several steps for each iteration defined by new observations. Let $x^i(k)$ be the i th particle of state $x(k)$ at time instant k . Assume there are N_s such particles, and these are weighted by $w^i(k)$. The particle filter update can be represented symbolically as follows:

$$\{x^i(k), w^i(k)\}_{i=1}^{N_s} = \text{PF} \{x^i(k-1), w^i(k-1)\}_{i=1}^{N_s}, y(k), \quad (47)$$

where $y(k)$ is the observation at the k th time instant. In order to update the state estimate, we sample $x^i(k)$ from the pdf $p(x(k)|x^i(k-1), y(k))$. For most models, this evaluation is not analytically possible. Therefore, a local linearization technique is applied where instead of $p(x(k)|x^i(k-1), y(k))$, we use

$$q(x(k)|x^i(k-1), y(k)) = p(x(k)|x^i(k-1)). \quad (48)$$

The weights are updated as follows:

$$w^i(k) \propto w^i(k-1) \frac{p(y(k)|x^i(k))p(x^i(k)|x^i(k-1))}{q(x^i(k)|x^i(k-1), y(k))} \quad (49)$$

Substituting (48), this expression simplifies to

$$w^i(k) \propto w^i(k-1)p(y(k)|x^i(k)). \quad (50)$$

These weights are then normalized:

$$w^i(k) = \frac{w^i(k)}{\sum_{i=1}^{N_s} w^i(k)}. \quad (51)$$

Although the algorithm above should ideally work, in practice a resampling technique is required in order to overcome a degeneracy problem. This problem occurs because after a few iterations, we often find that all but one particle have a negligible weight. It has been shown in [24] that the

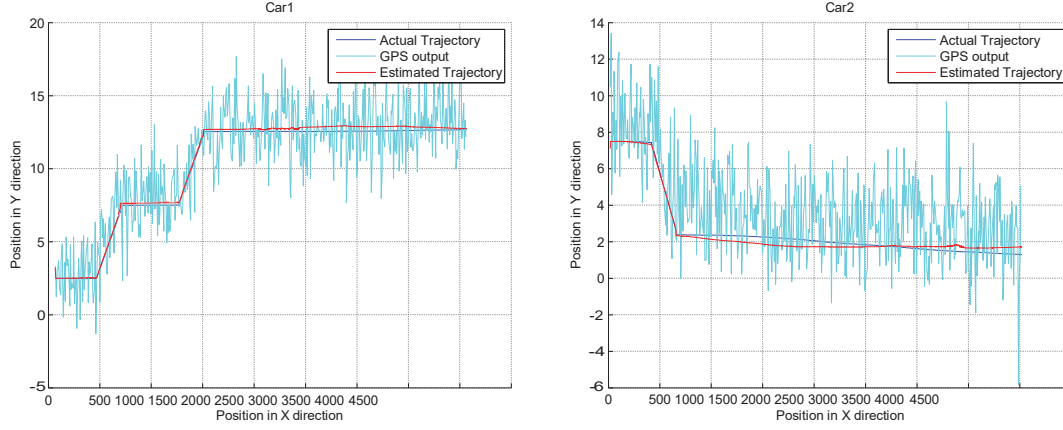


Fig. 9. Example computer simulations of car positions based on GPS measurements using a particle filter (PF).

variance of these so-called "importance weights" can only increase over time, and thus it is impossible to avoid degeneracy without resampling. A suitable measure of degeneracy of the PF algorithm is the following estimate of effective sample size:

$$N_{\text{eff}} = \frac{1}{\frac{1}{N_s} \sum_{i=1}^{N_s} (w^i(k))^2}. \quad (52)$$

Whenever a significant degeneracy is observed (i.e., when N_{eff} falls below some threshold N_T), we would apply the symbolic resampling algorithm:

$$\{x(k), w(k)\}_{i=1}^{N_s} = \text{RESAMPLE} \{x(k-1), w(k-1)\}_{i=1}^{N_s}. \quad (53)$$

The basic idea of resampling is to eliminate particles that have small weights and to concentrate on particles with large weights. The resampling step involves generating a new set $\{x^{i*}(k)\}_{i=1}^{N_s}$ by resampling (with replacement) N_s times from an approximate discrete representation of $p(x(k)|y(1:k))$ given by

$$p(x(k)|y(1:k)) \approx \sum_{i=1}^{N_s} w^i(k) \delta(x(k) - x^i(k)), \quad (54)$$

so that $\Pr(x^{i*}(k) = x^i(k)) = w^i(k)$, where $\delta(m)$ is the Kronecker delta function. The resulting sample is in fact an independent and identically distributed sample from a discrete density, and so the weights are reset to have a uniform distribution: $w^i(k) = 1/N_s$.

For the following example, the state-space model in (18) and measurement model in (26) are used. The pdfs for the PF are Gaussian as follows:

$$p(x(k)|x(k-1)) = \mathbf{N}(\mathbf{A}x(k-1) + \mathbf{D}u(k-1), \mathbf{C}_{ww}), \quad (55)$$

$$p(y(k)|x(k)) = \mathbf{N}(\mathbf{F}_{\text{GPS}}x(k), \mathbf{C}_{vv}), \quad (56)$$

where \mathbf{C}_{ww} and \mathbf{C}_{vv} are the noise covariance matrices perviously defined. Assume there are only two vehicles, where each vehicle changes lanes. GPS data was generated at a rate of 50 Hz ($\Delta t = 1/50$ in

A), there were $N_s = 100$ particles, and the resampling threshold was $N_T = 1/2N_s$. Figure 9 shows the actual trajectories for the two cars, as well as the GPS observations around those trajectories, which we see have relatively large errors (on the order of 3 meters). The PF estimator accurately tracks the motions of both vehicles, even during lane changes.

D. Cramer-Rao Lower Bound

In this section, we provide an expression for the Cramer Rao lower bound (CRLB) [4] for the vehicle scenario with anchors and probe vehicles that have enhanced GPS. Let the positions of N vehicles with low-accuracy GPS be denoted by the vector \mathbf{u}_1 , whose components are complex-valued and specify the horizontal and vertical coordinates. The positions of the fixed anchors and probe vehicles are denoted by the vector \mathbf{u}_2 , which has M complex components. These two vectors are collected together into the following composite vector:

$$\mathbf{z} = \begin{bmatrix} \mathbf{u}_1 \\ \mathbf{u}_2 \end{bmatrix} \in \mathbb{C}^{N+M} \quad (57)$$

The distance between two components of \mathbf{z} is computed as

$$z_i - z_j = \mathbf{e}_{ij}^T \mathbf{z} \quad (58)$$

where element i of \mathbf{e}_{ij} is 1 and element j is -1 . Suppose for some neighborhood of vehicles and anchors that there are L such distance measurements. All location differences can be written as

$$\mathbf{s} = \mathbf{E}\mathbf{z} \in \mathbb{C}^{L \times 1} \quad (59)$$

where $\mathbf{E} \in \mathbb{R}^{L \times (N+M)}$ has L rows \mathbf{e}^T corresponding to all the measurements. Observe that this vector can be written as the sum of \mathbf{u}_1 and \mathbf{u}_2 as follows:

$$\mathbf{s} = \mathbf{E}_1 \mathbf{u}_1 + \mathbf{E}_2 \mathbf{u}_2, \quad (60)$$

where we have partitioned $\mathbf{E} = [\mathbf{E}_1 \ \mathbf{E}_2]$ with $\mathbf{E}_1 \in \mathbb{R}^{L \times N}$ and $\mathbf{E}_2 \in \mathbb{R}^{L \times M}$. The actual distances are given by $d = |\mathbf{s}|$, where this notation takes the absolute value of each element of \mathbf{s} . Let the k th distance estimate be $\hat{d}_k = d_k + n_k$, where n_k is zero-mean Gaussian with variance σ^2 . The covariance matrix is

$$\mathbf{E}(\hat{\mathbf{d}} - |\mathbf{s}|)^T(\hat{\mathbf{d}} - |\mathbf{s}|) | \mathbf{u} = \sigma^2 \mathbf{I}, \quad (61)$$

and so the joint Gaussian pdf for the estimates is

$$f(\hat{\mathbf{d}} | \mathbf{u}) = \prod_{k=1}^L \frac{1}{\sqrt{2\pi}\sigma} \exp(-(\hat{d}_k - |s_k|)^2 / 2\sigma^2). \quad (62)$$

It is shown in [4] that the Fisher information matrix is

$$\mathbf{F} = \frac{1}{2} \begin{bmatrix} \mathbf{E}_1^T \mathbf{D}_R^2 \mathbf{E}_1 & \mathbf{E}_1^T \mathbf{D}_R \mathbf{D}_I \mathbf{E}_1 \\ \mathbf{E}_1^T \mathbf{D}_R \mathbf{D}_I \mathbf{E}_1 & \mathbf{E}_1^T \mathbf{D}_I^2 \mathbf{E}_1 \end{bmatrix} \in \mathbb{R}^{2N \times 2N}, \quad (63)$$

which contains the following real-valued diagonal matrices:

$$D_R = \text{Re} \begin{bmatrix} s_1/|s_1| & 0 & \cdots & 0 \\ 0 & \ddots & & \\ \vdots & & \ddots & \\ 0 & \cdots & 0 & s_L/|s_L| \end{bmatrix}, \quad D_I = \text{Im} \begin{bmatrix} s_1/|s_1| & 0 & \cdots & 0 \\ 0 & \ddots & & \\ \vdots & & \ddots & \\ 0 & \cdots & 0 & s_L/|s_L| \end{bmatrix} \quad (64)$$

Observe that F has rank $2N$ corresponding to the horizontal and vertical location estimates for the N vehicles with low-accuracy GPS. The CRLB is obtained by inverting F .

Consider an example with $N = 6$ vehicles with low-accuracy GPS, and $M = 3$: one anchor and two probe vehicles. The actual coordinates on a simple rectangular grid are $u_1 = [1 + j, 2 + j, 3 + j, 1 + j, 3 + j, 2 + j]^T$ and $u_2 = [4 + j, 2 + j, 1 + j, 5 + j, 1 + j, 2 + j]^T$. We assume that the six low-accuracy vehicles communicate with each other in both directions, which means 30 measurements. Also, these vehicles receive information (one direction) from the anchor and probe vehicles, corresponding to 18 more measurements for a total of $L = 48$ distance measurements. The CRLB for each of the 6 vehicles is obtained from the diagonal elements of F^{-1} , which in this example are

$$\text{CRLB} = [0.4410, 0.4426, 0.3299, 0.2577, 0.3278, 0.5531, 0.2440, 0.1763, 0.2480, 0.2373, 0.1801, 0.1460]^T, \quad (65)$$

where $\sigma^2 = 1$ has been used. Observe that these variance values are less than the distances between vehicles.

E. Summary

The First Responder Support Systems Testbed (FiRST) has developed innovative solutions to improve transportation safety using ITS cooperative systems. This report addresses the following Caltrans goals.

- Safety: Provides a safer work-zone, with deployable solutions that can save the lives of many Caltrans workers for both urban and rural settings.
- Service: Maintains Caltrans competitive advantage at the national level by providing a unique and cost-effective ITS proving grounds. It also provides specialized training to improve Caltrans workforce professional capacity.

Finally, we summarize features of the high-mobility localization approaches.

- Models have been developed for vehicle mobility that includes clusters of cars traveling on several lanes in both directions. A car-following model can be included where the behavior of one group of vehicles (speed, acceleration, and so on) is controlled by a lead group [14]. The model can incorporate construction zones with smart cones where the number of lanes is reduced, and include a smart drum that communicates with on-coming lead vehicles.

- Each vehicle is assumed to be equipped with standard GPS, a WAVE radio, an IMU, and RSSI. GPS provides initial rough position estimates that are improved by a combination of the following measurements [8]: (i) received signals from vehicles in a neighborhood, (ii) received signal strength (RSSI), (iii) speed and orientation information from the IMU. Particle filtering (PF) initialized by a Kalman filter (KF) can be used to fuse the data and generate improved position estimates, which are in turn transmitted to vehicles in the neighborhood.
- Markov chains can be developed for estimating the probabilities that vehicles are in particular lanes. They would include a prediction step that propagates these probabilities in between measurements, and a correction step that incorporates the KF/EKF/PF results to refine lane estimates. Road curvature could be included in order to evaluate the lane estimation algorithms.

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BEAGLEBOARD-XM CONFIGURATION FOR COMPATIBILITY WITH SIMULINK MODELS, A DETAILED MANUAL

I. INTRODUCTION

The *BeagleBoard-xM* is an open hardware embedded device that can be used for many engineering systems thanks to its Texas Instruments' 1 GHz ARM Cortex-A8 processor, and to support package called BeagleBoard Package from Simulink to run standalone simulink application models. This package is only supported on Windows. This manual details the configuration requirements and steps that need to be followed in order to be able to have a fully functioning BeagleBoard-xM on which standalone Simulink models can be run. We describe a simple model showing how to configure and run a Simulink model on the BeagleBoardxM.

