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As California and other states continue to invest in connected vehicle (CV) infrastructure, such as Roadside Units (RSUs), there is a growing need to ensure these deployments are strategic, effective, and justified. Many current infrastructure upgrades are being implemented in an ad hoc manner, without a standardized tool to evaluate the performance of CV applications or to determine whether the benefits justify the costs. Transportation agencies like Caltrans face critical questions: Is it worth upgrading infrastructure for specific CV applications? What are the expected safety and mobility benefits? And how do factors like communication latency, packet loss, and CV penetration rates affect performance?

To address these challenges, a robust, replicable, and cost-effective evaluation method was needed—one that could simulate real-world traffic conditions and assess the impact of CV applications without relying on expensive and difficult-to-replicate field tests. This project aimed to fill that gap by developing a microsimulation-based planning tool that could guide RSU placement and CV application deployment decisions.

16. Abstract

The project successfully delivered a fully functional V2X Microsimulation Platform with integrated CV applications and a comprehensive final report detailing system designs, simulation results, and deployment recommendations. Key findings include the identification of optimal CV penetration rates for Curve Speed Warning, the limited mobility benefits of Queue Warning and Speed Harmonization under certain conditions, and the strong safety potential of Red Light Violation and Pedestrian in Crosswalk Warnings. The Eco-Approach and Departure application was found to be effective only under low traffic demand and not recommended for coordinated arterial corridors.

The project also laid the groundwork for future research, including the development of an open testing platform for CV applications, feasibility studies on adaptive fixed-time signal control, and training programs to build workforce capacity in CV deployment.

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Guidance on Roadside Unit Placement for Future Deployment of Connected and Automated Vehicles

Task 4081 (65A1030)

Final Report

October 19, 2025

Partners for Advanced Transportation Technology works with researchers, practitioners, and industry to implement transportation research and innovation, including products and services that improve the efficiency, safety, and security of the transportation system.

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Acronyms

API	Application Programming Interface
ARC-IT	National ITS Reference Architecture
AV	Automated Vehicle
BSM	Basic Safety Message
CAV	Connected and Automated Vehicle
CV	Connected Vehicle
C-V2X	Cellular-Vehicle to Everything
DMS	Dynamic Message Sign
ICM	Integrated Corridor Management
IOO	Infrastructure Owner Operator
LiDAR	Light Detection and Ranging
MAP	Map Message
OBU	On-Board Unit
OD	Origin-Destination
P2I	Pedestrian-to-Infrastructure
PSM	Personal Safety Message
RSM	Road Safety Message
RSU	Roadside Unit
SPaT	Signal Phase and Timing Message
SSAM	Surrogate Safety Assessment Model
TIC	Transportation Information Center
TMC	Traffic Management Center
V2I	Vehicle to Infrastructure
V2N	Vehicle to Network
V2P	Vehicle-to-Pedestrian
V2V	Vehicle to Vehicle
V2X	Vehicle to Everything
VDS	Vehicle Detector Station
VRU	Vulnerable Road User

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Executive Summary

Nowadays, many pilots across California and the nation are upgrading road infrastructure, such as installing Roadside Units (RSUs), to enable Vehicle-to-Everything (V2X) communications and support various Connected Vehicle (CV) applications. However, these infrastructure upgrades are carried out in an ad hoc manner, and there is a lack of a tool that can justify the need for such upgrades and thoroughly evaluate the performance of targeted CV applications before deployment.

To address this gap, this project has developed a V2X Microsimulation Platform in Aimsun that supports comprehensive performance assessment of CV applications to guide future deployment. Five CV applications, including Curve Speed Warning, Queue Warning, Speed Harmonization, Intersection Safety Warning, and Collision Avoidance, as well as Eco-Approach and Departure at Signalized Intersections, have been implemented based on the latest physical diagrams provided in ARC-IT 9.3. For Intersection Safety Warning and Collision Avoidance, two sub-use cases are included: Red Light Violation Warning and Pedestrian in Crosswalk Warning. Various test networks and scenarios have been created to enable thorough performance evaluation across different road layouts, V2X communications configurations, traffic demand levels, and connected vehicle penetration rates.

After running numerous simulations, we have obtained several valuable findings for the five implemented CV applications, which are summarized below.

- Curve Speed Warning
  We find that the delay at the curve increases when Curve Speed Warning is activated, as this application aims to promote vehicles traveling at excessive speeds to slow down while navigating through the curve. There exists an “optimal” penetration rate of connected vehicles, which is a trade-off between safety improvement and mobility degradation. This “optimal” penetration rate has little correlation with the curve settings, such as the number of lanes and speed limits. Instead, it is closely tied to traffic demands. As demonstrated in numerous simulation runs, the penetration rates are 10% at 100% traffic demand (at road capacity), 15% at 90% traffic demand, 20% at 80% traffic demand, 25% at 70% traffic demand, and 30% at 60% traffic demand.

  Although communications latency and packet loss rate are not critical in Curve Speed Warning since it isn't a latency-sensitive application, it's important to ensure the RSU's communications range covers the entire curve. This allows connected vehicles to receive timely notifications as they pass through.

- Queue Warning
  Queue Warning offers reasonable mobility benefits only under specific traffic conditions, closely tied to the demand-to-capacity ratio and the implemented speed reduction strategies. This benefit becomes apparent when traffic demand slightly surpasses the reduced capacity. In other cases, Queue Warning can easily overreact to minor congestion or fail to create enough space for vehicles in the queue to move faster under extremely heavy traffic, resulting in increased travel delays.

A high percentage of connected vehicles is not necessary to realize the mobility benefits of Queue Warning. Simulation results show that a 10% penetration rate is sufficient for Queue Warning. Additionally, the current road sensing infrastructure with detectors is adequate to support the deployment of Queue Warning. Although additional BSM data can help detect vehicle queues more quickly, its effect on reducing vehicle delays is minor.

Similar to Curve Speed Warning, communications latency and packet loss rate are not critical in Queue Warning because it is not a latency-sensitive application that requires drivers to take immediate action to prevent safety hazards. Simulation results also show that communications range is not the main factor affecting Queue Warning's performance.

Although this project assessed the impact of speed recommendations in Queue Warning, other strategies like lane changes and detours should be examined in future studies. Specifically, during severe traffic congestion when demand far exceeds capacity, redirecting traffic from freeways to local arterials through detour suggestions can result in significant improvements in mobility and safety.

- Speed Harmonization
  We find that achieving the mobility benefits of Speed Harmonization at traffic bottlenecks is challenging. Reducing the inflow just before a traffic bottleneck may not create enough space for downstream weaving flows to exit more quickly and efficiently. This is also supported by the simulation results of Queue Warning, which aims to alert drivers about vehicle queues further upstream but only results in mobility improvements when traffic demand slightly surpasses capacity.

  Similarly, communications latency and packet loss rate are not critical in Speed Harmonization since it is not a latency-sensitive application that requires drivers to take immediate action to prevent safety hazards. Simulation results further show that communications range is not the main factor affecting Speed Harmonization's performance.

  For traffic bottlenecks caused by heavy weaving flows, alternative traffic management strategies should be implemented, such as rerouting on-ramp flows at the bottleneck to upstream or downstream on-ramps.

- Intersection Safety Warning and Collision Avoidance -- Red Light Violation Warning
  We find that effective algorithms can be developed to use real-time signal phase and MAP information to prevent red light running. This highlights the potential of connected vehicle technology to improve intersection safety.

  It is essential to maintain high-quality V2X communications because high latency and packet loss can significantly impair the performance of Red Light Violation Warning algorithms. Additionally, it is shown that communications latency is more critical than the packet loss rate.

Interestingly, we find that higher penetration rates of connected vehicles tend to stabilize transportation systems more, reducing the impacts of degraded V2X communications with non-zero latency and packet loss rates. Therefore, it is essential for transportation agencies like Caltrans to collaborate with the private sector and explore practical solutions to expand V2X communications on a larger scale.

- Intersection Safety Warning and Collision Avoidance -- Pedestrian in Crosswalk Warning
  We find that effective algorithms can be developed to use real-time data from intersections, such as pedestrians in crosswalks, signal phases, and MAP, to help prevent vehicle-pedestrian crashes. This highlights the potential of connected vehicle technology to enhance intersection safety.

  Detecting pedestrians' presence at crosswalks and broadcasting this information at a high frequency are crucial for the effectiveness and reliability of Pedestrian in Crosswalk Warning. An additional important aspect is maintaining a sufficiently long V2X communications range, which allows connected vehicles to receive alerts earlier upstream, giving them more time to decelerate and prevent potential collisions.

  Additionally, we find that with frequent detection and broadcasting of pedestrians' presence at crosswalks and a sufficiently long V2X communications range, the effects of processing and communications delays and packet loss rates on the Pedestrian in Crosswalk Warning are minimal.

- Eco-Approach and Departure at Signalized Intersections
  We find that applying Eco-Approach and Departure at Signalized Intersections is not recommended for arterial intersections under coordinated actuated control. The EAD algorithm implemented in this project provides mobility benefits only during low traffic demand. During periods of high traffic demand, it tends to cause negative effects, such as increasing the average vehicle delay.

  Two main reasons explain the poor performance of the implemented EAD algorithm.
  - Under actuated control, uncertainty in the signal information provided by the SPaT messages significantly restricts the scenarios where an EAD algorithm can operate safely.
  - EAD algorithms generally help vehicles form platoons. This vehicle control module works independently of intersection coordination plans, which could negatively impact the performance of existing vehicle platoons. This indicates that if an arterial corridor is well-coordinated, implementing EAD algorithms might not be necessary.

In addition to the valuable insights mentioned earlier, all test networks (Aimsun ANG files) with embedded DLLs are available for more detailed analysis. Users can adjust simulation parameters based on their deployment needs and run tests to assess the performance of the CV application. These files are available upon request.

For future research, the following three topics are recommended: (i) developing an open testing platform that enables vendors and OEMs to evaluate their CV applications before deployment; (ii) conducting a feasibility study on adaptive fixed-time control to speed up the deployment of CV technologies; and (iii) creating training courses on CV applications to improve the workforce skills of Caltrans and other public agencies.

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1. Introduction

Today, many pilots across California and the nation are upgrading road infrastructure, such as installing Roadside Units (RSUs), to enable Vehicle-to-Everything (V2X) communications and support various Connected Vehicle (CV) applications. However, this infrastructure upgrade raises several questions about deployment. For example,

- Is it worth upgrading the infrastructure to support targeted CV applications?
- How can we evaluate the network-level mobility and safety improvements offered by the CV applications? Or could there be any potential negative effects?
- How can we identify key factors such as communications latency, packet loss rate, CV penetration rate, and traffic conditions that affect the performance of deployed CV applications?

There is a lack of a tool that can justify the need for infrastructure upgrades and thoroughly evaluate the performance of targeted CV applications before deployment.

Instead of conducting numerous expensive field tests that are hard to replicate under the same conditions, this project uses microsimulations to develop a sketch-level planning tool to support the deployment of CV applications that require infrastructure upgrades to RSUs and are in line with Caltrans' CAV implementation plan.