This report documents the basic steps required to be familiar with this embedded system in order to experiment with more complex Simulink models that are required for the cooperative localization methods described in the above report. The adaptive algorithms such as the Kalman filter (KF) and other techniques such as particle filter (PF) are required to process the vehicles data to achieve the required highway lane localization. The following Matlab code fuses GPS, signal strength (RSSI), and vehicles parameters to achieve sub-meter localization in both line-of-sight (LOS) and multipath (NLOS) environment.

II. SYSTEMS ACCESSORIES AND REQUIREMENTS

- A Windows 32-bit or 64-bit computer. The computer should be equipped with a COM port or a USB port. A laptop computer is easier to use—and it is suggested that you use one—because of connectivity reasons. This is because as shown later in the process, the computer needs to be connected to the BeagleBoard using an Ethernet cable. Also, internet availability on the host computer is necessary. This is easily possible if the host computer is connected to the internet wirelessly.
- USB to serial port cable (in the case of a computer with just a serial port). Or a serial cable (for a computer with a COM port). It is important to check the cable connectivity and compatibility, otherwise connectivity may not be possible. A new cable (with available driver software on a CD or online) is always suggested in any case (if funds are available). A Gigaware USB to serial cable from Radio Shack is suggested.
- Micro SD memory card of 4 GB or more capacity. A micro SD card adapter (which usually comes with the memory card itself) is also required for needed connectivity to the computer.
- Ethernet cable (of an average length).
- Beagleboard-xM. The only way to know if it is a fully functional one without suffering through so much troubleshooting is to use a new board (if funds are available).
- A +5 V/2.5 A power cable. A D-Link made cable is suggested.

III. BEAGLEBOARD SUPPORT PACKAGE, BEAGLEBOARD-XM CONFIGURATION, AND SIMULINK

I. SUPPORT PACKAGE INSTALLATION:

- Open MATLAB.
- In the MATLAB command window, type *targetupdater* and press enter.
- In the *set up support package* window that pops up, choose the *BeagleBoard* option and click *next*.
- In the *select a board* window that appears, choose *BeagleBoard-xM* for the board version.
- Connect the host computer to the BeagleBoard-xM using the USB to serial cable (USB end on the host computer and the serial port end on the BeagleBoard-xM). If your computer has COM port, you can use the serial cable in this step. Either connectivity method works well.
- Connect the host computer to the BeagleBoard-xM using the Ethernet cable (one end on the host computer and another end on the board).
- Connect a 5 V/2.5 A power cable (from board to power to power socket).
- If you have them, connect headphones/speakers to the BeagleBoard (this is an optional step although it may be helpful in the end).
- Click *next*.
- In the *get firmware* window, choose *download from internet* then click on *download*.
- Insert a 4 GB micro SD card or larger into the host computer. Note that this card should be formatted in the exFAT mode and with the quick format option disabled. (If prompted to format it, in case it has not already been formatted, you can still do it at this step but remove it and insert it back into the computer for connectivity purposes.)
- On the select a drive page, click *refresh*, and then click *next*.
- On the *write firmware* page, click on *write*.
- On the *select serial port* page, select *the serial port* to which the BeagleBoard is connected then click *next*. The proper port number on a specific computer usually shows up as the default choice.
- Remove the micro SD memory card from the host computer and insert it into the BeagleBoard-xM.
- Press the *reset* button on the BeagleBoard-xM. (It is an easily recognizable white button on the board closer to the corner.) Then click *next*.
- In this step, you need to set up IP configurations. The easy way to do this is to *minimize* the *configure board* window. Then activate the Internet Connection Sharing (ICS):
 - i) Go to Windows start menu, click *Start*, click *Control Panel*, type *adapter* in the control panel search box, and click on *View network connections*.
 - ii) *Right* click on the connection that you want to share. (Note that sharing the wireless network is the easiest way.) And then click on *properties*.

iii) Click on the *sharing* tab, and then select *allow other network users to connect through this computer's internet connection* box. If prompted to choose a private network, choose the LAN connection. This will allow automatic IP assignment to your computer's Ethernet port (the one where the Ethernet cable is connected). Then click *OK*.

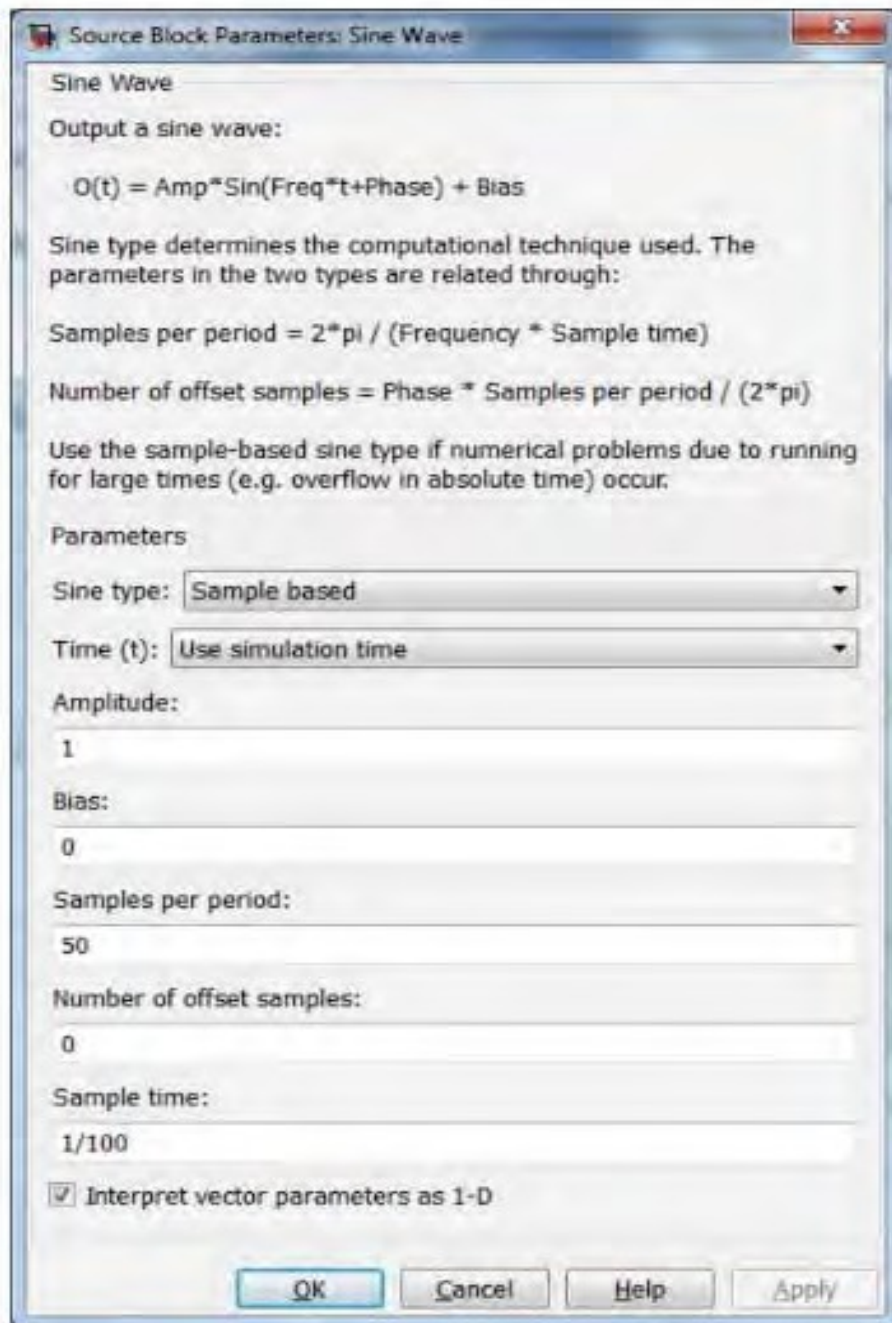
- On the *configure board* window, give the board a name if you do not like the automatically generated one. Then choose *automatically get IP address*. (This is the best option in assigning IP unless you are using your own home network with readily available IP address to assign automatically.)
- On the *confirm board configuration* page, an automatically assigned *IP address*, a *user name*, and a *password* are displayed. Please write them down since they are required for future log in.
- You may now disconnect the USB to serial cable since it is no longer needed.
- Since the password is assigned automatically (not static), it may change in the future. To know the new IP address in the future, you may press and release the USER button to listen to the board hardware speak its IP. (This where your headphones/speakers help.)
- On the *support package complete* window, select the *show support package examples* box, if you want to see different examples. Then click *finish*.
- Keep your board connected to the computer.

II. RUNNING SIMULINK MODEL ON BEAGLEBOARD-XM

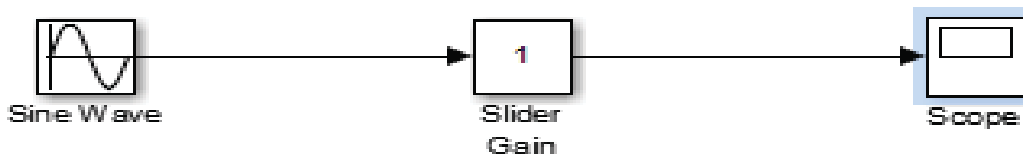
Depending upon the needed application, the user may run a more complex Simulink standalone model on the BeagleBoard-xM. The example below is a simple sine model that takes the user through how to configure communication between the BeagleBoard-xM and Simulink, tune parameters of the algorithm that is running on the board through Simulink, and use Simulink to monitor results of the algorithm being run on the board. The results can be displayed on a Scope or a Display. It should also be noted that, depending upon the application at hand, some other accessories may be required (say when doing audio processing, image processing, or data collection, for example).

A. CREATE A SIMULINK MODEL

- In MATLAB, click on *home*, *new*, and then choose *Simulink Model*.
- In the MATLAB command window, enter *simulink*.
- In the Simulink Library browser, click on *simulink*, and then on *sources*.
- *Drag* a Sine Wave block and *drop* it in the new model window. To change parameters, *double* click on the sine wave and set the parameters as shown below.



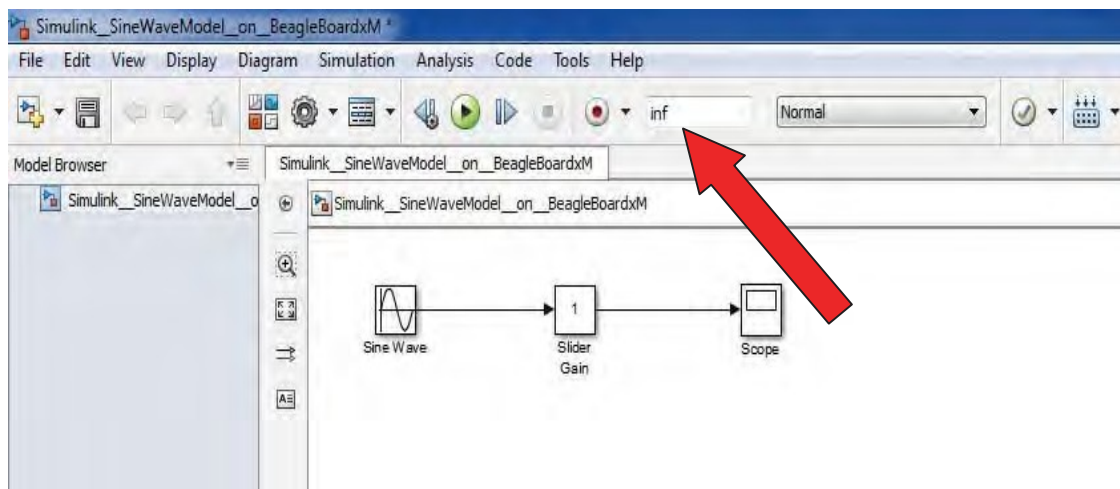
- Click on *Simulink*, then click on *math operations*, and then drag and drop a *Slider Gain* into the model window
- *Connect* the output of the Sine Wave to the input of the *Slider Gain*.
- Click on *Simulink*, then click on *Sinks*, and then drag drop a *Scope* and *connect* the output of the *Slider Gain* to the input of the *Scope*.
- *Save* the Simulink model. The basic model designed above is displayed below.