Past efforts[1] have demonstrated the feasibility of building a mixed traffic simulation environment with human drivers and connected and automated vehicles (CAVs) using the microsimulation software, Aimsun[2]. This project further develops a V2X Microsimulation Platform with integrated CV applications, which is shown in Figure 1. As shown in the figure, this V2X microsimulation platform is supported by two main software development kits (SDKs) provided by Aimsun: the V2X SDK and the Aimsun API. After a comprehensive review of CV applications available in ARC-IT 9.3[3] and discussions with the Division of Traffic Operations and the Division of Research, Innovation, and System Information (DRISI) at Caltrans Headquarters, the following five CV applications have been selected and integrated into the V2X Microsimulation Platform:

- Three Freeway CV Applications
  - Curve Speed Warning
  - Queue Warning
  - Speed Harmonization
- Two Arterial CV Applications
  - Intersection Safety Warning and Collision Avoidance
  - Eco-Approach and Departure at Signalized Intersections

Note that Vulnerable Road User Safety is not implemented because it shares a similar physical diagram with Intersection Safety Warning and Collision Avoidance when only the actions of connected vehicles are

[1] System impact of connected and automated vehicles: An application to the 1-210 Connected Corridors pilot. Final Report. https://dot.ca.gov/-/media/dot-media/programs/research-innovation-system-information/documents/final-reports/ca22-task3712-a11y.pdf

[2] Aimsun Next. https://www.aimsun.com/editions/

[3] The National ITS Reference Architecture (ARC-IT 9.3). https://www.arc-it.net/index.html

modeled. Under the application of Intersection Safety Warning and Collision Avoidance, two sub-use cases are implemented in the V2X Microsimulation Platform: Red Light Violation Warning and Pedestrian in Signalized Crosswalk Warning.

Furthermore, lane closures caused by events such as work zones and accidents can result in traffic congestion and vehicle queues on freeways. Therefore, the applications of Work Zone Management and Reduced Speed Zone Warning/Lane Closure are not included in the V2X Microsimulation Platform because they share a similar physical diagram with Queue Warning.

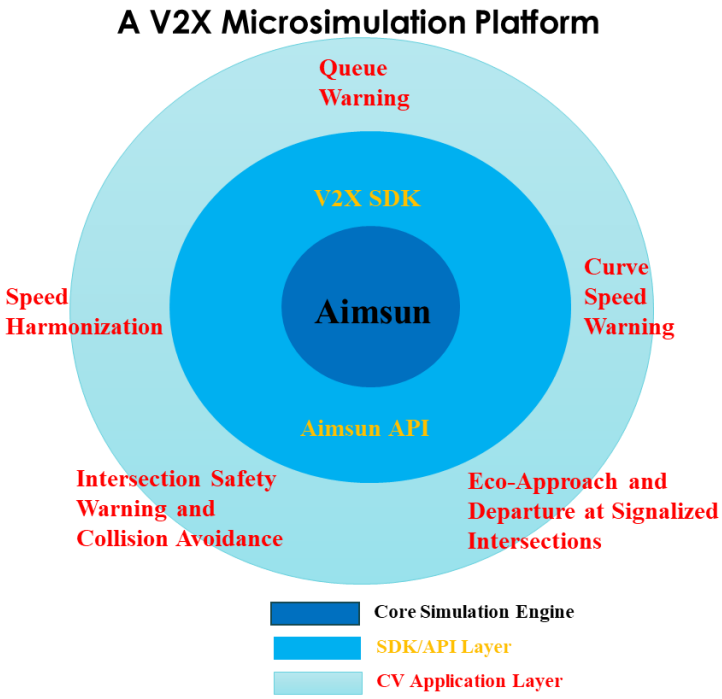

Figure 1. A V2X Microsimulation Platform with integrated CV applications in Aimsun.

Although Caltrans is interested in the following CV applications, they are not implemented in the V2X Microsimulation Platform due to limitations in Aimsun.

- Wrong Way Vehicle Detection and Warning
  - Aimsun Technical Support confirms that a simulated vehicle cannot travel in the wrong direction on a road link.
- Emergency Vehicle Preemption, Transit Signal Priority, and Freight Signal Priority
  - Aimsun does not have Application Programming Interface (API) functions to adjust signal timings, such as extending or shortening green times for specific signal phases, during simulations of coordinated signalized intersections.

To support a comprehensive performance evaluation and considering the inherent properties of the five CV applications, this project creates two different types of test networks described below.

- Artificial networks that follow design standards and real-world implementations for road geometries, signs, speed limits, and traffic control. While developing the artificial test networks and simulation scenarios, we referenced the following technical sources.
    - The physical diagrams provided in the National ITS Reference Architecture, i.e., ARC-IT 9.3[3].
    - Manual on Uniform Traffic Control Devices (MUTCD) for Streets and Highways (11th Edition)[4].
    - A Policy on Geometric Design of Highways and Streets (2018, 7th Edition)[5].
- Subnetworks generated from the I-210 corridor network[6] with the actual settings in the field, which are shown in Figure 2.
    - The I-210 corridor network comprises 1000 lane miles of road links, 5000 traffic detectors, 459 signalized intersections, 45 freeway ramp meters, the Metro Gold Line, and all bus routes. All signal timing and ramp metering plans in the field, along with response plans for freeway incidents, have been integrated into the network. Additionally, it is calibrated with 24-hour traffic demand profiles for weekdays, Saturdays, and Sundays. As a result, this I-210 corridor network is comprehensive enough to create various subnetworks to support the research needs of this project.

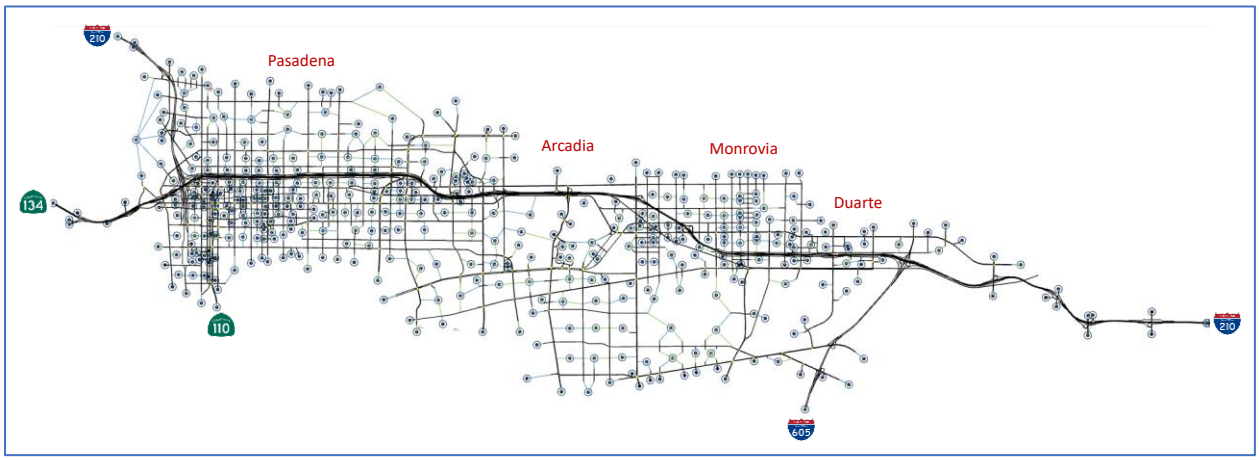

Figure 2. The I-210 Corridor Network in Aimsun.

Supported by the V2X Microsimulation Platform, this project conducts numerous simulations in the test networks under different settings of V2X Communications, CV penetration rates, traffic control, and traffic demands to evaluate the performance of the five CV applications. To assess potential mobility improvements, measurements of average vehicle speed and delay are used. However, for safety assessments, the Surrogate Safety Assessment Model[7] (SSAM) cannot be used because it fails to identify potential vehicle collisions from the output files generated by Aimsun simulations. Therefore, higher-level

[4] Manual on Uniform Traffic Control Devices for Streets and Highways. https://mutcd.fhwa.dot.gov/
[5] AASHTO. https://downloads.transportation.org/publications/GDHS-7_SummaryOfChanges.pdf
[6] The I-210 Connected Corridors Pilot. https://connected-corridors.berkeley.edu/i-210-pilot-landing-page
[7] The Open Source Surrogate Safety Assessment Model (SSAM) 3.0 project. https://github.com/OSADP/SSAM

measurements such as average curve speed for Curve Speed Warning and the number of red-light violations for Red Light Violation Warning are used.

Based on the simulation results, a sketch-level planning tool for the five CV applications will be developed, which includes the following two components:

- A performance assessment report (i.e., this final report) that details the following key aspects:
  - System Design
  - Test Networks and Scenario Design
  - Simulation Results
  - Findings and Recommendations

  This report serves as a general reference to address some high-level deployment questions while piloting a CV application. For example,
  - Does the CV application enhance mobility or safety? Or, is it worthwhile to enable V2X communications (e.g., installing RSUs) to support the CV application?
  - How much improvement in mobility or safety can we expect?
  - Under what conditions does the CV application provide the greatest benefits?
  - How do V2X communications settings affect the performance of the CV application?
  - What other key factors will impact the performance of the CV application?
- All test networks (Aimsun ANG files) with embedded DLLs are provided for more detailed analysis. Users can set the simulation parameters based on their deployment needs and run simulations to assess the performance of the CV application. Although these files are not included in this report, they are available upon request.

The rest of the report is organized as follows. Section 2 details the implementation and performance results for Curve Speed Warning. Section 3 covers the implementation and results for Queue Warning. Section 4 discusses the implementation and findings for Speed Harmonization. Section 5 presents the implementation and assessment results for Intersection Safety Warning and Collision Avoidance. Section 6 details the implementation and performance for Eco-Approach and Departure at Signalized Intersections. Section 7 summarizes the research findings and recommends future research directions.

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2. Curve Speed Warning

Curve Speed Warning uses V2X communications to notify connected vehicles approaching a curve about the recommended speed for that curve. This enables the vehicle to take additional warning actions if its current speed exceeds the suggested limit. With timely alerts from the infrastructure, this application aims to improve the safety of the transportation system for both motorized and non-motorized users (e.g., reducing potential crashes and fatalities).

As illustrated in the physical diagram[8] in Figure 3, direct communications between connected vehicles and the infrastructure/RSUs is recommended for deploying Curve Speed Warning.

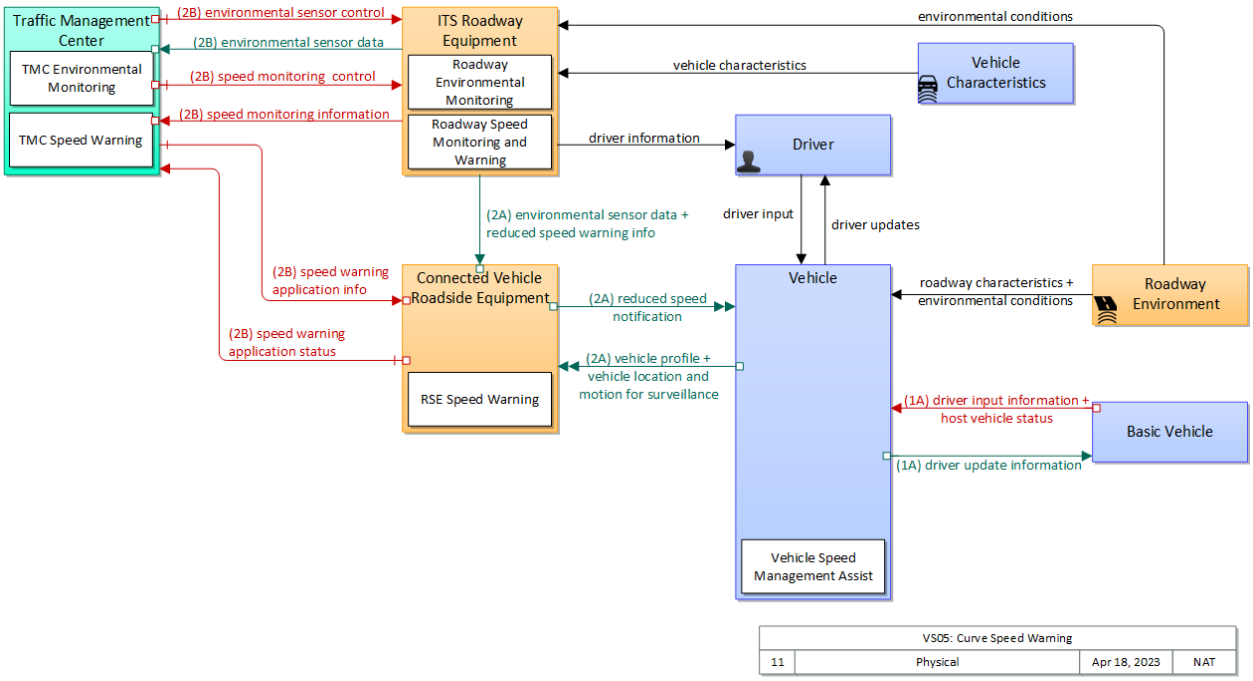

Figure 3. Physical diagram of the Curve Speed Warning application.

However, for the implementation in the integrated simulation framework in Aimsun, we further simplify the modeling framework for Curve Speed Warning, as illustrated in Figure 4. For simplicity, we combine the ITS Roadway Equipment, the Traffic Management Center (TMC), and the RSU into a single entity, removing the need to model explicit data flows among them.

[8] Curve Speed Warning in ARC-IT 9.3. https://www.arc-it.net/html/servicepackets/sp13.html#tab-3

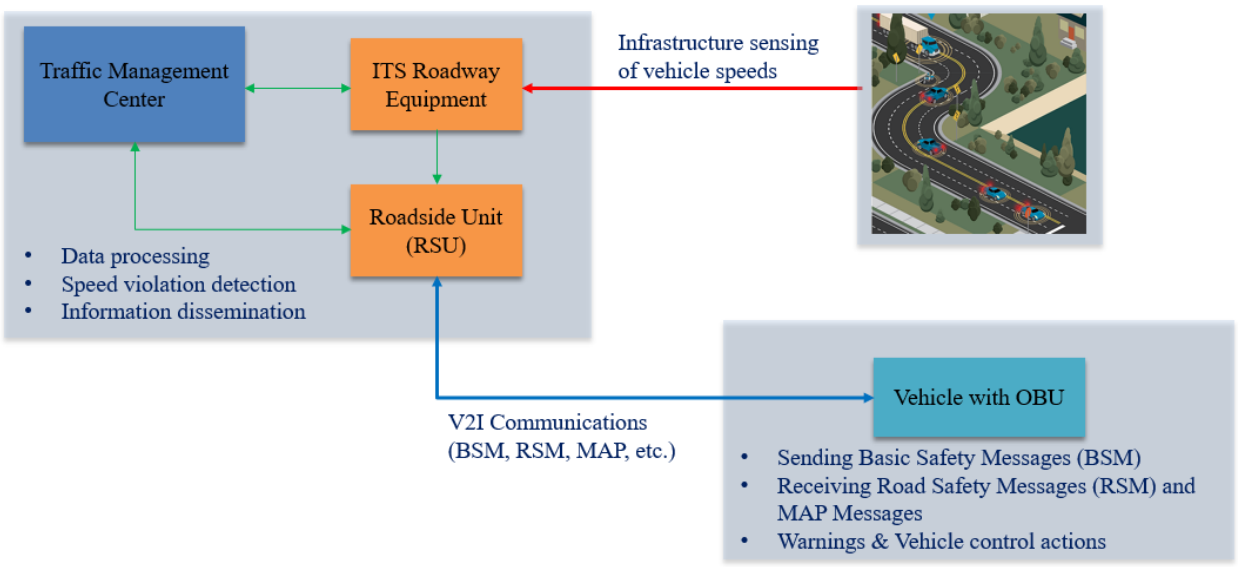

Figure 4. Proposed modeling framework for Curve Speed Warning in Aimsun.

2.1 System Design

Figure 5[9] illustrates the system design of Curve Speed Warning in Aimsum. As shown in the figure, the road curve is divided into two regions:

- **An upstream speed detection region.** Speed information can be collected in various ways, such as from advanced video and radar sensors, as well as from the BSMs sent by connected vehicles.
- **A curve speed warning and speed adjustment region.** Connected vehicles in this region will receive a warning when approaching a downstream curve and will slow down if they exceed the posted or recommended speed limits. While navigating the curve, connected vehicles will adhere to the posted or recommended speed limits. They will resume normal speeds once they exit the curve.

Two approaches have been implemented for the modeling framework illustrated in Figure 5, which are provided below:

- **Passive approach**.
  - The RSU continuously broadcasts RSMs with advisory speeds and curve geometry information to nearby connected vehicles.
  - A connected vehicle receives these messages and responds accordingly if its speed goes beyond the advisory speed.
- **Proactive approach**.
  - Speed information is gathered either from field devices (such as advanced video, radar, or Lidar sensors) or from connected vehicles (using BSMs).

[9] Vehicle-to-Infrastructure (V2I) Safety Applications Performance Requirements, Vol. 2, Curve Speed Warning (CSW). Final Report —August 2015 FHWA-JPO-16-249. https://rosap.ntl.bts.gov/view/dot/32028/dot_32028_DS1.pdf

- The infrastructure (TMC & RSU) detects excessive speeds and broadcasts RSMs to nearby connected vehicles.
- Connected vehicles reduce speed when their speeds go over the advisory limit.

Speed data in the upstream detection region can be gathered using various sensing technologies, which generate different formats, as outlined below.

- **Format #1:** individual vehicles with excessive speeds detected by infrastructure sensors (e.g., advanced video, radar, or Lidar sensors).
- **Format #2:** average speeds in the speed detection region measured by infrastructure sensors (e.g., loop detectors and advanced video, radar, or Lidar sensors).
- **Format #3:** connected vehicles identified from BSM data for excessive speeds.

Therefore, the Curve Speed Warning in Aimsun can be activated by the following four options:

- **Option #1**: Always broadcasting.
- **Option #2**: Detection of excessive average speeds from field devices.
- **Option #3**: Detection of vehicles with excessive speeds from field devices.
- **Option #4**: Detection of connected vehicles with excessive speeds from BSM data.

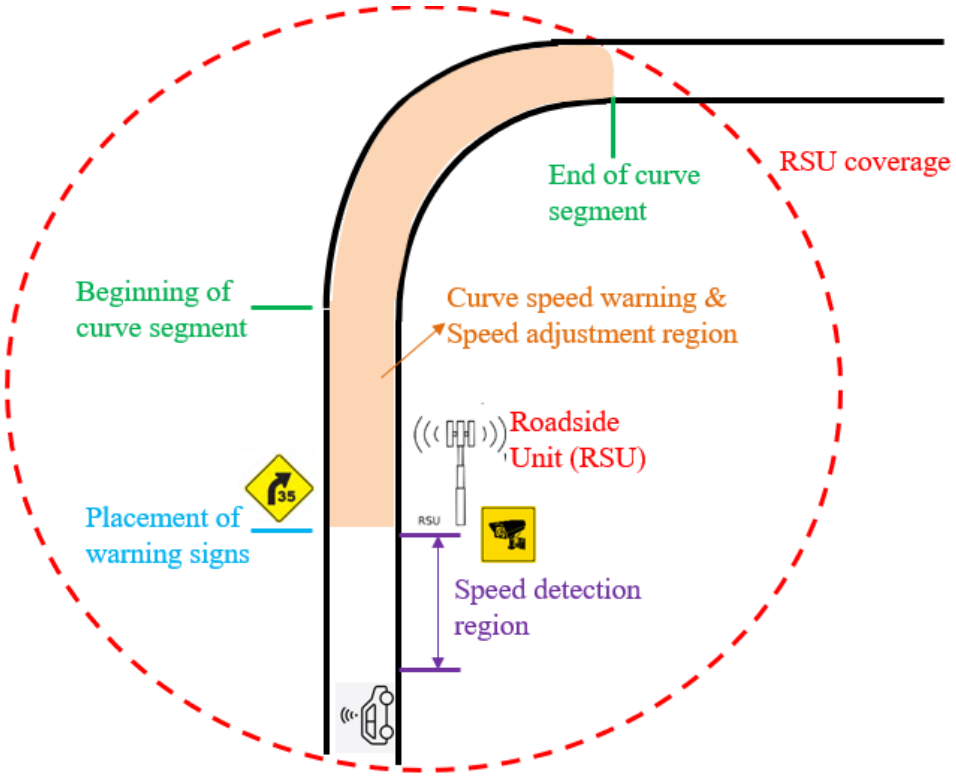

Figure 5. System design of Curve Speed Warning in Aimsun.

2.2 Test Networks and Scenario Design

2.2.1 Test Networks

To support more comprehensive performance analysis, we generate artificial test networks in Aimsun that adhere to engineering design requirements. For example, according to Table 2C-3 in the *Manual on Uniform Traffic Control Devices (MUTCD) for Streets and Highways (11th Edition)*[4], we used a distance of 150 ft for the advance placement of warning signs. Additionally, we followed Table 3-7 in *A Policy on Geometric Design of Highways and Streets (2018, 7th Edition)*[5] to determine the appropriate curve radius for various speed limits.

Considering various curve geometries in the field, we have created the following four test networks to evaluate the performance of Curve Speed Warning:

- **Test Network #1**: A 2-lane 65mph road curve with a reduced speed of 45mph at the curve.
- **Test Network #2**: A 2-lane 55mph road curve with a reduced speed of 35mph at the curve.
- **Test Network #3**: A 3-lane 65mph road curve with a reduced speed of 45mph at the curve.
- **Test Network #4**: A 3-lane 55mph road curve with a reduced speed of 35mph at the curve.

An example of Test Network #2 is provided in Figure 6. For each test network, an RSU is placed at the location of the static signage. The speed detection region extends from the static signage to 150 ft upstream.

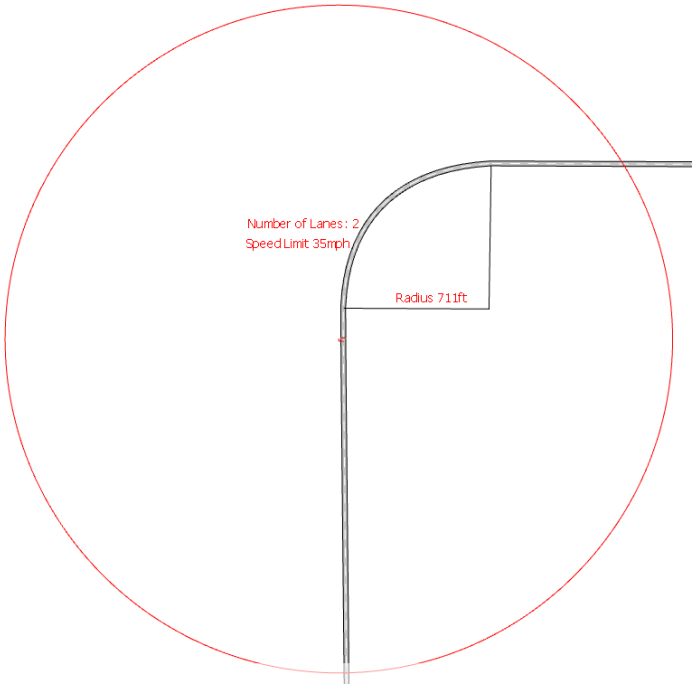

Figure 6. Example of test networks in Aimsun for Curve Speed Warning.