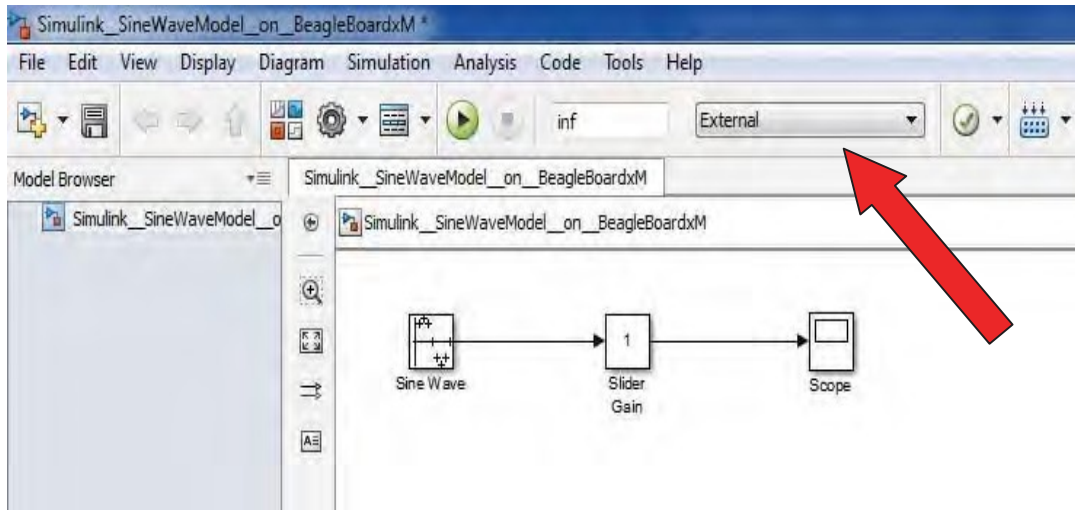
B. CONFIGURATION AND RUNNING THE MODEL ON THE BEAGLEBOARD-XM

With your board still connected to the computer:

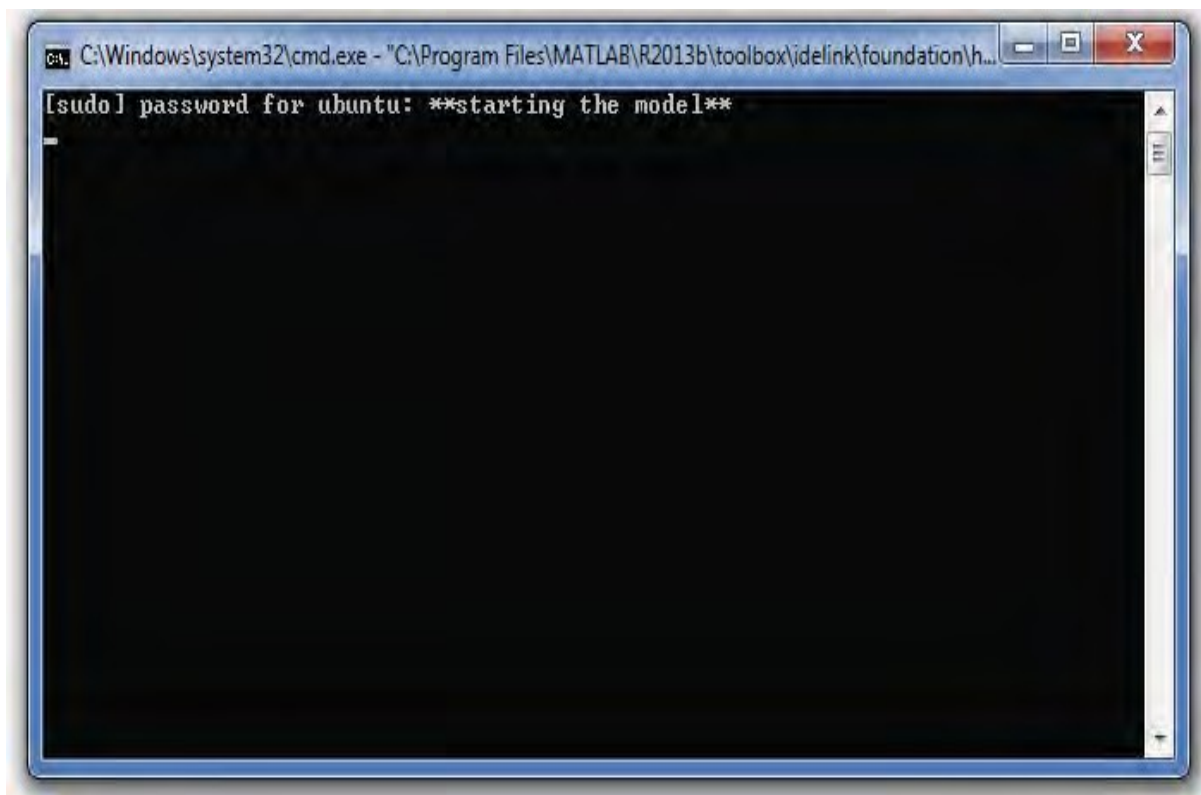
- In the Simulink model window create above, *set* the stop time to *inf*. This means infinite period; once the simulation starts running, it stops only when you pause or stop it.



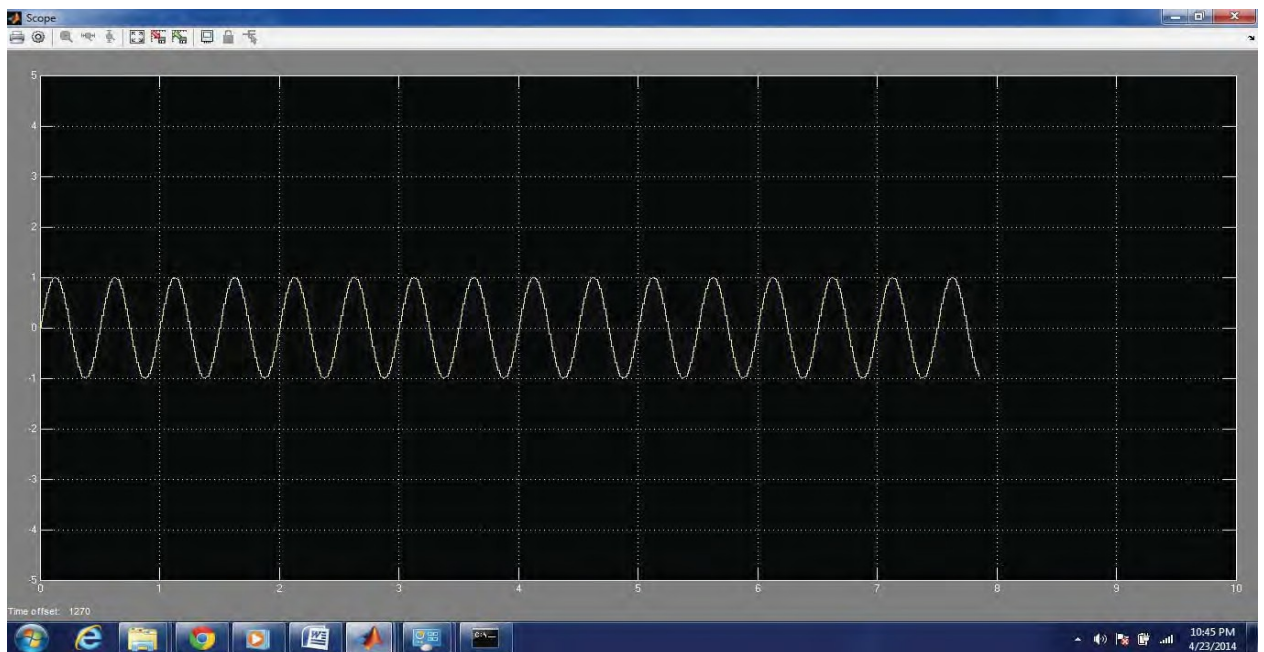
- In the Simulink model, choose *tools*, then choose *run on target hardware*, and then choose *prepare to run*.
- In the pop up window, in the drop down menu, choose *BeagleBoard* as target hardware. After that, all the parameters and settings on that page will be automatically populated (TCP/IP port number, host name shown as IP address, user name, password, and build/directory). To check if the displayed IP address matches the BeagleBoard one, with your speakers or headphones on, *press and release* the BeagleBoard *user button* (the easily identifiable white button next to the reset button) to hear it read out loud by the board.
- Leave the TCP/IP port number to the default value (that is 17725). This port is used for communication between Simulink and the board.
- Press *OK*.
- In the simulink model, set the *simulation mode* to *external* as shown in the image below. Then click *Run*.



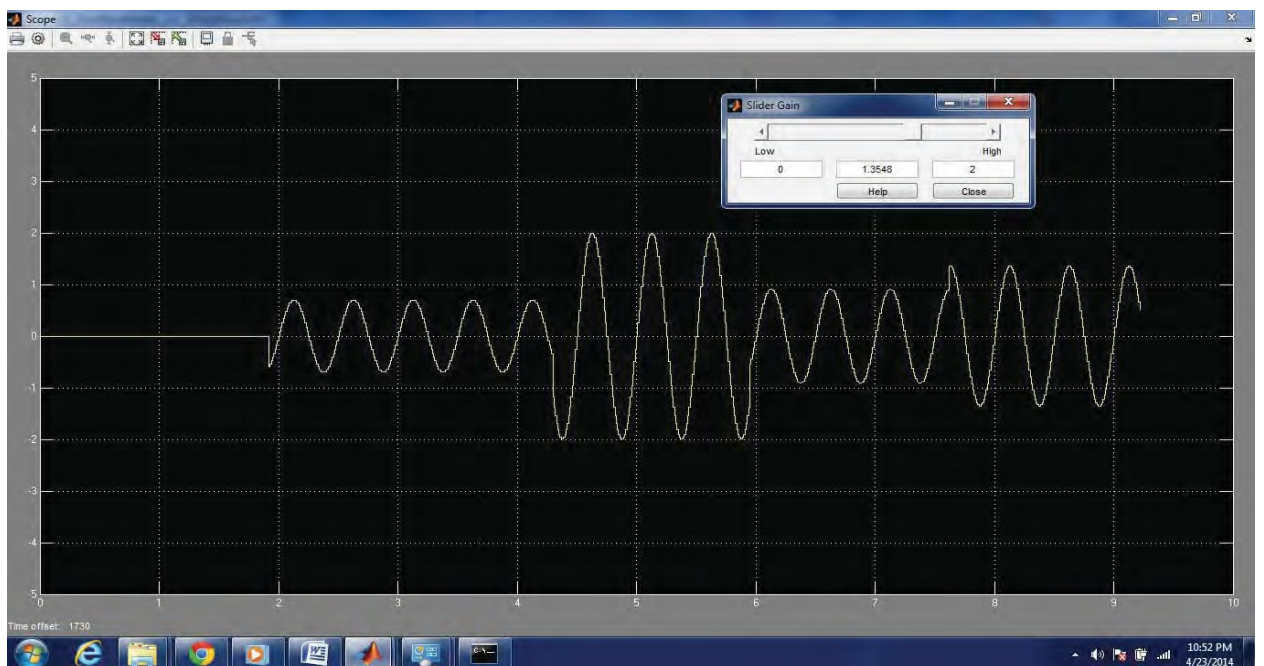
- Now that when the model is running on the BeagleBoard, a command window like then one below will appear. Note that, since technically speaking, BeagleBoardxM is only compatible with Ubuntu/Linux (and not compatible with Windows), this method of running Simulink models externally allows us to use the BeagleBoard externally using a Windows computer. It should also be noted that this is the easiest way to run a Simulink model on the BeagleBoard-xM since running it directly through linux is not that ubiquitous yet (if it has been done at all).



- Right click on the *Scope* block, then click *open* to observe the continuously running Sine Wave model.



- Double click on the Slider Gain, and vary the amplitude by sliding to the right to increase it and to the left to reduce it. You will notice an amplitude change on the Scope. Another big advantage here is the fact that we are able to change the parameters or variables of a running model without stopping it.



- In the Simulink model, press the *Stop* button. The command window that appeared above should now display a new message showing that the simulation has been stopped.



```
Administrator: C:\Windows\system32\cmd.exe
[sudo] password for ubuntu: **starting the model**
** starting the model **
**stopping the model**
**Simulation finished**
C:\Users\Mutangana\Documents\MATLAB\Simulink__SineWaveModel__on__BeagleBoard\M_r
tt>_
```

- Save the model. Close everything. You may now disconnect the board.

III. CONCLUSION

That concludes our intended process of showing how a Simulink model can be run on a BeagleBoard and the advantages of doing so. It obvious that, thanks to MathWorks, the BeagleBoard can be configured and different Simulink models can be created and run on it for different engineering applications, even with the ability to change model parameters and variables without stopping or pausing the running model at hand.