2.2.2 Scenario Design

Curve Speed Warning is an application designed to improve roadway safety by giving drivers timely alerts of posted speed limits as they approach curves. However, we cannot use the Surrogate Safety Assessment Model (SSAM) for safety evaluations because we found that it fails to identify potential vehicle collisions

from the output files produced by Aimsun simulations. Therefore, the assessment of Curve Speed Warning will focus on higher-level performance measures such as average speeds and delays at the curve.

- **Network Settings**

For the four test networks, we consider a 20-mph speed reduction at the curve, which is common in the field. Additionally, we only analyze 2-lane and 3-lane roads with posted speed limits of 55 mph and 65 mph before and after the curve, which are typical settings in the field.

However, we want to highlight that the implementation framework is flexible enough and can be easily expanded to other lane configurations for performance evaluation.

- **Vehicle Reaction to Posted Speed Limit**

Although it is possible to install Dynamic Message Signs (DMS) to show posted speed limits in Aimsun, they do not influence the simulated vehicles; in other words, the simulated vehicles ignore the regulations or suggestions displayed on the DMS. Therefore, we do not model DMS or the reactions of regular vehicles or drivers in this application.

Connected vehicles will follow the posted speed limits received from the RSUs via RSMs. With a 100% compliance rate, the penetration rate of connected vehicles in the network can be considered the "effective" penetration rate of those that adhere to the posted speed limits.

- **Settings of Direct Communications**

Three essential factors to consider in Direct Communications are Range, Latency, and Packet Loss Rate.

Curve Speed Warning is not a latency-sensitive application because it does not require drivers to take immediate action to prevent safety hazards. Therefore, the values for communications latency and packet loss rate are set to zero in this application.

Regarding the communications range, it should be long enough to fully cover the road curve so that connected vehicles can receive posted speed limits while navigating through the curve. In the four test networks, a default range of 1640 feet (i.e., 500 meters) is adequate to meet this requirement.

- **Data Collection and Triggers of Curve Speed Warning**

In the current setup, speed data can be collected from either road infrastructure or connected vehicles. The Curve Speed Warning will activate when vehicles exceeding the speed limit are detected. Since connected vehicles are the only road users that respond to the posted speed limit, there is little difference among the four options for triggering the warning. Therefore, we allowed connected vehicles to send BSMs to the RSUs and selected the following option to trigger the Curve Speed Warning.

    - Option #4: Detection of connected vehicles with excessive speeds from BSM data.

- **Traffic Demand**

We examine five different levels of traffic demand, ranging from 100% to 60% of capacity in 10% increments: 100%, 90%, 80%, 70%, and 60%.

- **Penetration Rate of Connected Vehicles**

Considering the size of the test networks, we run simulations with CV penetration rates from 0% to 100% at 10% intervals: 0%, 10%, 20%, 30%, 40%, 50%, 60%, 70%, 80%, 90%, and 100%.

- **Random Seed and Number of Replications**

The random seed in microsimulations affects many factors, such as vehicle generation and release into the simulation network. Considering the simulation time for each scenario and the potential influence of random seeds, we have decided to perform 10 replications (with 10 different random seeds) for each scenario.

Therefore, the scenario design for the Curve Speed Warning can be summarized as follows:

- Four test networks
    - A 2-lane 65mph road curve with a reduced speed of 45mph at the curve.
    - A 2-lane 55mph road curve with a reduced speed of 35mph at the curve.
    - A 3-lane 65mph road curve with a reduced speed of 45mph at the curve.
    - A 3-lane 55mph road curve with a reduced speed of 35mph at the curve.
- 100% compliance rate of connected vehicles with posted speed limits.
- Five demand levels ranging from 100% capacity to 60%, at 10% intervals.
- Eleven different penetration rates of CVs ranging from 0% to 100%, at 10% intervals.
- A default communication range of 1640 feet (i.e., 500 meters) for roadside units (RSUs).
- No communication latency and zero packet loss rate.
- The application is triggered by speed data from the basic safety messages (BSMs) sent by connected vehicles.
- Ten replications for each of the scenarios described above.

2.3 Performance Evaluation Results

2.3.1 Simulation Parameter Settings

The following settings are applied to the simulation scenarios outlined above.

- **Simulation Settings**

The simulation lasts for 1 hour, from 8:00 AM to 9:00 AM. The warm-up period is 5 minutes. Curve Speed Warning remains active throughout. When vehicles with excessive speeds are identified, RSUs broadcast the posted speed limits to connected vehicles within coverage.

- **RSU Settings**

For RSUs, the default communication range is 1640 feet (i.e., 500 meters). They broadcast RSMs at a frequency of 1 Hz (once per second) if they detect vehicles traveling at excessive speeds. They will continue

broadcasting and will stop if no vehicles with excessive speeds are found in the upcoming data collection interval.

- **Connected Vehicle Settings**

Connected vehicles are allowed to send BSMs at a frequency of 10 Hz (i.e., every 0.1 seconds). They maintain a 100% compliance rate. When they receive posted speed limits from nearby RSUs via RSMs, they will adjust their speeds accordingly to comply with these limits.

- **Penetration Rates of Connected Vehicles**

The simulated penetration rates of connected vehicles are 0%, 10%, 20%, 30%, 40%, 50%, 60%, 70%, 80%, 90%, and 100%.

- **Data Collection and Trigger Method**

BSM data from connected vehicles is collected and analyzed every second. When vehicles with excessive speeds are identified from the BSM data, Curve Speed Warning is activated, and RSUs broadcast posted speed limits to nearby connected vehicles.

- **Traffic Demand Settings**

We assume each freeway lane has a capacity of 2100 vehicles per hour. Therefore, for the two 3-lane test networks, we use the following traffic demands:

- 6300 vph (100%), 5670 vph (90%), 5040 vph (80%), 4410 vph (70%), and 3780 vph (60%)

Similarly, for the two 2-lane test networks, we use the following traffic demands:

- 4200 vph (100%), 3780 vph (90%), 3360 vph (80%), 2940 vph (70%), and 2520 vph (60%)

2.3.2 Simulation Results

Table 1 and Table 2 summarize the changes in harmonic speed and vehicle delay while Curve Speed Warning is applied at the 2-lane test network with a speed limit of 35mph at the curve (i.e., Test Network #2). According to the results shown in the tables, we have the following findings:

- In baseline scenarios with 0% connected vehicles, vehicles tend to travel faster than the posted speed limit, aligning with field observations. The lighter the traffic, the faster vehicles tend to go.
- Reaching a 100% penetration of connected vehicles can ensure the average curve speed stays within the posted limit, but the average vehicle delay in the test networks can double or more.
- Lower traffic demand requires a higher penetration rate of connected vehicles to reduce the average curve speed to the level associated with high traffic demand.

For the other three test networks, the simulation results are similar and therefore not included in this report.

Furthermore, Figure 7 to Figure 10 illustrate the relationship between the average curve speed and the average vehicle delay under different penetration rates of connected vehicles and traffic demands in the four test networks. From the figures, we have the following findings:

- There is an “optimal” penetration rate of connected vehicles that can help lower the average curve speed while keeping the increase in delay "acceptable.”
- The “optimal” penetration rate of connected vehicles is closely linked to traffic demand rather than the number of lanes or speed limits at curves. The “optimal” penetration rates for various levels of traffic demand across the four test networks are identified as
    - 10% for 100% of traffic demand at road capacity, 15% for 90% demand, 20% for 80% demand, 25% for 70% demand, and 30% for 60% demand.

Table 1. Changes in Harmonic Speeds with Curve Speed Warning Applied at a 2-lane 35mph Road Curve.

2-Lane 35mph Curve	Harmonic Speed																					
	Penetration Rate of Connected Vehicles																					
	0%		10%		20%		30%		40%		50%		60%		70%		80%		90%		100%	
Demand	Flow (vph)	Speed (mph)	Speed (mph)	Speed Change (%)	Speed (mph)	Speed Change (%)	Speed (mph)	Speed Change (%)	Speed (mph)	Speed Change (%)	Speed (mph)	Speed Change (%)	Speed (mph)	Speed Change (%)	Speed (mph)	Speed Change (%)	Speed (mph)	Speed Change (%)	Speed (mph)	Speed Change (%)	Speed (mph)	Speed Change (%)
100%	4183.6	39.00	37.45	-3.97	36.52	-6.36	35.99	-7.72	35.67	-8.54	35.46	-9.08	35.31	-9.46	35.19	-9.77	35.12	-9.95	35.06	-10.10	35.01	-10.23
90%	3773.8	39.19	37.82	-3.50	36.94	-5.74	36.37	-7.20	35.97	-8.22	35.70	-8.91	35.48	-9.47	35.29	-9.95	35.18	-10.23	35.09	-10.46	35.02	-10.64
80%	3376.6	39.37	38.18	-3.02	37.33	-5.18	36.72	-6.73	36.27	-7.87	35.93	-8.74	35.65	-9.45	35.42	-10.03	35.25	-10.46	35.13	-10.77	35.03	-11.02
70%	2965.5	39.50	38.46	-2.63	37.65	-4.68	37.05	-6.20	36.57	-7.42	36.17	-8.43	35.83	-9.29	35.54	-10.03	35.34	-10.53	35.18	-10.94	35.04	-11.29
60%	2546.4	39.66	38.77	-2.24	38.01	-4.16	37.39	-5.72	36.92	-6.91	36.44	-8.12	36.08	-9.03	35.72	-9.93	35.48	-10.54	35.26	-11.09	35.08	-11.55

Table 2. Changes in Average Delay with Curve Speed Warning Applied at a 2-lane 35mph Road Curve.

2-Lane 35mph Curve	Average Delay																					
	Penetration Rate of Connected Vehicles																					
	0%		10%		20%		30%		40%		50%		60%		70%		80%		90%		100%	
Demand	Flow (vph)	Delay (sec/mile)	Delay (sec/mile)	Delay Change (%)	Delay (sec/mile)	Delay Change (%)	Delay (sec/mile)	Delay Change (%)	Delay (sec/mile)	Delay Change (%)	Delay (sec/mile)	Delay Change (%)	Delay (sec/mile)	Delay Change (%)	Delay (sec/mile)	Delay Change (%)	Delay (sec/mile)	Delay Change (%)	Delay (sec/mile)	Delay Change (%)	Delay (sec/mile)	Delay Change (%)
100%	4183.6	5.22	6.99	33.91	8.15	56.13	8.83	69.16	9.29	77.97	9.60	83.91	9.85	88.70	10.07	92.91	10.22	95.79	10.33	97.89	10.45	100.19
90%	3773.8	4.50	5.98	32.89	7.00	55.56	7.67	70.44	8.19	82.00	8.58	90.67	8.91	98.00	9.19	104.22	9.43	109.56	9.57	112.67	9.71	115.78
80%	3376.6	3.82	5.08	32.98	6.03	57.85	6.72	75.92	7.27	90.31	7.70	101.57	8.07	111.26	8.43	120.68	8.67	126.96	8.88	132.46	9.05	136.91
70%	2965.5	3.27	4.36	33.33	5.23	59.94	5.89	80.12	6.43	96.64	6.89	110.70	7.32	123.85	7.70	135.47	7.98	144.04	8.21	151.07	8.42	157.49
60%	2546.4	2.76	3.67	32.97	4.47	61.96	5.13	85.87	5.65	104.71	6.19	124.28	6.61	139.49	7.05	155.43	7.36	166.67	7.63	176.45	7.88	185.51

2.4 Discussion

It's not surprising to see the delay increase at the curve when Curve Speed Warning is activated, as this application aims to prompt vehicles traveling at high speeds to slow down while navigating the curve. From the detailed analysis above, it's exciting to find that there is an “optimal” penetration rate of connected vehicles, which balances safety improvements with mobility degradation. It's also interesting to note that this “optimal” rate has little correlation with the curve settings, such as the number of lanes and speed limits. This makes assessing system requirements—like the minimum or optimal penetration of connected vehicles—for Curve Speed Warning much easier, as it closely relates to traffic demands.

Since we cannot apply the SSAM to outputs from Aimsun simulations, we cannot provide a more detailed analysis of the safety benefits of Curve Speed Warning. Future research is needed to find or create suitable tools that can generate more comprehensive safety metrics, such as near misses and potential crashes.

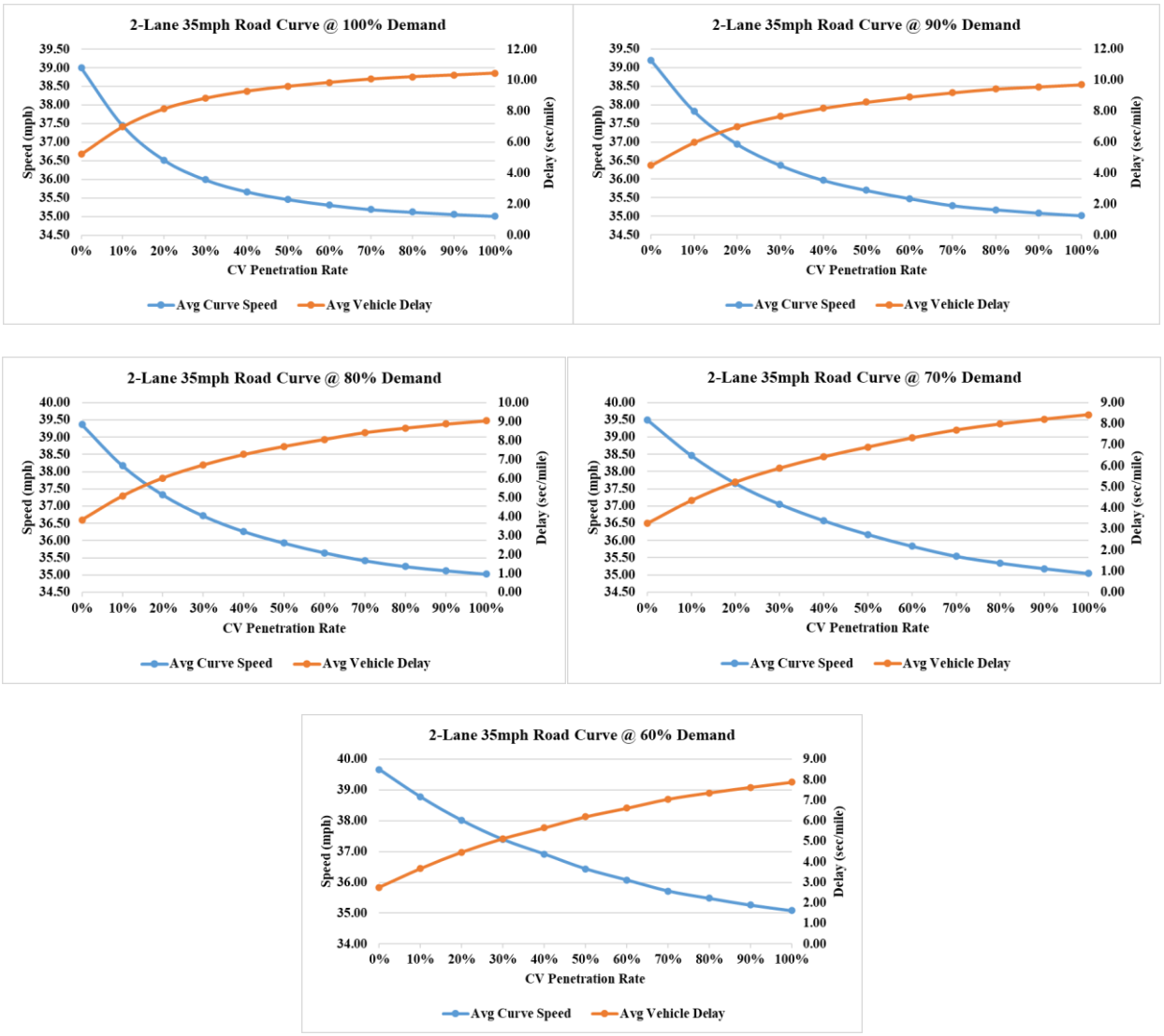

Figure 7. Average curve speed vs. average vehicle delay under different CV penetration rates and traffic demands at a 2-lane 35mph road curve.

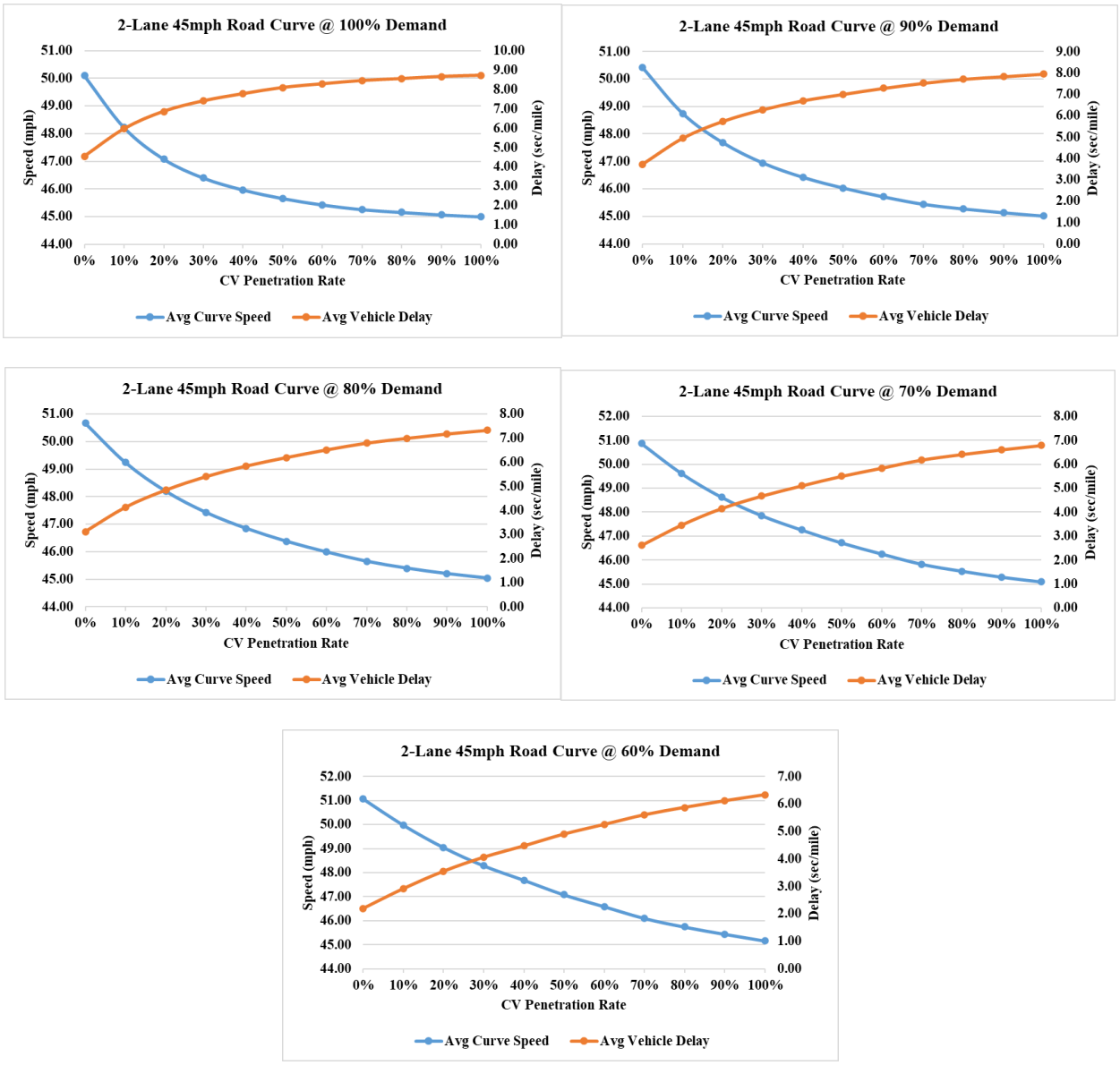

Figure 8. Average curve speed vs. average vehicle delay under different CV penetration rates and traffic demands at a 2-lane 45mph road curve.

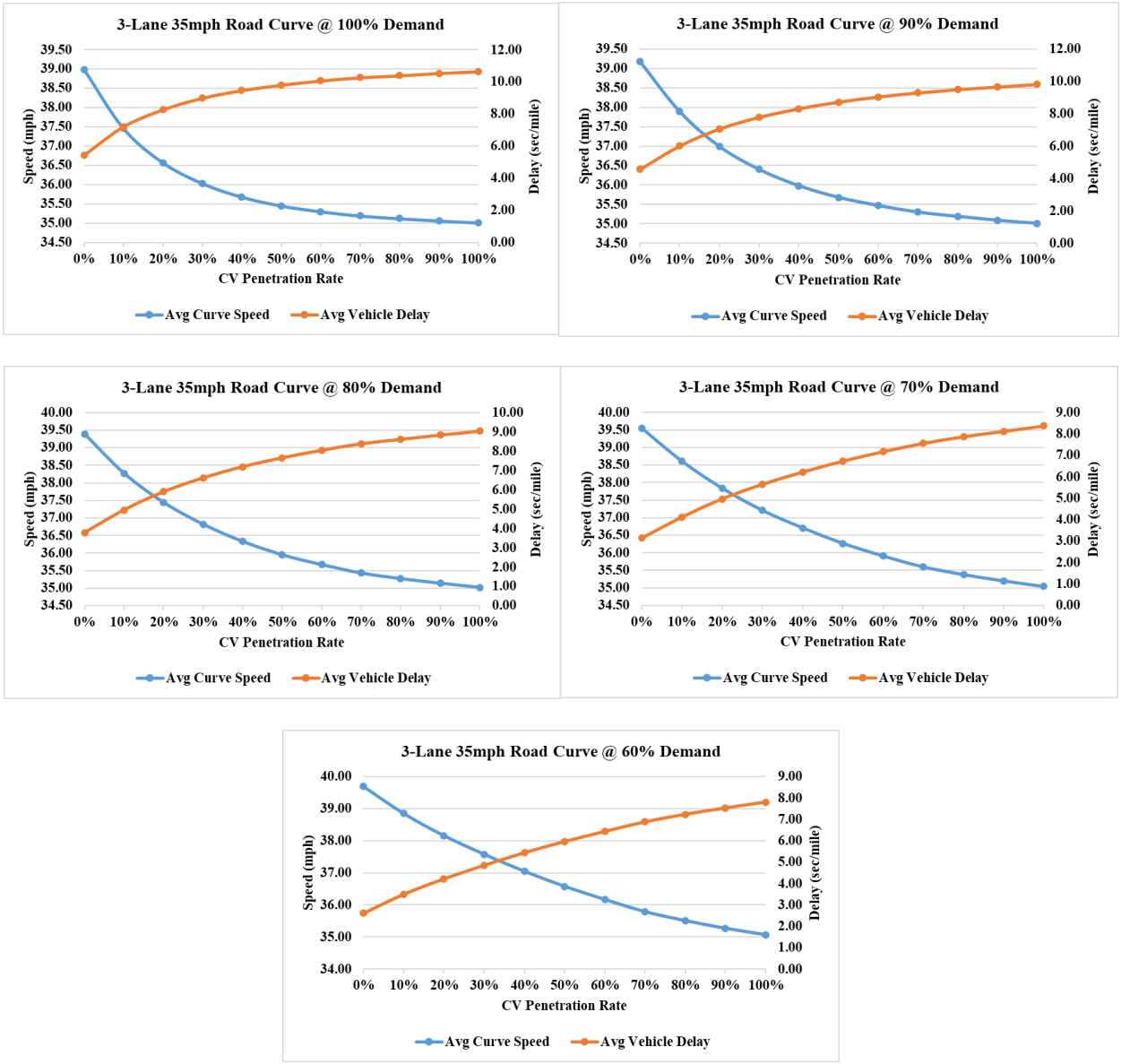

Figure 9. Average curve speed vs. average vehicle delay under different CV penetration rates and traffic demands at a 3-lane 35mph road curve.