MATLAB Code

```

clear , close all;

dAlM = 0.1; %i n m
range = 50; %i n m

lamda = 2 * range; r
es = 0.001;

errorTable(1) = 0.1;
errorTable(2) = 0.05;
errorTable(3) = 0.01;
errorTable(4) = 0.0;

for i = 1:4
    error = errorTable(i);
    %error = 0.1; %i n degrees

    count = 0;
    for phase = 0:res:dAlM/lamda * 360 - res
        count = count + 1;
        %phaseMeasured = pi/180 * phase;
        phaseMeasured = pi/180 * normrnd(phase, error);
        dAlMR = phaseMeasured / (2 * pi) * lamda;

        beta(count, i) = abs(atan((sqrt((dAlM/2)^2 - (dAlMR/2)^2)) / (dAlMR/2))) * 180 / pi;
        phaseVal(count, i) = phase;
    end
end

figure
plot(phaseVal(:,2), beta(:,2), 'k', 'LineWidth', 1.5);
title('Angle versus Phase', 'FontSize', 16);
xlabel('Phase \Delta \phi (degrees)', 'FontSize', 16)
ylabel('Angle \theta (degrees)', 'FontSize', 16)
set(gca, 'FontSize', 15, 'LineWidth', 1.5)
grid

figure
plot(phaseVal(:,3), beta(:,3), 'k', 'LineWidth', 1.5);
title('Angle versus Phase', 'FontSize', 16);

```

```

xlabel('Phase \Delta \phi (degrees)', 'FontSize', 16)
ylabel('Angle \theta (degrees)', 'FontSize', 16)
set(gca, 'FontSize', 15, 'LineWidth', 1.5)
grid

```

```

clear , close all

```

```

clearvars

```

```

LOS = 1;

```

```

Pt = 30; % in dB

```

```

f = 5.9; % in Ghz

```

```

ha = 0.5;

```

```

hb = 0.5;

```

```

lamda = 3 * 10^8 / (f * 10^9);

```

```

%Old Model

```

```

% Rbp = 4*(ha - 1)*(hb - 1)/ lamda;

```

```

% n1 = 2.27;

```

```

% n2 = 4;

```

```

% L01 = 41 + 20 log10 ( f / 5 );

```

```

% L02 = 41 + 20 * log10 ( f / 5 ) - 17.3 * log10 ( Rbp );

```

```

% sigma 1 = 1;

```

```

% sigma 2 = 1;

```

```

%New Model

```

```

Rbp = 6.2;

```

```

n1 = 2.34;

```

```

n2 = 3.73;

```

```

L01 = 41 + 20 log10 ( f / 5 );

```

```

L02 = 41 + 20 * log10 ( f / 5 ) - 17.3 * log10 ( Rbp );

```

```

sigma1 = 0.6;

```

```

sigma2 = 0.42;

```

```

for LOS = 0 : 1

```

```

    count = 0;

```

```

    for d = 1: 0.25: 50

```

```

        count = count + 1; if

```

```

        LOS

```

```

            if d < Rbp

```

```

                loss = L01 + 10 * n1 * log10 ( d );

```

```

                shadow = lognrnd ( 0 , sigma1 );

```

```

            else

```

```

        loss = L02 + 10 * n2 * log10 ( d );
        shadow = lognrnd ( 0 , sigma2 );
    end
else
    if d < Rbp
        loss = L01 + 10 * n1 * log10 ( d );
        shadow = lognrnd ( 0 , sigma1 );
    else
        loss = L02 + 10 * n2 * log10 ( d );
        shadow = lognrnd ( 0 , sigma1 );
    end
    temp = 2.8 - 0.0024 * d;
    nj = max ( [ temp , 1.84 ] );
    loss = loss + 20 - 12.5 * nj + 10 * nj * log10 ( d );
end
RSSIMeasured ( count , LOS+1 ) = Pt-loss - shadow ;
end
end

figure
plot ( [ 1 : 0.25 : 50 ] , RSSIMeasured ( : , 1 ) , 'k' , 'Line Width' , 2 );
xlabel ( ' Distance (m): d_{RSSI} for LOS, d_A = d_B for NLOS' , 'Font Size' , 16)
ylabel ( ' RSSI (dB)' , 'FontSize' , 16)
title ( ' RSSI Between Master and Sensor Cones ' , 'FontSize' , 16)
axis ([ 0 50 -100 10 ])
set ( gca , ' Font Size ' , 15 , ' Line Width ' , 1.5) grid
hold on
plot ( [ 1 : 0.25 : 50 ] , RSSIMeasured ( : , 2 ) , 'k--' , 'Line Width' , 2 );
h = legend ( ' NLOS' , ' LOS' , 1 );



---


clear , close all;

dAlM = 0.1; %i n m
range = 50; %i n m

%Assuming master node is at 0,0 and M and A1 at +c,0,-c,0
posCone.x = 10;
posCone.y = 5;

lamdaRange = 2 * range;

betaRef = atan ( posCone.x / posCone.y ) * 180 / pi ;
dRef = sqrt ( posCone.x^2 + posCone.y^2 );

```

```

dA1MR    = dA1M*cos ( betaRef*pi/180);
phase     = dA1MR*360/ lamdaRange ;

error=0.01;
clear posMeasured

f    = 5.9 ; %i n Ghz
Pt = 30; %i n dB

%Old Model
% Rbp  = 4*( ha - 1) *(hb - 1)/ lamda ;
% n1 = 2.27;
% n2 = 4 ;
% L01 = 41+20 log10 ( f/5 );
% L02 = 41+20 *log10 ( f/5) - 17.3 *log10 ( Rbp );
% sigma 1 = 1;
% sigma 2 = 1;

%New Model
Rbp = 6.2;
n1 = 2.34;
n2 = 3.73;
L01 = 41+20 log10 ( f/5 );
L02 = 41+20 *log10 ( f/5) - 17.3 *log10 ( Rbp );
sigma1 = 0.6 ;
sigma2 = 0.42;

for i=1:100
    phase Measured = normrnd ( phase , error );
    dA1MR=phaseMeasured / ( 360) * lamdaRange ;

    betaMeasured  = abs ( atan (( sqrt ((dA1M/2)^2 -(dA1MR/2)^2 ))/(dA1MR/2)) * 180/ pi );

    d = d Ref;
    LOS = 1 ;
    if LOS
        if d<Rbp
            loss = L01 + 10 n1 log10 ( d );
            shadow    = lognrnd (0 , sigma 1 );

        else
            loss = L02 + 10 n2 log10 ( d );
            shadow    = lognrnd (0 , sigma 2 );
        end
    end
end

```



```

else
    if d<Rbp
        loss = L01 + 10 * n1 * log10 ( d );
        shadow = lognrnd ( 0 , sigma1 );
    else
        loss = L02 + 10 * n2 * log10 ( d );
        shadow = lognrnd ( 0 , sigma1 );
    end
    temp = 2.8 - 0.0024 * d;
    nj = max ( [ temp , 1.84 ] );
    loss = loss + 20 - 12.5 * nj + 10 * nj * log10 ( d );
end
RSSI = Pt - loss - shadow ;

dMeasured = 10 ^ ( ( Pt - RSSI - L01 ) / ( 10 * n1 ) );
if dMeasured > Rbp
    dMeasured = 10 ^ ( ( Pt - RSSI - L02 ) / ( 10 * n2 ) );
end
posMeasured ( i , 2 ) = dMeasured * cos ( betaMeasured * pi / 180 );
posMeasured ( i , 1 ) = dMeasured * sin ( betaMeasured * pi / 180 );
end

figure
scatter ( posMeasured ( : , 1 ) , posMeasured ( : , 2 ) , 'k' , 'Line Width' , 1 )
title ( 'Cone Position Estimates using RSSI and Phase Measurements' , 'FontSize' , 16 )
xlabel ( 'Position x (m)' , 'FontSize' , 16 );
ylabel ( 'Position y (m)' , 'FontSize' , 16 );
set ( gca , 'FontSize' , 15 , 'Line Width' , 1.5 );
axis ( [ 0 12 0 7 ] )
grid
hold on
scatter ( posCone . x , posCone . y , 'k' , '*' , 'Line Width' , 1 )
hold on
scatter ( 0.05 , 0.05 , 'k' , '*' , 'Line Width' , 1 )

legend ( 'Sensor Cone Estimates' , 'Actual Positions' , 2 )

```

```

% Lane and car grid
% Modified to include very noisy
% measurements of the GPS offsets

clear , close all;

% Standard lane width is 12 feet = 3.66 meters
% Assume 4 lanes with edges 0, 3.66, 7.32, 10.98, and 14.64 m
% and with centers 1.83, 5.49, 9.15, and 12.81 m
width = 3.66;
lane1 = 1.83;
lane2 = 5.49;
lane3 = 9.15;
lane4 = 12.81;

% Parameters
alphaLOS/NLOS = 0.1; % Probability for Markov chain
w_Sigma = 0.00001; % Process noise standard deviation
GPS_Sigma = 0.25; % GPS measurement noise standard deviation
RSSI_Sigma = 0.25; % RSSI measurement noise standard deviation
RSSI2D_Sigma = 5; % 2DRSSI measurement noise standard deviation
TOF_Sigma = 0.25; % TOF noise standard deviation
w_x_Sigma = w_Sigma; % Standard deviation of process noise w(k)
w_y_Sigma = w_Sigma; % in x- and y-directions

NumOfCars = 3; % Number of cars
NumOffsets = 2; % Number of offsets, x- and y-directions

% Sample rate is 50 Hz
Ts = 1/50; % Sample period is 0.02 s
Tsim = 100; % Simulation time in seconds
Nsamp = Tsim/Ts; % Number of discrete-time samples in simulation

% Random offsets
offsetX = normrnd(0,2) % Random
offsetY = normrnd(0,2)
offsetX = 4 % Override with specific values
offsetY = 4

% State vector defined: [p_x1; p_y1; p_dot_x1; p_dot_y1; ... offsetX; offsetY]
% 30 m/s = 67.1 mph
% Initial values
x_0_1 = [10; lane1; 30; 0; 30; lane2; 30; 0; 50; lane3; 30; 0; offsetX; offsetY];

```

```

% Initialize accelerations of all cars in the x-direction to zero
p_ddot_x = zeros (Nsamp, NumOfCars);

% Override x-direction accelerations
p_ddot_x(6/Ts:8/Ts,1) = 4;
p_ddot_x(9/Ts:10/Ts,1) = -4;
p_ddot_x(20/Ts:21/Ts,2) = 4;
p_ddot_x(28/Ts:30/Ts,2) = -4;
p_ddot_x(65/Ts:67/Ts,3) = -4;
p_ddot_x(75/Ts:77/Ts,3) = 4;

% Initial positions of all cars in the x-direction
p_x = zeros(Nsamp, NumOfCars);
p_x(1,1) = x_0_1(1);
p_x(1,2) = x_0_1(5);
p_x(1,3) = x_0_1(9);

% Initial positions of all cars in the y-direction
p_y = zeros(Nsamp+2, NumOfCars); % Need k+2 because of derivatives below
p_y(1,1) = x_0_1(2);
p_y(1,2) = x_0_1(6);
p_y(1,3) = x_0_1(10);

% Describe car lane change along y-direction (meters)

% Specify start time of lane changes (s) and sign (+ move left/right)
% Car 1: 10(+), 40(-)
% Car 2: 30(+), 70(+)
% Car 3: 50(+)
% Need a loop for each car change

for i = 2:10/Ts
    p_y(i,1) = p_y(i-1,1);
    p_y(i,2) = p_y(i-1,2);
    p_y(i,3) = p_y(i-1,3);
end

change = 5; % Seconds to change lanes
for i = 10/Ts+1:(10+change)/Ts
    p_y(i,1) = p_y(i-1,1) + width*Ts/change;
    p_y(i,2) = p_y(i-1,2);
    p_y(i,3) = p_y(i-1,3);
end

for i = (10+change)/Ts+1:30/Ts

```

```

    p_y(i,1)=p_y(i-1,1);
    p_y(i,2)=p_y(i-1,2);
    p_y(i,3)=p_y(i-1,3);
end

change = 6; % Seconds to change lanes
for i = 30/Ts+1:(30+change)/Ts
    p_y(i,1) = p_y(i-1,1);
    p_y(i,2) = p_y(i-1,2) + width*T_s/change;
    p_y(i,3)=p_y(i-1,3);
end

for i = (30+change)/Ts+1:40/Ts
    p_y(i,1)=p_y(i-1,1);
    p_y(i,2) = p_y(i-1,2);
    p_y(i,3) = p_y(i-1,3);
end

change = 4; % Seconds to change lanes
for i = 40/Ts+1:(40+change)/Ts
    p_y(i,1) = p_y(i-1,1) - width*T_s/change;
    p_y(i,2)=p_y(i-1,2);
    p_y(i,3) = p_y(i-1,3);
end

for i = (40+change)/Ts+1:50/Ts
    p_y(i,1)=p_y(i-1,1);
    p_y(i,2) = p_y(i-1,2);
    p_y(i,3) = p_y(i-1,3);
end

change = 5; % Seconds to change lanes
for i = 50/Ts+1:(50+change)/Ts
    p_y(i,1) = p_y(i-1,1);
    p_y(i,2) = p_y(i-1,2);
    p_y(i,3)=p_y(i-1,3)+width*T_s/change;
end

for i = (50+change)/Ts+1:70/Ts
    p_y(i,1)=p_y(i-1,1);
    p_y(i,2) = p_y(i-1,2);
    p_y(i,3) = p_y(i-1,3);
end

change = 7; % Seconds to change lanes