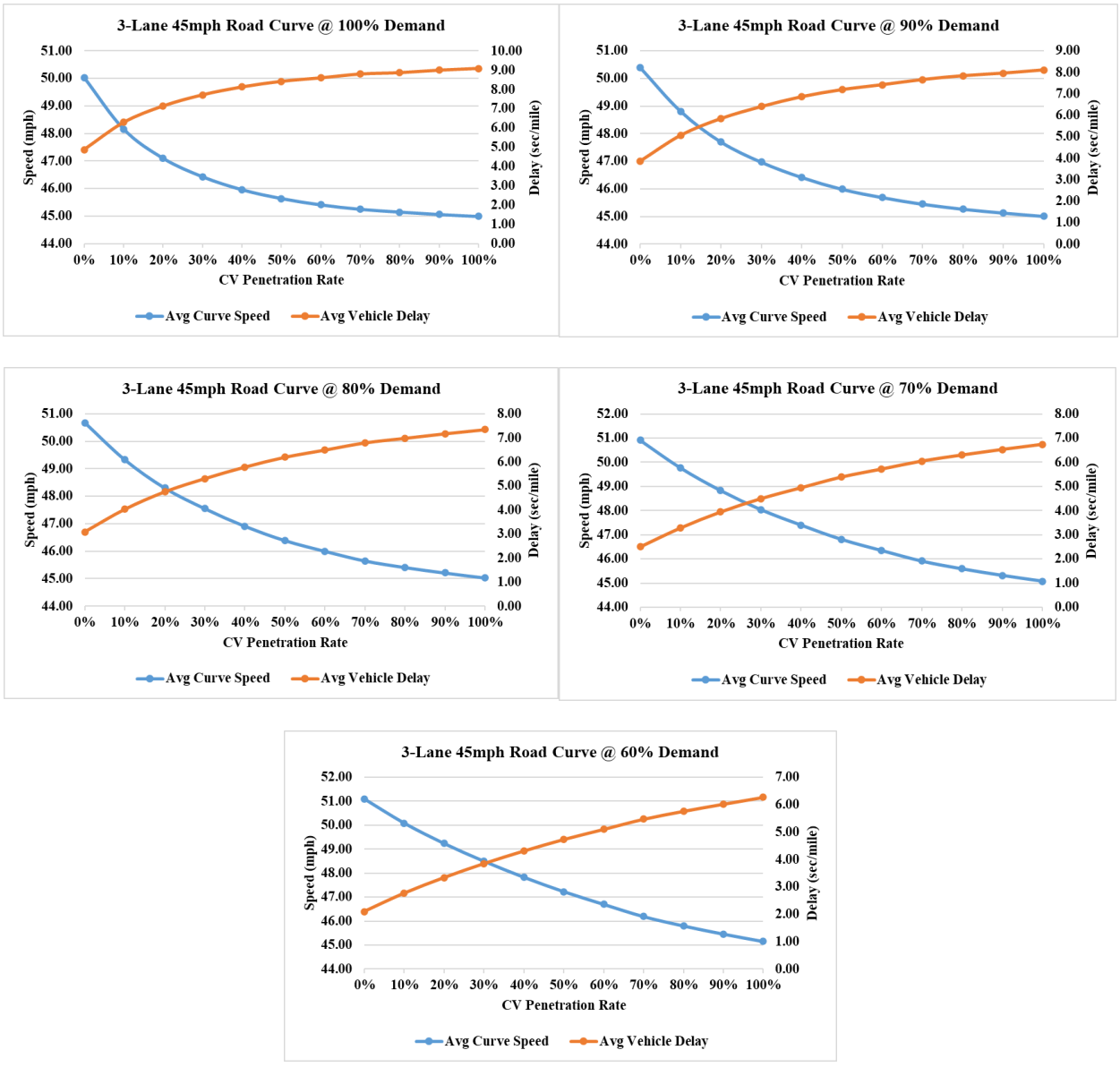

Figure 10. Average curve speed vs. average vehicle delay under different CV penetration rates and traffic demands at a 3-lane 45mph road curve.

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3 Queue Warning

Queue Warning uses existing road sensing infrastructure, connected vehicle data, and V2X communications to enable real-time queue detection and share queue information or warnings with nearby upstream vehicles and centers, such as the Traffic Management Center (TMC). This application aims to alert the driver of potential crash situations to reduce the need for crash avoidance or mitigation actions later.

As illustrated in the physical diagram[10] in Figure 11. There are two communications approaches for applying Queue Warning: (i) direct communications via RSUs and (ii) network communications through the Transportation Information Center (TIC). However, given the scope of this project, we only examine the performance of Queue Warning under the direct communications approach using RSUs.

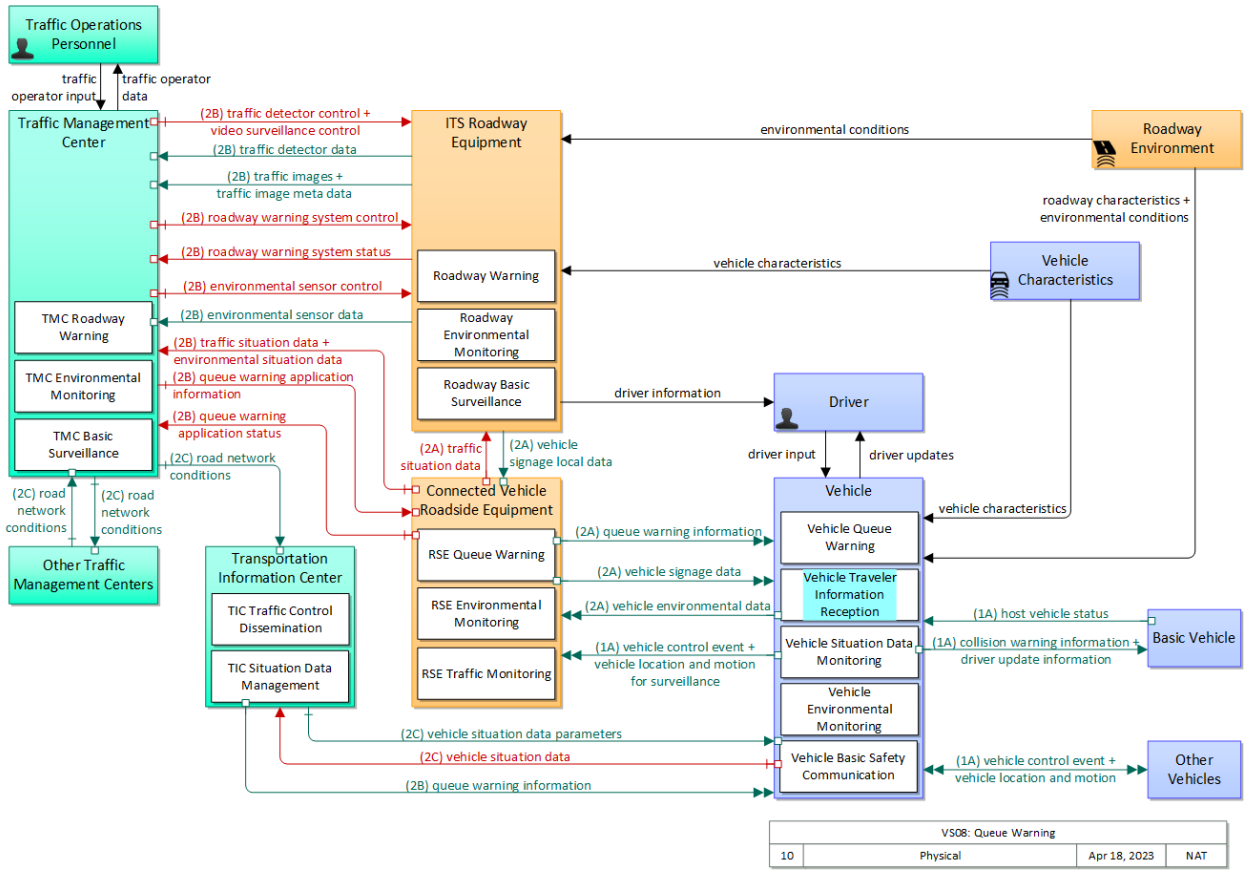

Figure 11. Physical diagram of the Queue Warning application.

For the implementation in the integrated simulation framework in Aimsun, we further simplify the modeling framework for the application of Queue Warning, which is illustrated in Figure 12. For simplicity, we combine ITS Roadway Equipment, Traffic Management Center (TMC), and RSU into a single system, removing the need to model explicit data flows between them.

[10] Queue warning in ARC-IT 9.3. https://www.arc-it.net/html/servicepackets/sp52.html#tab-3

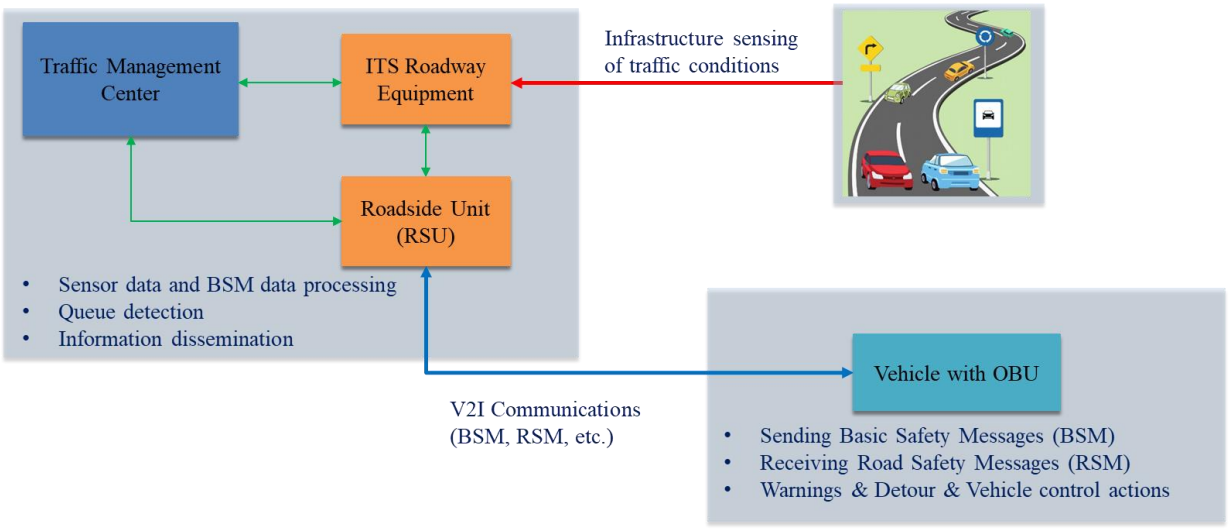

Figure 12. Proposed modeling framework for the application of Queue Warning in Aimsun.

3.1 System Design

The implementation of Queue Warning in this project aims to understand how Infrastructure Owner Operators (IOOs) can use real-time data from various sources to detect vehicle queues on the freeway and provide timely recommendations to connected vehicles upstream to reduce congestion. For emergency situations, such as crash avoidance, vehicles should rely on onboard sensors and Vehicle-to-Vehicle (V2V) communications, which are outside the scope of this project.

Therefore, Figure 13 illustrates the system design of Queue Warning in Aimsum. As shown in the figure, an RSU is installed at each weaving section along the freeway segment to facilitate data collection and message dissemination. The implemented workflow is described as follows:

- The TMC and RSUs at the weaving sections collect real-time infrastructure sensor data (e.g., loop detectors) and/or BSMs from connected vehicles.
- The TMC analyzes the collected data and identifies the end of vehicle queues, if any.
- The information of identified vehicle queues and recommended actions is relayed to the RSUs involved in the queue warning zone, the length of which is specified by the user. The RSUs will broadcast RSMs with this information to nearby connected vehicles.
- Connected vehicles within the queue warning zone will receive RSMs and follow the recommended actions to reduce downstream traffic congestion.

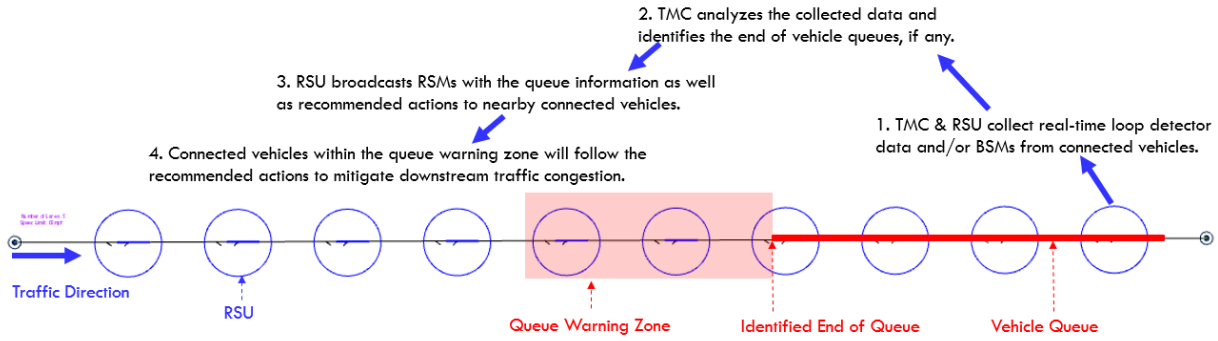

Figure 13. System design of Queue Warning in Aimsun.

3.1.1 Detection of End of Queue

A key part of Queue Warning is recognizing traffic congestion and detecting the End of Queue on a freeway segment. To identify traffic congestion from various data sources, the following criteria are used:

- For loop detector data (5-minute averages), traffic at a vehicle detector station (VDS) is considered congested if the average occupancy Occ_{avg} exceeds a user-defined threshold, such as 25%.
- For BSM data collected from connected vehicles, vehicle speed is averaged over a user-defined period, such as 30 seconds. Traffic within a detection zone, such as the area covered by an RSU, is considered congested if the average vehicle speed V_{avg} drops below a user-defined threshold, such as 25 mph.

If traffic congestion is detected on the freeway, the TMC will use the following criteria to identify the End of Queue.

- Traffic is uncongested in the upstream.
- Traffic is congested in the downstream.

However, we need to point out that due to sensing limitations, the actual End of Queue will differ from the identified one if it is outside the communications range of the RSUs. For example, Figure 14 illustrates that if the actual End of Queue is in the detection gap not covered by RSUs, the identified End of Queue can only be the most upstream edge covered by the RSUs. This issue would not occur if the communications range of RSUs is long enough to eliminate the detection gap.

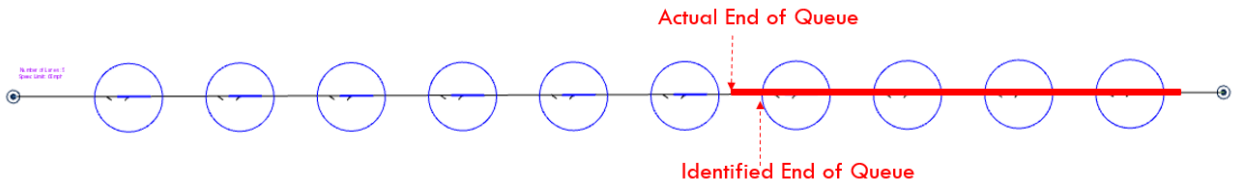

Figure 14. Difference between the actual End of Queue and the one identified from observed data.

Furthermore, we want to clarify how the End of Queue and the Queue Warning Zone behave. When traffic becomes more congested, such as during the start of traffic buildup, these zones move further upstream. Conversely, when traffic eases, like during the dissipation of congestion, they shift further downstream.

3.1.2 Recommendation on Speed Reduction

Another important part of Queue Warning is recommended actions based on the detected traffic congestion and End of Queue. Common recommendations include slowing down, changing lanes, and taking a detour. In this project, we only focus on the suggestion of slowing down for the following reasons:

- When the Aimsun API for vehicle lane change is called, the subject vehicle will immediately change lanes when the surrounding traffic conditions allow. This sudden action does not match real-world driver behavior. It can cause unnecessary traffic fluctuations and unrealistic congestion. Therefore, instead of offering lane change suggestions, it is better to use Aimsun's lane-changing module to make decisions for the connected vehicles.
- Detour route recommendations to local arterials involve modeling integrated corridor management with both freeways and arterials. This will complicate the simulation model and make it harder to evaluate the performance of Queue Warning. Therefore, detour route recommendations are not implemented in this project.

Instead of recommending a single speed limit for all connected vehicles within the queue warning zone, we allow them to have different recommended speeds based on their distances from the End of Queue. Currently, the queue warning zone is divided into two speed reduction zones. As shown in Figure 15, the first speed reduction zone is a default 1-mile-long segment located upstream of the End of Queue. The second speed reduction zone covers the remainder of the queue warning zone. Different speed limits will be recommended for these two zones. Connected vehicles traveling at higher speeds will gradually slow down to adhere to the recommended speed limits. For example, along a freeway segment with a posted speed limit of 65mph,

- A lower speed limit, such as 45 mph, is recommended in the first speed reduction zone.
- A higher speed limit, such as 60 mph, is recommended in the second speed reduction zone.

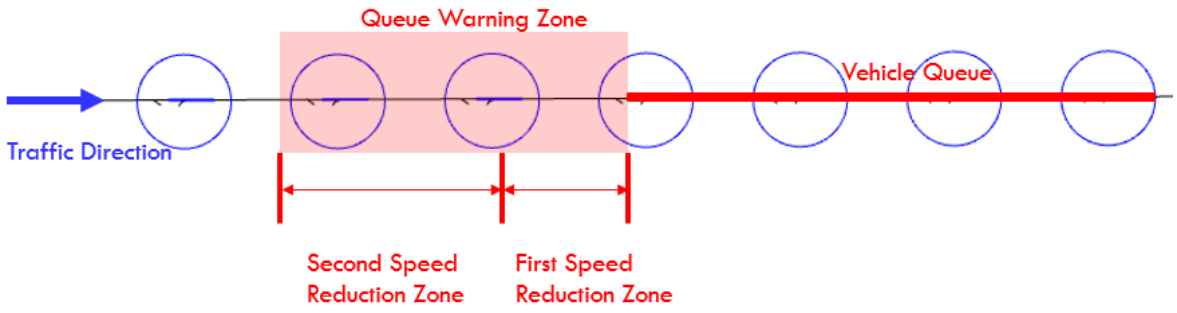

Figure 15. Queue Warning Zone settings.

The above setting of speed reduction zones aims to slow down upstream vehicles, creating more space for downstream vehicles to exit the queue more quickly. With fewer vehicles coming from upstream, the

capacity reduction (or drop) caused by weaving flows at the downstream bottleneck (either recurrent or non-recurrent) can be mitigated, which in turn leads to higher throughput and reduces travel delays for the entire network.

3.2 Test Networks and Scenario Design

3.2.1 Test Networks

To support a more comprehensive performance analysis, we generate artificial test networks in Aimsun that are consistent with the design of freeway weaving sections in the field. Figure 16 provides an example of test networks in Aimsun for Queue Warning. As shown in Figure 16, the test network consists of a 10-mile freeway segment with 10 weaving sections spaced 1 mile apart. Each weaving section is approximately 1 mile long and features an on-ramp and an off-ramp. The distance between the on-ramp and off-ramp is set at 1000 feet. There are two Vehicle Detector Stations (VDSs) installed upstream and downstream of the merging gore. The upstream VDS is located 500 feet from the merging gore, while the downstream VDS is 1,000 feet away.

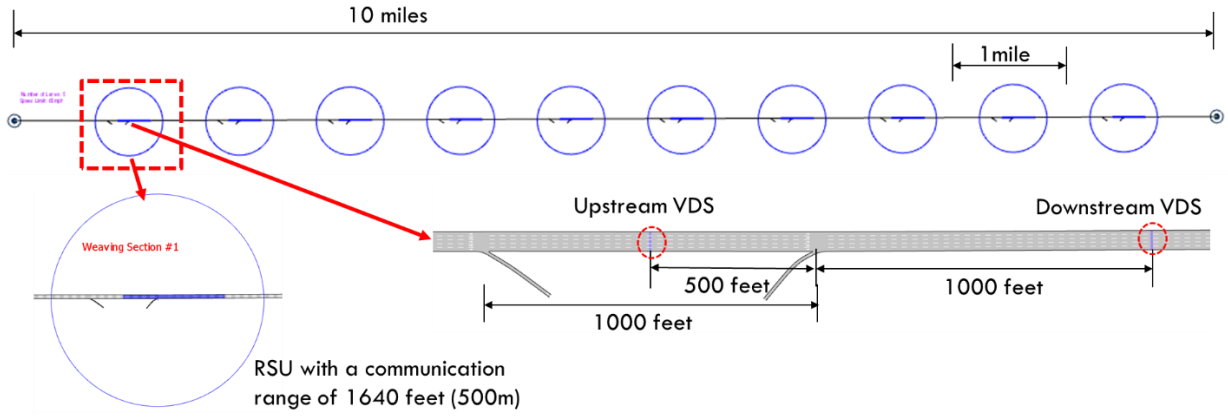

Figure 16. Example of test networks in Aimsun for Queue Warning.

An RSU is installed near the merging gore at each weaving section, with a default communications range of 1640 ft (500 meters). Therefore, a total of 10 RSUs are deployed in the test network. Each RSU connects to the upstream and downstream VDSs to obtain real-time detector measurements of flow, speed, and occupancy. All RSUs are linked to share detector data and BSM messages from connected vehicles with a TMC. The TMC uses this data to identify the presence and location of vehicle queues in the network. The queue information, along with the recommended speed limits, is then relayed to the RSUs to broadcast to the connected vehicles within their coverage area.