```

```

for i = 70/Ts+1:(70+change)/Ts
    p_y(i,1)=p_y(i-1,1);
    p_y(i,2) = p_y(i-1,2) + width*T_s/change;
    p_y(i,3)=p_y(i-1,3);
end

for i = (70+change)/Ts+1:100/Ts+2
    p_y(i,1)=p_y(i-1,1);
    p_y(i,2) = p_y(i-1,2);
    p_y(i,3) = p_y(i-1,3);
end

% Compute accelerations in y direction
p_dot_y=diff(p_y)./Ts;
p_ddot_y=diff(p_dot_y)./Ts;

% Construct input vector for state-space model
% based on accelerations
u=zeros(Nsamp,2*NumOfCars);
for i=1:NumOfCars
    u(:,2*i-1)=p_ddot_x(i,i);
    u(:,2*i)=p_ddot_y(i,i);
end

% Matrices for state-space model

% A matrix for updating states
A=eye(4*NumOfCars+NumOffsets);
tempA=[1 0 Ts 0;
        0 1 0 Ts;
        0 0 1 0;
        0 0 0 1];
for i=1:NumOfCars
    A(4*i-3:4*i,4*i-3:4*i) = tempA; % Repeats temp along diagonal
end

% D matrix for incorporating accelerations
D=zeros(4*NumOfCars+NumOffsets,2*NumOfCars); tempD
=Ts.*[Ts/2 0 *
       0 Ts/2;
       1 0;
       0 1];
for i=1:NumOfCars
    D(4*i-3:4*i,2*i-1:2*i) = tempD; % Repeats pattern for accelerations
end

```

```

% F matrix for GPS: extracts positions with offsets
FGPS = zeros(2*NumOfCars+ NumOffsets, 4*NumOfCars+ NumOffsets); tempF
= eye(2);
for i=1:NumOfCars
    FGPS(2*i-1:2*i, 4*i-3:4*i-2) = tempF; % Repeats pattern for positions
    FGPS(2*i-1:2*i, end-1:end) = tempF; % Add offsets
end
FGPS(7,13) = 1; % Measure offsets
FGPS(8,14) = 1;

% Q matrix for process noise
Q = eye(4*NumOfCars+ NumOffsets);
tempQ = [(Ts^2/2 * w_x_Sigma)^2 0 (Ts^2/2 * w_x_Sigma)*(Ts * w_x_Sigma);
          0 (Ts^2/2 * w_y_Sigma)^2 0 (Ts^2/2 * w_y_Sigma)*(Ts * w_y_Sigma);
          (Ts * w_x_Sigma)*(Ts^2/2 * w_x_Sigma) 0 (Ts * w_x_Sigma)^2 0;
          0 (Ts * w_y_Sigma)*(Ts^2/2 * w_y_Sigma) 0 (Ts * w_y_Sigma)^2];
for i=1:NumOfCars
    Q(4*i-3:4*i, 4*i-3:4*i) = tempQ;
end
Q = w_Sigma^2.* eye(4*NumOfCars+ NumOffsets); % Override previous form
%Q(end-1, end-1) = 0; % Zero variance for GPS position offsets
%Q(end, end) = 0;

% Generate actual car trajectories from state-space model
x = zeros(Nsamp, 4*NumOfCars+ NumOffsets);
w = normrnd(0, w_Sigma, Nsamp, 4*NumOfCars+ NumOffsets); % Process noise
w(:, 4*NumOfCars+ NumOffsets-1) = 0; % No noise for offsets
w(:, 4*NumOfCars+ NumOffsets) = 0;
x(1,:) = x_0_1; % Initial state vector

for instant = 2:Nsamp
    x(instant,:) = A*x(instant-1,:) + D*u(instant,:) + w(instant,:);
end

% Generate GPS signals
for instant = 1:Nsamp
    v = normrnd(0, GPS_Sigma, 2*NumOfCars+ NumOffsets, 1);
    v(7,1) = normrnd(0,5); % Large noise for offset measurements
    v(8,1) = normrnd(0,5);
    y_GPS(instant,:) = FGPS*x(instant,:) + v; % F incorporates offsets
end

% Simulate LOS / NLOS
zvar = GenLOS/NLOS(Nsamp, NumOfCars, alphaLOS/NLOS);

```

```

% Generate RSSI signals
for instant = 1:Nsamp
    v = normrnd ( 0, RSSI_Sigma, 2 NumOfCars, 1 );
    zv = zvar(:, :, instant);
    RSSI = GenRSSI([ x(instant, 1) x(instant, 5) x(instant, 9)], ...
        [ x(instant, 2) x(instant, 6) x(instant, 10)], NumOfCars, zv );
    y_RSSI(instant, :) = [RSSI(1, 2); RSSI(2, 1); RSSI(1, 3); RSSI(3, 1); RSSI(2, 3); RSSI(3, 1);
end

% Generate TOF Signal
%vt = zeros(2 nchoosek(NumOfCars, 2), 1); % Check if noise should be included
%for instant = 1:Nsamp
    %vt = normrnd ( 0, TOF_Sigma, 2 nchoosek(NumOfCars, 2), 1 );
    %[TOF] = GenTOF([ x(1) x(5) x(9)], [ x(2) x(6) x(10)], NumOfCars );
    %y_TOF(instant, :) = [TOF(1, 2); TOF(2, 1); TOF(1, 3); TOF(3, 1); TOF(2, 3); TOF(3, 2)] +
%end

% Generate 2D RSSI signals
for instant = 1:Nsamp
    v = normrnd ( 0, RSSI2D_Sigma, 2 2 NumOfCars, 1 ); zv =
    zvar(:, :, instant);
    Dxy = Gen2DRSSI([ x(instant, 1) x(instant, 5) x(instant, 9)], ...
        [ x(instant, 2) x(instant, 6) x(instant, 10)], NumOfCars );
    y_Dxy(instant, :) = [Dxy(1, 2, 1); Dxy(1, 2, 2); Dxy(2, 1, 1); Dxy(2, 1, 2); Dxy(1, 3, 1); Dxy(1, 3, 2);
end

%RunGPSOnly4
%RunRSSIonly

%RunGPS_RSSI
RunGPS_2DRSSI



---




---



% KF and EKF ( GPS and RSSI )
% u = state_space input vector
% x_k = current state estimate vector
% clock = time instant * T_s
% Q = process covariance matrix
% REKF = measurement covariance matrix
% P_k = current innovations covariance matrix
% A = state_space transition matrix
% D = state_space input matrix
% F = measurement matrix

```



```

% y = GPS measurement vector
% yRSSI = RSSI measurement vector

function [ x_hat , P ] = KFEKF ( u , x_k , clock , Q , R , REKF , P_k , A , D , F , y , yRSSI )

% PREDICTION STAGE ( for KF and EKF ) :
x_hat = A * x_k + D * u ;
P = A * P_k * A' + Q;

% If GPS is available, go to KF filtering stage
if mod(clock,1)==0 % Update rate for KF

% FILTERING STAGE:
K = P * F' / ( F * P * F' + R ); % Kalman gain
y_hat = F * x_hat ;
x_hat = x_hat + K * ( y - y_hat );
P = ( eye ( length ( A ) ) - K * F ) * P;

else

if 1
    FRSSI = GenF ( x_hat );
    KRSSI = P * FRSSI' / ( FRSSI * P * FRSSI' + REKF ); % EKF gain
    [ RSSI_hat ] = GenyForRSSI ( [ x_hat ( 1 ) x_hat ( 5 ) x_hat ( 9 ) ] , [ x_hat ( 2 ) x_hat ( 6 ) x_hat ( 10 ) ] );
    y_hatRSSI = [ RSSI_hat ( 1 , 2 ); RSSI_hat ( 2 , 1 ); RSSI_hat ( 1 , 3 ); RSSI_hat ( 3 , 1 ); RSSI_hat ( 1 , 4 ); RSSI_hat ( 4 , 1 ) ];
    % Include estimates of offsets
    yRSSI = [ yRSSI , y ( 7 ) , y ( 8 ) ]; % Include measured offsets
    x_hat = x_hat + KRSSI * ( yRSSI' - y_hatRSSI );
    P = ( eye ( length ( A ) ) - KRSSI * FRSSI ) * P;
end
end



---




---



% KF and EKF ( GPS and RSSI )
% u = state_space input vector
% x_k = current state estimate vector
% clock = time instant * T_s
% Q = process covariance matrix
% REKF = measurement covariance matrix
% P_k = current innovations covariance matrix
% A = state_space transition matrix
% D = state_space input matrix
% F = measurement matrix
% y = GPS measurement vector
% yRSSI = RSSI measurement vector

```

```

function[ x_hat , P ] =KFKE( u , x_k_cloc k , Q , R , RKF , P_k_A , D , F , y , y_Dxy )

% PREDICTION STAGE ( for KF and EKF ) :
x_hat = A* x_k + D*u ' ;
P = A*P_k*A' + Q;

% If GPS is available, go to KF filtering stage
if mod(clock ,1)==0 % Update rate for KF

% FILTERING STAGE:
K = P*F' / ( F*P*F' + R ); % Kalman gain
y_hat = F* x_hat ;
x_hat = x_hat + K*(y' - y_hat );
P = ( eye ( length (A)) - K*F ) * P;

else

if 1
F2DRSSI=zeros(14,14);
F2DRSSI(1,1) = 1; F2DRSSI(5,1) = -1; %c ar 121
F2DRSSI(2,2) = 1; F2DRSSI(6,2) = -1; %c ar 122
F2DRSSI(1,3) = -1; F2DRSSI(5,3) = 1; %c ar 211
F2DRSSI(2,4) = -1; F2DRSSI(6,4) = 1; %c ar 212
F2DRSSI(1,5) = 1; F2DRSSI(9,5) = -1; %c ar 131
F2DRSSI(2,6) = 1; F2DRSSI(10,6)= -1; %c ar 132
F2DRSSI(1,7) = -1; F2DRSSI(9,7) = 1; %c ar 311
F2DRSSI(2,8) = -1; F2DRSSI(10,8)= 1; %c ar 312
F2DRSSI(5,9) = 1; F2DRSSI(9,9) = -1; %c ar 231
F2DRSSI(6,10)= 1; F2DRSSI(10,10)= -1; %c ar 232
F2DRSSI(5,11)= -1; F2DRSSI(9,11) = 1; %c ar 321
F2DRSSI(6,12)= -1; F2DRSSI(10,12)= 1; %c ar 322
F2DRSSI(13,13)=1; F2DRSSI(14,14)= 1; %Offsets
F2DRSSI = F2DRSSI';

K2DRSSI = P F2DRSSI' / ( F2DRSSI P F2DRSSI' + RKF ); % EKF gain
y_hat2_DRSSI = F2DRSSI*x_hat; % Include estimates of offsets
y2DRSSI = [ y_Dxy , y(7) , y(8)]; % Include measured offsets
x_hat = x_hat + K2DRSSI*( y2DRSSI' - y_hat2_DRSSI );
P = ( eye ( length (A)) - K2DRSSI*F2DRSSI ) * P;
end
end

```

```

%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%

```



```

x_k = x_hat + K*(y_GPS(1,:) - y_hat);
P_k = (eye(length(A)) - K*FGPS)*P;
Output(1,:) = x_k';

% KF / EKF loop
for instant = 2:Nsamp % Start at time instant 2
    clock = instant*Ts; % 1 Hz rate for GPS
    [x_hat, P_hat] = KF(KF(u(instant,:), x_k, clock, Q, R_KF, R_2DKF, P_k, A, D, ... ,
        FGPS, y_GPS(instant,:), y_Dxy(instant,:)));
    x_k = x_hat; % Save for next iteration
    P_k = P_hat;
    Output(instant,:) = x_hat; % Save for plotting
end

%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
% Plot trajectories
figure; hold all; % Actual positions
plot(x(:,1), x(:,2), 'LineWidth', 2);
plot(x(:,5), x(:,6), 'LineWidth', 2);
plot(x(:,9), x(:,10), 'LineWidth', 2); grid;
set(gca, 'FontSize', 15, 'LineWidth', 1.5);
xlabel('Position in x-direction (m)', 'FontSize', 16);
ylabel('Position in y-direction (m)', 'FontSize', 16);
title('Car Trajectories', 'FontSize', 16);

figure; hold all; % Actual velocities in y direction
plot(x(:,4), 'LineWidth', 2);
plot(x(:,8), 'LineWidth', 2);
plot(x(:,12), 'LineWidth', 2); grid;
set(gca, 'FontSize', 15, 'LineWidth', 1.5);
xlabel('Time (samples)', 'FontSize', 16);
ylabel('Velocity in y-direction (m/s)', 'FontSize', 16);
title('Car Velocities in y-Direction', 'FontSize', 16);

figure; hold all; % Actual velocities in x direction
plot(x(:,3), 'LineWidth', 2);
plot(x(:,7), 'LineWidth', 2);
plot(x(:,11), 'LineWidth', 2); grid;
set(gca, 'FontSize', 15, 'LineWidth', 1.5);
xlabel('Time (samples)', 'FontSize', 16);
ylabel('Velocity in x-direction (m/s)', 'FontSize', 16);
title('Car Velocities in x-Direction', 'FontSize', 16);

```

```

figure; hold all; %GPS positions
plot(y_GPS(:,1),y_GPS(:,2),'LineWidth',2);
plot(y_GPS(:,3),y_GPS(:,4),'LineWidth',2);
plot(y_GPS(:,5),y_GPS(:,6),'LineWidth',2); grid;
set(gca,'FontSize',15,'LineWidth',1.5)
xlabel('GPS Position in x-direction (m)','FontSize',16);
ylabel('GPS Position in y-direction (m)','FontSize',16);
title('GPS Measurements','FontSize',16);

figure; hold all; %KF Positions
plot(Output(:,1),Output(:,2),'LineWidth',2);
plot(Output(:,5),Output(:,6),'LineWidth',2);
plot(Output(:,9),Output(:,10),'LineWidth',2); grid;
set(gca,'FontSize',15,'LineWidth',1.5)
xlabel('KF Filter Estimate in x-direction (m)','FontSize',16);
ylabel('KF Filter Estimate in y-direction (m)','FontSize',16);
title('KF Position Estimates Based on GPS','FontSize',16);

figure; hold all; %KF Velocities in x-direction
plot(Output(:,3),'LineWidth',2);
plot(Output(:,7),'LineWidth',2);
plot(Output(:,11),'LineWidth',2); grid;
;
set(gca,'FontSize',15,'LineWidth',1.5)
xlabel('Time (samples)','FontSize',16);
ylabel('KF velocity in x-direction (m)','FontSize',16);
title('KF Velocities in x-Direction','FontSize',16);

figure; hold all; %KF Velocities in y-direction
plot(Output(:,4),'LineWidth',2);
plot(Output(:,8),'LineWidth',2);
plot(Output(:,12),'LineWidth',2); grid;
;
set(gca,'FontSize',15,'LineWidth',1.5)
xlabel('Time (samples)','FontSize',16);
ylabel('KF velocity in y-direction (m)','FontSize',16);
title('KF Velocities in y-Direction','FontSize',16);

figure; hold all; %Offset estimates
plot(Output(:,13),'LineWidth',2);
plot(Output(:,14),'LineWidth',2); grid;
;

```

```

set(gca,'FontSize',15,'LineWidth',1.5)
xlabel('Time (samples)','FontSize',16);
ylabel('Offsets (m)','FontSize',16);
title('Offset Estimates','FontSize',16);

```

```

%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
% KALMAN FILTER AND EKF ( GPS and RSSI signals )

% R matrix for KF
R_KF = eye(2*NumOfCars+ NumOffsets).*GPS_Sigma^2;
R_KF(7,7)=5;
R_KF(8,8)=5;
%R_KF=eye(2*NumOfCars).*100; % Override previous

% R_EKF matrix for EKF
R_EKF = eye(2*NumOfCars+ NumOffsets).*RSSI_Sigma^2;
R_KF(7,7)=5;
R_KF(8,8)=5;

% Initial conditions
% Actual starting conditions :
%x_k = x0;
% Everything zero :
%x_k = zeros(14,1);
% Everything zero , except correct offsets
%x_k = [zeros(12,1); offsetX; offsetY];
% Correct velocities only :
x_k = [y_GPS(1,1); y_GPS(1,2); 30; 0; y_GPS(1,3); y_GPS(1,4); 30; 0; y_GPS(1,5); y_GPS(1,6); 30; 0; y_GPS(1,7); y_GPS(1,8); 30; 0];
% Correct velocities and offsets :
%x_k = [y_GPS(1,1); y_GPS(1,2); 30; 0; y_GPS(1,3); y_GPS(1,4); 30; 0; y_GPS(1,5); y_GPS(1,6); 30; 0; y_GPS(1,7); y_GPS(1,8); 30; 0];
% Correct velocities and lanes ( y positions ) :
%x_k = [y_GPS(1,1); lane1; 30; 0; y_GPS(1,3); lane2; 30; 0; y_GPS(1,5); lane3; 30; 0; y_GPS(1,7); lane4; 30; 0];

P_k = 100.*eye(4*NumOfCars+ NumOffsets);
%P_k = Q;

% Use KF/ GPS for time instant l
% PREDICTION STAGE :
x_hat = A*x_k + D*u(1,:);
P = A*P_k*A' + Q;

% FILTERING STAGE:
K = P*FGPS'/(FGPS*P*FGPS' + R_KF); % Kalman gain
y_hat = FGPS*x_hat;

```

```

x_k = x_hat + K*(y_GPS(1,:) - y_hat);
P_k = (eye(length(A)) - K*FGPS)*P;
Output(1,:) = x_k';

% KF / EKF loop
for instant = 2:Nsamp % Start at time instant 2
    clock = instant*Ts; % 1 Hz rate for GPS
    [x_hat, P_hat] = KF_EKF(instant, x_k, clock, Q, R_KF, R_EKF, P_k, A, D, ...
        FGPS, y_GPS(instant,:), y_RSSI(instant,:));
    x_k = x_hat; % Save for next iteration
    P_k = P_hat;
    Output(instant,:) = x_hat; % Save for plotting
end

%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
% Plot trajectories
figure; hold all; % Actual positions
plot(x(:,1), x(:,2), 'LineWidth', 2);
plot(x(:,5), x(:,6), 'LineWidth', 2);
plot(x(:,9), x(:,10), 'LineWidth', 2); grid;
set(gca, 'FontSize', 15, 'LineWidth', 1.5)
xlabel('Position in x-direction (m)', 'FontSize', 16);
ylabel('Position in y-direction (m)', 'FontSize', 16);
title('Car Trajectories', 'FontSize', 16);

figure; hold all; % Actual velocities in y direction
plot(x(:,4), 'LineWidth', 2);
plot(x(:,8), 'LineWidth', 2);
plot(x(:,12), 'LineWidth', 2); grid;
set(gca, 'FontSize', 15, 'LineWidth', 1.5)
xlabel('Time (samples)', 'FontSize', 16);
ylabel('Velocity in y-direction (m/s)', 'FontSize', 16);
title('Car Velocities in y-Direction', 'FontSize', 16);

figure; hold all; % Actual velocities in x direction
plot(x(:,3), 'LineWidth', 2);
plot(x(:,7), 'LineWidth', 2);
plot(x(:,11), 'LineWidth', 2); grid;
set(gca, 'FontSize', 15, 'LineWidth', 1.5)
xlabel('Time (samples)', 'FontSize', 16);
ylabel('Velocity in x-direction (m/s)', 'FontSize', 16);
title('Car Velocities in x-Direction', 'FontSize', 16);

```



```

figure; hold all; %GPS positions
plot(y_GPS(:,1),y_GPS(:,2),'LineWidth',2);
plot(y_GPS(:,3),y_GPS(:,4),'LineWidth',2);
plot(y_GPS(:,5),y_GPS(:,6),'LineWidth',2); grid;
set(gca,'FontSize',15,'LineWidth',1.5)
xlabel('GPS Position in x-direction (m)','FontSize',16);
ylabel('GPS Position in y-direction (m)','FontSize',16);
title('GPS Measurements','FontSize',16);

figure; hold all; %KF Positions
plot(Output(:,1),Output(:,2),'LineWidth',2);
plot(Output(:,5),Output(:,6),'LineWidth',2);
plot(Output(:,9),Output(:,10),'LineWidth',2); grid;
set(gca,'FontSize',15,'LineWidth',1.5)
xlabel('KF Filter Estimate in x-direction (m)','FontSize',16);
ylabel('KF Filter Estimate in y-direction (m)','FontSize',16);
title('KF Position Estimates Based on GPS','FontSize',16);

figure; hold all; %KF Velocities in x-direction
plot(Output(:,3),'LineWidth',2);
plot(Output(:,7),'LineWidth',2);
plot(Output(:,11),'LineWidth',2); grid;
;
set(gca,'FontSize',15,'LineWidth',1.5)
xlabel('Time (samples)','FontSize',16);
ylabel('KF velocity in x-direction (m)','FontSize',16);
title('KF Velocities in x-Direction','FontSize',16);

figure; hold all; %KF Velocities in y-direction
plot(Output(:,4),'LineWidth',2);
plot(Output(:,8),'LineWidth',2);
plot(Output(:,12),'LineWidth',2); grid;
;
set(gca,'FontSize',15,'LineWidth',1.5)
xlabel('Time (samples)','FontSize',16);
ylabel('KF velocity in y-direction (m)','FontSize',16);
title('KF Velocities in y-Direction','FontSize',16);

figure; hold all; %Offset estimates
plot(Output(:,13),'LineWidth',2);
plot(Output(:,14),'LineWidth',2); grid;
;

```

```

set(gca,'FontSize',15,'LineWidth',1.5)
xlabel('Time (samples)', 'FontSize',16);
ylabel('Offsets (m)', 'FontSize',16);
title('Offset Estimates', 'FontSize',16);

```

```

% Generate measurement estimates for RSSI signals between all cars
% x = car x positions
% y = car y positions
% N=number of cars

```

```

function RSSI_hat = GenyForRSSI(x,y)

```

```

f=5.9; %in Ghz
N=length(x);

```

```

    for i=1:N
        posCar i . x = x ( i ) ;
        posCar i . y = y ( i ) ; fo
        rj=1:N
            posCar j . x = x ( j ) ;
            posCar j . y = y ( j ) ;
            dij = sqrt (( posCar i . x - posCar j . x ) ^ 2 + ( posCar i . y - posCar j . y ) ^ 2
        if dij ~= 0
            RSSI_hat ( i , j ) = 22.7 log10 ( dij ) + 41 + 20.0 log10 ( f / 5 ) ;
        else
            RSSI_hat ( i , j ) = -1;
        end
    end
end
end

```

```

% Compute loss due to shadowing
% d = distance

```

```

function shadow = GenShadowing(d)

```

```

nu = 4; % 4 to 12 dB
m = eps; % a very small number close to 0
%D = d + 10;
%ds = D / log(2);
%autoCorr = nu ^ 2 * exp(-abs(d)/ds);

```

```

sig=sqrt (log (nu / (m^2+1 )) );
%mu = log (m^2 / ( sqrt (nu+m^2)));
shadow=lognrnd (0.01 , sig );

```

```

% O v e r r i d e a b o v e
shadow = 0 ;

```

```

end

```

```

% G e n e r a t e R S S I s i g n a l s b e t w e e n a l l c a r s
% x = c a r x p o s i t i o n s
% y = c a r y p o s i t i o n s
% N = n u m b e r o f c a r s
% z = L O S N L O S m a t r i x

```

```

function RSSI = GenRSSI(x,y,N,z)

```

```

    for i=1:N
        posCar i . x = x ( i );
        posCar i . y = y ( i );
        for j = 1:N
            posCar j . x = x ( j );
            posCar j . y = y ( j );
            d i j = sqrt (( posCar i . x - posCar j . x ) ^ 2 + ( posCar i . y - posCar j . y ) ^ 2
            if d i j ~= 0
                if z == 0
                    RSSI ( i , j ) = GenPathLoss ( 1 , d i j , 0 , 0 ) + GenShadowing ( d i j ); %
                else
                    RSSI ( i , j ) = GenPathLoss ( 0 , d i j , d i j , d i j ) + GenShadowing ( d i j )
                end
            else
                RSSI ( i , j ) = -1;
            end
        end
    end
end

```

```

end

```

```

% D e t e r m i n e p a t h l o s s
% d = d i s t a n c e
% L O S = l i n e o f s i g h t
% d A =

```

```

% dB =

function loss = GenPathLoss(LOS,d,dA,dB)

f = 5.9;% frequency in Ghz
ha = 5;
hb = 5;
lambda = 3 * 10^ 8/ ( f * 10^ 9) ;
Rbp = 4 *( ha - 1) *(hb - 1)/ lambda ;

if LOS
    if d < Rbp
        loss = 22.7 log10 ( d)+ 41+20.0 log10 ( f/ 5);
    else
        loss = 40.0 * log10 ( d)+ 41 - 17.3* log10 ( Rbp )+ 20 * log10 ( f/ 5);
    end
else
    if dA < Rbp
        loss = 22.7 log10 ( d)+ 41+20.0 log10 ( f/ 5);
    else
        loss = 40.0 * log10 ( d)+ 41 - 17.3* log10 ( Rbp )+ 20 * log10 ( f/ 5);
    end
    temp = 2.8 - 0.0024 * dA;
    nj = max ( [ temp,1.84] );
    loss = loss+20 - 12.5* nj +10* nj * log10 ( dB);
end

% Override above
loss = 22.7 * log10 ( d)+41+20.0 * log10 ( f/ 5);

end

```

```

% Generate LOS/NLOS Markov variables for all cars
% at each time instant

```

```

% T = number of samples
% N = number of cars
% alpha = Markov parameter with range [0,1]

```

```

function zvar = GenLOSNNLOS(T,N, alpha)

```

```

for i = 1:N          %initial
    for j = 1:N
        markov = rand;
    end
end

```

```

        if markov <= alpha
            zvar(i,j,1) = 1;
        else
            zvar(i,j,1) = 0;
        end
    end
end
for k = 2:T
    for i = 1:N           % for all time
        for j = 1:N
            markov = rand;
            if zvar(i,j,k-1) == 0
                if markov <= alpha/2
                    zvar(i,j,k) = 1;
                else
                    zvar(i,j,k) = 0;
                end
            else
                if markov <= (1-alpha)/2;
                    zvar(i,j,k) = 0;
                else
                    zvar(i,j,k) = 1;
                end
            end
        end
    end
end
end
end
end

```

% Generates F matrix for EKF

function F = GenF(x)

% Distances

```

d12 = sqrt( (x(1)-x(5))^2 + (x(2)-x(6))^2 );
d21 = sqrt( (x(5)-x(1))^2 + (x(6)-x(2))^2 );
d13 = sqrt( (x(1)-x(9))^2 + (x(2)-x(10))^2 );
d31 = sqrt( (x(9)-x(1))^2 + (x(10)-x(2))^2 );
d23 = sqrt( (x(5)-x(9))^2 + (x(6)-x(10))^2 );
d32 = sqrt( (x(9)-x(5))^2 + (x(10)-x(6))^2 );

```

% Elements

```

F11 = 22.7/d12 * abs(x(1)-x(5))/d12;

```

```

F12 = 22.7/d12 * abs (x(2) - x ( 6))/ d12 ;
F15 = 22.7/d12 * -abs ( x(1) - x ( 5))/ d12 ;
F16 = 22.7/d12 * -abs ( x(2) - x ( 6))/ d12 ;

F21 = 22.7/d21 * -abs ( x(5) - x ( 1))/ d21 ;
F22 = 22.7/d21 * -abs ( x(6) - x ( 2))/ d21 ;
F25 = 22.7/d21 * abs (x(5) - x ( 1))/ d21 ;
F26 = 22.7/d21 * abs (x(6) - x ( 2))/ d21 ;

F31 = 22.7/ d13 * abs ( x(1) - x ( 9))/ d13 ;
F32 = 22.7/ d13 * abs ( x(2) - x ( 10))/ d13 ;
F39 = 22.7/ d13 * -abs ( x(1) - x ( 9))/ d13 ;
F310 = 22.7/ d13 * -abs (x(2) - x ( 10))/ d13 ;

F41 = 22.7/ d31 * -abs ( x(9) - x ( 1))/ d31 ; F42 =
22.7/ d31 * -abs ( x (10) - x ( 2))/ d31 ;
F49 = 22.7/ d31 * abs ( x(9) - x ( 1))/ d31 ;
F410 = 22.7/ d31 * abs (x(10) - x ( 2))/ d31 ;

F55 = 22.7/ d23 * abs ( x(5) - x ( 9))/ d23 ;
F56 = 22.7/ d23 * abs ( x(6) - x ( 10))/ d23 ;
F59 = 22.7/ d23 * -abs ( x(5) - x ( 9))/ d23 ;
F510 = 22.7/ d23 * -abs (x(6) - x ( 10))/ d23 ;

F65 = 22.7/ d32 * -abs ( x(9) - x ( 5))/ d32 ; F66 =
22.7/ d32 * -abs ( x (10) - x ( 6))/ d32 ;
F69 = 22.7/ d32 * abs ( x(9) - x ( 5))/ d32 ;
F610 = 22.7/ d32 * abs ( x(10) - x ( 6))/ d32 ;

F = [ F11 F12 0 0 F15 F16 0 0 0 0 0 0 0 0 ;
      F21 F22 0 0 F25 F26 0 0 0 0 0 0 0 0 ;
      F31 F32 0 0 0 0 0 0 F39 F310 0 0 0 0 ;
      F41 F42 0 0 0 0 0 0 F49 F410 0 0 0 0 ;
      0 0 0 0 F55 F56 0 0 F59 F510 0 0 0 0 ;
      0 0 0 0 F65 F66 0 0 F69 F610 0 0 0 0 ;
      0 0 0 0 0 0 0 0 0 0 0 1 0 ;
      0 0 0 0 0 0 0 0 0 0 0 1]; % Includes offsets

end

```

```

% Generate RSSI signals between all cars
% x = car x positions
% y = car y positions
% N = number of cars

```

```

% z = LOSNLOS matrix

function Dxy = Gen2DRSSI(x, y, N)

for i = 1:N
    posCar i . x = x ( i ) ;
    posCar i . y = y ( i ) ; for
    rj = 1:N
        posCar j . x = x ( j ) ;
        posCar j . y = y ( j ) ;
        dij = sqrt (( posCar i . x posCar j . x )^2+( posCar i . y posCar j . y )^2);
        if dij ~= 0
            %shadow = GenShadowing ( dij ) ;
            shadow = 0 ;
            Dxy( i , j , 1 ) = posCar i . x posCar j . x + shadow / 2 ;
            Dxy( i , j , 2 ) = posCar i . y posCar j . y + shadow / 2 ;
        else
            Dxy( i , j , 1 ) = 0 ;
            Dxy( i , j , 2 ) = 0 ;
        end
    end
end
end
end

```

```
%% Programed by Adam M o r t a z a v i
% U n i v e r s i t y o f C a l i f o r n i a S a n t a B a r b a r a , M a y 2 5 , 2 0 1 4
```

```
%% c l e a r m e m o r y , s c r e e n , a n d c l o s e a l l f i g u r e s
```

```
cl ear , cl c , cl o s e a l l ;
```

```
%% P a r a m e t e r s
```

```
Ts = 1 / 50 ;
```

```
% A m a t r i x
```

```
A = eye ( 2 4 + 2 ) ;
```

```
temp = [ 1 0 Ts 0 ;
```

```
0 1 0 Ts ;
```

```
0 0 1 0 ;
```

```
0 0 0 1 ; ] ;
```

```
for i = 1 : 2
```

```
    A ( 4 * i - 3 : 4 * i , 4 * i - 3 : 4 * i ) = temp ;
```

```
end
```

```
% D m a t r i x
```

```
D = zer os ( 2 4 + 2 , 2 2 ) ;
```

```
temp = Ts [ 0 0 ;
```

```
0 0 ;
```

```
1 0 ;
```

```
0 1 ; ] ;
```

```
for i = 1 : 2
```

```
    D ( 4 * i - 3 : 4 * i , 2 * i - 1 : 2 * i ) = temp ;
```

```
end
```

```
% F m a t r i x
```

```
F = zer os ( 2 2 , 2 4 + 2 ) ;
```

```
temp = [ 1 0 ;
```

```
0 1 ; ] ;
```

```
for i = 1 : 2
```

```
    F ( 2 * i - 1 : 2 * i , 4 * i - 3 : 4 * i - 2 ) = temp ;
```

```
    F ( 2 * i - 1 : 2 * i , end - 1 : end ) = temp ;
```

```
end
```

```
%%
```

```
%Sigma of w(k) i n X a n d Y d i r e c t i o n
```

```
w_uX_Sigma = . 0 1 ;
```

```
w_uY_Sigma = . 0 1 ;
```

```
%Sigma of v(k) i n X a n d Y d i r e c t i o n
```

```

GPS_Xmeas_Sigma = 2; %GPS standard deviation
GPS_Ymeas_Sigma = 2; %GPS standard deviation
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
%% Initialize Q matrix: used by KF, EKF and EKF&KF
% Initialize RKF matrix, REKF matrix
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
%Process error for Q matrix
u_x_Sigma = w_uX_Sigma * 15;
u_y_Sigma = w_uY_Sigma * 15;
% Setup Q matrix
Q = eye(2*4);
temp = [(Ts^2/2*u_x_Sigma)^2 0 Ts^2/2*u_x_Sigma*T_s_u_x_Sigma 0; * _ _
        0 (Ts^2/2*u_y_Sigma)^2 0 Ts^2/2*u_y_Sigma*T_s_u_y_Sigma;
        T_s*u_x_Sigma*T_s^2/2*u_x_Sigma 0 (T_s*u_x_Sigma)^2 0;
        0 T_s*u_y_Sigma T_s^2/2*u_y_Sigma 0 (T_s*u_y_Sigma)^2;];
for i = 1:2
    Q(4*i-3:4*i, 4*i-3:4*i) = temp;
end
Q(end-1, end-1) = .05^2;
Q(end, end) = .05^2;

%%
%B
Bw = zeros(10,1);
Bw(1) = Ts^2/2;
Bw(2) = Ts;
Bw(3) = Ts^2/2;
Bw(4) = Ts;
Bw(5) = Ts^2/2;
Bw(6) = Ts;
Bw(7) = Ts^2/2;
Bw(8) = Ts;

%%
GPS_Xmeas_Sigma = 2;
GPS_Ymeas_Sigma = 2;
%Measurement error for measurement matrix, RKF
GPS_x_Sigma = GPS_Xmeas_Sigma;
GPS_y_Sigma = GPS_Ymeas_Sigma;
% Setup RKF matrix
R = eye(2*2);
for i = 1:2
    R(i*2-1, i*2-1) = (GPS_x_Sigma * 1)^2;
    R(i*2, i*2) = (GPS_y_Sigma * 1)^2;

```

```

end
a= acceleration();
%% Process equation  $x[k] = \text{sys}(k, x[k-1], u[k])$ ;
nx = 10; % number of states
sys = @(k, xkm1, uk) A * xkm1 + D * uk; %  $+ 25 x_{km1} / (1 + x_{km1}^2) + 8 c$ 
% (returns column vector)

%% Observation equation  $y[k] = \text{obs}(k, x[k], v[k])$ ;
ny = 4; % number of observations
obs = @(k, xk, vk) F * xk + vk; % (returns column vector)

%% PDF of process noise and noise generator function
nu = 10; % size of the vector of process
sigma_u = sqrt(Q);
p_sys_noise = @(u) mvnpdf(u, zeros(1, nu)', sigma_u);
gen_sys_noise = @(u) normrnd(0, diag(sigma_u), 10, 1); % sample from p_sys_n

%% PDF of observation noise and noise generator function
nv = 4; % size of the vector of observation
sigma_v = sqrt(R);
p_obs_noise = @(v) mvnpdf(v, zeros(1, nv)', sigma_v);
gen_obs_noise = @(v) normrnd(0, diag(sigma_v), 4, 1); % sample from p_obs_n

%% Initial PDF
% p_x0 = @(x) normpdf(x, 0, sqrt(10)); % initial pdf
% Initial Conditions for Particle_Filter
offsetX = normrnd(0, 2);
offsetY = normrnd(0, 2);
x_0_PF1 = [70; 2.5; 40; 0; ... carl: p_x p_y p_dot_x p_dot_y _
20; 7.5; 40; 0; ...
offsetX; offsetY;]; %offsetX and offsetY
gen_x0 = x_0_PF1; % @(x) normrnd(0, sqrt(10)); % sample from p_x0(re t

%% Transition prior PDF  $p(x[k] | x[k-1])$ 
% (under the suposition of additive process noise)
% p_xk_given_xkm1 = @(k, xk, xkm1) p_sys_noise(xk - sys(k, xkm1, 0));

%% Observation likelihood PDF  $p(y[k] | x[k])$ 
% (under the suposition of additive process noise)
% p_yk_given_xk = @(k, yk, xk) p_obs_noise(yk - obs(k, xk, 0));

%% Number of time steps
T = 100 / Ts;

%% Separate memory space

```

```

x = zeros ( nx , T );      y =  zeros ( ny , T );
u = zeros ( nu , T );      v =  zeros ( nv , T );

%%Simulate system
init=@(v) normrnd ( gen_x0, 2 ones ( 10,1),10,1); %
xh0 =init ();              % initial state
u( : , 1 ) = 0;            % initial process noise
v( : , 1 ) = gen_obs_noise ();      % initial observation noise
x( : , 1 )= x0 PF1;
y( : , 1 )= obs ( 1 , x0 PF1 ,v( : ,1));
for k=2:T
    % here we are basically sampling from p_xk given x_{k-1} and from p_yk given x_k
    u( : , k ) = gen_sys_noise ();      % simulate process noise
    v( : , k ) = gen_obs_noise ();      % simulate observation noise
    x( : , k ) = sys ( k , x( : , k-1 ), u( : , k ));      % simulate state
    y( : , k ) = obs ( k , x( : , k ) , v( : , k ));      % simulate observation
end

%% Separate memory
xh = zeros ( nx , T ); xh( : , 1 ) = xh0;
yh = zeros ( ny , T ); yh( : , 1 ) = obs ( 1 , xh0 , 0);

pf.k          = 1;          % initial iteration number
pf.Ns         = 100;        % number of particles
pf.w          = zeros ( pf.Ns , T );      % weights
pf.particles  = zeros ( nx , pf.Ns , T ); % particles
pf.gen_x0     = gen_x0;      % function for sampling from initial pdf
pf.p_yk_given_xk = p_yk_given_xk;      % function of the observation likelihood
pf.gen_sys_noise = gen_sys_noise;      % function for generating system noise
%pf.p_x0 = p_x0;          % initial prior PDF p(x[0])
%pf.p_xk_given_x_{k-1} = p_xk_given_x_{k-1}; % transition prior PDF p(x[k] | x[k-1])

%% Estimate state
for k=2:T
    % fprintf ( ' Iteration = %d/%d \n' , k , T );
    % state estimation
    pf.k=k ;
    % [xh( : , k ) , pf] = particle_filter ( sys , y( : , k ) , pf , ' multinomial_resampling ' );
    [xh( : , k ) , pf] = particle_filter ( sys , y( : , k ) , pf , ' systematic_resampling ' );

    % filtered observation
    yh( : , k ) = obs ( k , xh( : , k ) , 0 );
end

%% Make plots of the evolution of the density

```

```

% figure
% hold on;
% xi = 1:T;
% yi = -25:0.25:25;
% [xx,yy] = meshgrid( xi , yi );
% den = zeros( size( xx ) );
% xhmode = zeros( size( xh ) );
%
% for i=xi
%     % for each time step perform a kernel density estimation
%     den(:,i) = ksdensity(pf.particles(1,:,i),yi,'kernel','epanechnikov');
%     [~,idx] = max( den(:,i));
%
%     % estimate the mode of the density
%     xhmode(i) = yi(idx);
%     plot3( repmat(xi(i),length(yi),1),yi',den(:,i));
% end
% view(3);
% box on;
% title('Evolution of the state density','FontSize',14)
%
% figure
% mesh( xx,yy,den );
% title('Evolution of the state density','FontSize',14)

%% plot of the state vs estimated state by the particle filter vs particle paths
y1=downsample(y(1,:),10);
y2=downsample(y(2,:),10);
y3=downsample(y(3,:),10);
y4=downsample(y(4,:),10);
figure
hold on;
% h1 = plot(1:T,squeeze(pf.particles),'y');
plot(x(1,:),x(2,:));
plot(y1,y2,'cyan')
plot(xh(1,:),xh(2:),'-r');
legend('Actual Trajectory','GPS output','Estimated Trajectory')
xlabel('Position in X direction')
ylabel('Position in Y direction')
title('Carl')
grid on

figure
hold on
plot(x(5,:),x(6,:));

```

```

plot(y3,y4,'cyan')
plot(xh(5,:),xh(6,:),'-r');
legend('Actual Trajectory','GPS output','Estimated Trajectory')
xlabel('Position in X direction')
ylabel('Position in Y direction')
title('Car2')
grid on

```

```

%% plot of the observation vs filtered observation by the particle filter

```

```

return ;

```

```

function u = acceleration()

```

```

Ts = 1/50; %Sampling time of 50Hz, 0.02 s
t = 500; %simulation time 100s
k = t/Ts; % number of time steps
time = (0:Ts:t-Ts)'; %initialize time vector
NumOfCar = 2;
alphaLOSNLOS = 0.1;
% seed = 20;
% seed = randi(100);
% seed = 66;
% seed = 81;
seed = 35;

```

```

%% %GENERATE Acceleration

```

```

%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%

```

```

p_ddot_x = zeros(k,1); %initialize car1 acceleration vector x-direction
p_ddot_x2 = zeros(k,1); %initialize car2 acceleration vector x-direction
p_y = zeros(k+2,1);
p_y2 = zeros(k+2,1);

```

```

%Position in y-direction during first 10 s

```

```

for i = 1: 10/Ts
    p_y(i) = 2.5;
    p_y2(i) = 7.5;
end

```

```

%From 6 s to 8 s car1 accelerate then decelerate to get in front of car2

```

```

% p_ddot x (6 / Ts : 8 / Ts ) = 4 ; p_ddot x (9 / Ts :10 / Ts ) = -4;

%From 10 s to 16 s , change lanes here :
for i = 10 / Ts : 16 / Ts
    p_y(i) = p_y(i-1) + 45 * Ts * pi / 180; %car 1 change to lane 2
    p_y2(i) = p_y2(i-1) - 45 * Ts * pi / 180; %car 2 change to lane 1
end

%From 16 s to 30 s , stay in new lanes
for i = 16 / Ts : 30 / Ts
    p_y(i) = 7.5; %car 1 stay in lane 2
    p_y2(i) = 2.5; %car 2 stay in lane 1
end

%From 30 s to 36 s , change lanes here :
for i = 30 / Ts : 36 / Ts
    p_y(i) = p_y(i-1) + 45 * Ts * pi / 180; %car 1 change to lane 3
    p_y2(i) = 2.5; %car 2 don't change lane , stay in lane 1
end

%From 36 s to end stay in new lanes
for i = 36 / Ts : k + 2
    p_y(i) = 12.5; %car 1 stay in lane 3
    p_y2(i) = 2.5; %car 2 stay in lane 1
end

p_dot_y = diff(p_y) ./ Ts;
p_ddot_y = diff(p_dot_y) ./ Ts;
p_dot_y2 = diff(p_y2) ./ Ts;
p_ddot_y2 = diff(p_dot_y2) ./ Ts;
u = [time p_ddot_x p_ddot_y p_ddot_x2 p_ddot_y2];

end

```

```

function [xhk, pf] = particle_filter(sys, yk, pf, resampling_strategy)
%% Generic particle filter
%
% Note: when resampling is performed on each step this algorithm is called
% the Bootstrap particle filter
%
% Usage :
% [xhk, pf] = particle_filter(sys, yk, pf, resampling_strategy)
%
% Inputs :

```



```

% sys = function handle to process equation
% yk = observation vector at time k (column vector)
% pf = structure with the following fields
% .k = iteration number
% .Ns = number of particles
% .w = weights (Ns * T)
% .particles = particles (nx * Ns * T)
% .gen_x0 = function handle of a procedure that samples from the initial distribution
% .p_yk_given_xk = function handle of the observation likelihood PDF p(y[k] | x[k])
% .gen_sys_noise = function handle of a procedure that generates system noise
% resampling_strategy = resampling strategy. Set it either to
% 'multinomial_resampling' or 'systematic_resampling'
%
% Outputs:
% xhk = estimated state
% pf = the same structure as in the input but updated at iteration k
%
% Reference:
% [1] Arulampalam et. al. (2002). A tutorial on particle filters for
% online nonlinear/non-gaussian bayesian tracking. IEEE Transactions on
% Signal Processing. 50(2). p 174--188

%% Programmed by:
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% Universidad Nacional de Colombia at Manizales, February 29, 2012

%% Modified by:
% Adam Mortazavi
% University of California Santa Barbara, May 25, 2014
% This code is modified to work for more than one state.

%%
k = pf.k;
if k == 1
    error('error: k must be an integer greater or equal than 2');
end

%% Initialize variables
Ns = pf.Ns; % number of particles
nx = size(pf.particles, 1); % number of states

wkml = pf.w(:, k-1); % weights of last iteration
if k == 2
    for i = 1:Ns % simulate initial particles
        pf.particles(:, i, 1) = pf.gen_x0(); % at time k=1
    end
end

```

```

end
wkml = repmat(1/Ns, Ns, 1); % all particles have the same weight

end

%%
% The importance sampling function:
% PRIOR: (this method is sensitive to outliers) THIS IS THE ONE USED HERE
%  $q(\underline{x}_k \text{ given } \underline{x}_{k-1}) = p(\underline{x}_k \text{ given } \underline{x}_{k-1})$ ;
%
% OPTIMAL:
%  $q(\underline{x}_k \text{ given } \underline{x}_{k-1}) = q(\underline{x}_k \text{ given } \underline{x}_{k-1}^i)$ ;
% Note this PDF can be approximated by MCMC methods: they are expensive but
% they may be useful when non-iterative schemes fail

%% Separate memory
xkml = pf.particles(:, :, k-1); % extract particles from last iteration;
xk = zeros(size(xkml)); % = zeros(nx, Ns);
wk = zeros(size(wkml)); % = zeros(Ns, 1);

%% Algorithm 3 of Ref [1]
for i = 1:Ns
    %  $\underline{x}_k(:, i)$  = sample vector from  $q(\underline{x}_k \text{ given } \underline{x}_{k-1})$  given  $\underline{x}_{k-1}(:, i)$  and  $y_k$ 
    % Using the PRIOR PDF:  $p(\underline{x}_k \text{ given } \underline{x}_{k-1})$ : eq 62, Ref 1.
    xk(:, i) = sys(k, xkml(:, i), pf.gensys_noise());

    % Equation 48, Ref 1.
    %  $w_k(i) = w_{k-1}(i) * p(y_k \text{ given } \underline{x}_k(y_k, \underline{x}_k(:, i)))$ 
    % weights (when using the PRIOR pdf): eq 63, Ref 1
    wk(i) = wkml(i) * pf.pyk_given_xk(k, yk, xk(:, i));

    % weights (when using the OPTIMAL pdf): eq 53, Ref 1
    %  $w_k(i) = w_{k-1}(i) * p(y_k \text{ given } \underline{x}_{k-1}(y_k, \underline{x}_{k-1}(:, i)))$ ; % we do not know this PDF
end;

%% Normalize weight vector
wk = wk ./ sum(wk);

%% Calculate effective sample size: eq 48, Ref 1
Neff = 1 / sum(wk.^2);

%% Resampling
% remove this condition and sample on each iteration:
% [xk, wk] = resample(xk, wk, resampling_strategy);

```

```

%if you want to implement the bootstrap particle filter
resample_percentage = 0.50;
Nt = resample_percentage * Ns;
if Neff < Nt
    disp('Resampling ...')
    [xk, wk] = resample(xk, wk, resampling_strategy);
    % {xk, wk} is an approximate discrete representation of  $p(x_k | y_{1:k})$ 
end

%% Compute estimated state
xhk = zeros(nx, 1);
for i = 1:Ns;
    xhk = xhk + wk(i) * xk(i);
end

%% Store new weights and particles
pf.w(:, k) = wk;
pf.particles(:, :, k) = xk; return

rn; % bye, bye !!!

%% Resampling function
function [xk, wk, idx] = resample(xk, wk, resampling_strategy)

Ns = length(wk); % Ns = number of particles

% wk = wk ./ sum(wk); % normalize weight vector (already done)

switch resampling_strategy
case 'multinomial_resampling'
    with_replacement = true;
    idx = randsample(1:Ns, Ns, with_replacement, wk);
%{
    THIS IS EQUIVALENT TO:
    edges = min([0 cumsum(wk)'], 1); % protect against accumulated round-off
    edges(end) = 1; % get the upper edge exact
    % this works like the inverse of the empirical distribution and returns
    % the interval where the sample is to be found
    [~, idx] = histc(sort(rand(Ns, 1)), edges);
%}
case 'systematic_resampling'
    % this is performing latin hypercube sampling on wk
    edges = min([0 cumsum(wk)'], 1); % protect against accumulated round-off
    edges(end) = 1; % get the upper edge exact
    ul = rand / Ns;

```

```

        % this works like the inverse of the empirical distribution and returns
        % the interval where the sample is to be found
        [~,idx] = histc(u1:1/Ns:1,edges);
    % case 'regularized_pf'          TO BE IMPLEMENTED
    % case 'stratified_sampling' TO BE IMPLEMENTED
    % case 'residual_sampling'      TO BE IMPLEMENTED
    otherwise
        error('Resampling strategy not implemented')
end;

xk = xk(:,idx);                % extract new particles
wk = repmat(1/Ns, 1, Ns);      % now all particles have the same weight

return ; %bye,bye!!!

```