3.2.2 Scenario Design

Queue Warning is an application that can enhance both safety and mobility. However, because we found that the Surrogate Safety Assessment Model (SSAM) does not identify potential vehicle collisions from the output files produced by Aimsun simulations, the assessment of Queue Warning in this project will focus on potential mobility improvements.

- **Network Settings**

The test network used for performance assessment is a 10-mile 4-lane freeway segment with a speed limit of 65 mph, as shown in Figure 16. Since the speed limit of 65 mph is commonly used for California freeways, we do not consider other speed limits for performance assessment. Because each simulation run will take a long time, we also do not consider other lane configurations, such as 5 or 3 lanes. However, the implementation framework is flexible enough and can be easily extended to evaluate other lane setups.

- **Vehicle Reaction to Speed Reduction**

Although it is possible to install Dynamic Message Signs (DMS) to display messages about speed reduction in Aimsun, they have no impact on the simulated vehicles; in other words, the simulated vehicles do not follow the regulations or suggestions indicated on the DMS. Therefore, we do not model DMS or the reaction of regular vehicles/drivers in this application.

For connected vehicles, they will strictly follow the recommended speed limits received from the RSUs via RSMs. The setting of speed reduction zones is provided in Figure 15. Since it is a 100% compliance rate, the penetration rate of connected vehicles in the network can be considered as the "effective" penetration rate of connected vehicles that follow the speed recommendations.

- **Detector Coverage**

The detector coverage follows the settings in Figure 16. We assume that all detectors are functioning properly and provide accurate traffic measurements of flow, speed, and occupancy.

- **Settings of Direct Communications**

There are three main factors to consider in Direct Communications: Range, Latency, and Packet Loss Rate.

We do not consider communications latency in this model because the data aggregation interval used to detect the End of Queue is much longer than the communication latency.

We also do not model the impact of packet loss rate because Queue Warning aims to provide early warnings to connected vehicles further upstream and is not a safety-critical application that requires drivers' immediate actions.

However, communications range will influence the detection of End of Queue when using connected vehicle data (i.e., BSMs). It will also impact the number of connected vehicles that follow the new speed limits recommended by the TMC/RSUs. Therefore, this study will initially examine the potential improvement with a default range of 1640 feet (i.e., 500 meters). If needed, we will consider a longer range of 2460 feet (i.e., 750 meters).

- **Data Collection**

Currently, we use two methods to gather data for identifying traffic congestion and vehicle queues on the freeway. The first method relies solely on data from loop detectors, while the second method includes additional BSM data from connected vehicles.

- **Traffic Demand**

We consider three levels of traffic demand: (i) high demand (at capacity), (ii) medium demand (90% of capacity), and (iii) low demand (80% of capacity).

- **Traffic Incidents and Traffic Congestion**

Traffic congestion happens when traffic demand exceeds the roadway's capacity. It becomes even worse when traffic incidents, such as work zones and accidents, further decrease the roadway's capacity.

To induce traffic congestion in the test network, we consider closing one or more lanes downstream of Weaving Section #10 for the entire simulation period, which is illustrated in Figure 17. This will force vehicles in the left lanes to shift to the right, further reducing throughput at the lane closure area.

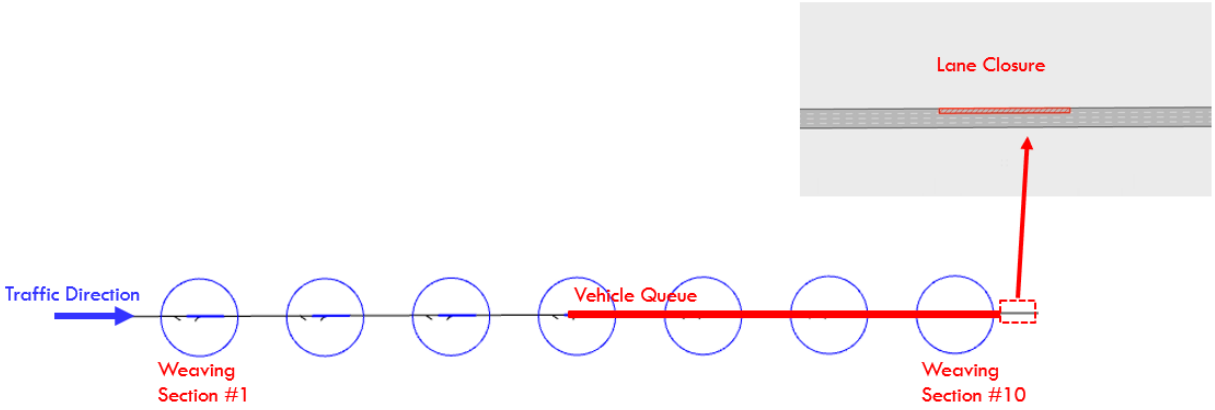

Figure 17. Generation of traffic congestion for Queue Warning.

- **Penetration Rate of Connected Vehicles**

We have observed that the simulation speed in Aimsun drops significantly when there is a large number of connected vehicles in the network. Given the size of the test networks, we only run simulations with CV penetration rates from 0% to 50%, including 0%, 10%, 20%, 30%, 40%, and 50%.

- **Random Seed and Number of Replications**

The random seed in microsimulations influences various factors, such as vehicle generation and release into the simulation network. Considering the simulation duration for each scenario and the potential effects of different random seeds, we have decided to run five replications with five different seeds for each scenario.

Therefore, the scenario design for Queue Warning can be summarized as follows:

- A 10-mile 4-lane freeway section with a speed limit of 65mph.
- 100% compliance rate of CVs with speed reduction recommendations.
- Three demand levels: high demand (at capacity), medium demand (90% of capacity), and low demand (80% of capacity).
- Complete detector coverage with both upstream and downstream VDSs at merging sections.
- Two lane-closure scenarios to generate congestion: 1-lane and two-lane closures.

- Six different penetration rates of CVs: 0%, 10%, 20%, 30%, 40%, 50%.
- Two different communication ranges for RSUs: 1640 ft (500 meters) and 2460 ft (750 meters; optional).
- Two data collection approaches: (i) detector-only, and (ii) detector combined with BSM.
- Five replications for each of the scenarios listed above.

3.3 Performance Evaluation Results

3.3.1 Simulation Parameter Settings

The settings below are used for the simulation scenarios mentioned above.

- **Simulation Settings**

The simulation lasts for 1 hour, from 8:00 AM to 9:00 AM, with a 15-minute warm-up period.

- **RSU Settings**

For RSUs, the default communication range is 1640 feet (500 meters). They broadcast RSMs at a frequency of 1 Hz- once every second- when a vehicle queue is detected. They will continue broadcasting for 60 seconds and then stop if no vehicle queue is present (indicating no traffic congestion).

If necessary, a broader range of 2460 feet (i.e., 750 meters) will be used to assess potential performance improvements.

- **Connected Vehicle Settings**

Connected vehicles can transmit BSMs at 10 Hz (every 0.1 seconds) and maintain a 100% compliance rate. When they receive recommended speed limits from nearby RSUs via RSMs, they adjust their speeds based on their distance to the End of Queue.

- **Lane Closure Settings**

Two lane closure scenarios are proposed for the performance assessment of Queue Warning: (i) a one-lane closure for one hour and (ii) a two-lane closure for one hour.

The lane closure will start at 8:00 a.m. and stay in effect throughout the entire simulation. The length of the lane closure is 328 feet (approximately 100 meters). For all vehicles, the visibility distance for the lane closure is 656 feet (about 200 meters). When vehicles are within this visibility range, they will take necessary actions, such as slowing down and changing lanes, to pass through the lane closure area. Specifically, a maximum speed of 50 mph applies to all vehicles within this visibility distance. Note that this speed reduction does not conflict with the new speed limits suggested by the Queue Warning application, because the locations they apply to differ: one is upstream of the lane closure, and the other is upstream of the detected End of Queue. These two points may slightly overlap at first when the lane closure is activated, but they will separate as traffic congestion increases and the End of Queue moves upstream.

- **Queue Warning Zone Settings**

The proposed queue warning zone spans 2 miles and is divided into two speed reduction zones. The first speed reduction zone is within the first mile upstream from the End of Queue, where a lower speed limit of 45 mph is recommended. The other speed reduction zone is the rest of the queue warning zone, where a higher speed limit of 60 mph is recommended.

- **Penetration Rates of Connected Vehicles**

The simulated penetration rates for connected vehicles are 0%, 10%, 20%, 30%, 40%, and 50%. To shorten the total simulation time, and since a 50% rate is already quite high, rates above 50% are not considered.

- **Data Collection and Congestion Identification Settings**

The interval for collecting BSM data is every 30 seconds, while the interval for collecting detector data is 5 minutes. The median speed measurement (i.e., 50th percentile) is used for the speeds obtained from the BSMs. In contrast, the average occupancy measurement is used for the occupancies gathered from the detectors within the same VDS.

For the BSM data, a speed threshold of 25 mph is used to identify traffic congestion when speeds drop below this level. For the detector data, an occupancy threshold of 25% is used, with congestion identified when occupancy exceeds this percentage. At locations where both BSM and detector data are available, traffic congestion is identified if either or both of these conditions are met.

- **Traffic Demand Settings**

To better evaluate the impact of Queue Warning, only the mainline traffic flow is included in the test network. In other words, there are no on-ramp or off-ramp flows during the simulations. For the proposed two lane closure scenarios, different mainline traffic demands are suggested as follows:

- One-lane closure for one hour
    - A high demand of 8000 vehicles per hour (i.e., at capacity) and a medium demand of 7200 vehicles per hour (i.e., 90% of capacity).
- Two-lane closure for one hour
    - A medium demand of 7200 vehicles per hour (i.e., 90% of capacity) and a low demand of 6400 vehicles per hour (i.e., 80% of capacity).

3.3.2 Simulation Results

Table 3 and Table 4 summarize the simulation results for the proposed lane closure scenarios with a default communications range of 1640 feet. For the scenario of 1-Lane Closure,

- Traffic is not very congested, with moderate demand. The network flow-to-demand ratio is high, at 0.97 for the baseline experiment with 0% CV.
- With high demand, traffic is more congested than with medium demand. The network flow-to-demand ratio is lower, at 0.93 for the baseline experiment with 0% CV.

For the scenario of 2-Lane Closure,

- Traffic is highly congested despite low demand. The network flow-to-demand ratio is relatively low, at 0.81 for the baseline experiment with 0% CV.
- With medium demand, traffic is more congested than with low demand. The network flow-to-demand ratio is significantly lower, at 0.73 for the baseline experiment with 0% CV.

Based on the simulation results, here are our findings:

- The use of Queue Warning can provide reasonable mobility benefits only under specific traffic conditions, which are closely linked to the demand-to-capacity ratio and the speed reduction strategies in place.
    - The use of Queue Warning negatively affects overall traffic, causing more delays during a one-lane closure with moderate demand. This indicates that, under the proposed speed reduction strategies—particularly a low speed limit of 45 mph in the first mile of the queue warning zone—connected vehicles tend to overreact to minor traffic congestion. As a result, the more connected vehicles follow the proposed speed reduction, the greater the delay for vehicles will be, as demonstrated in Table 3.
    - As illustrated in Table 4, the proposed speed reduction strategies cannot effectively mitigate traffic congestion when traffic demand significantly exceeds the reduced capacity caused by lane closures. This is because, although connected vehicles are required to slow down upstream of the queue, it does not create enough space for the vehicles in the queue to move faster.
    - Queue Warning can provide reasonable mobility benefits when traffic demand slightly exceeds the reduced capacity, as shown in the case of high demand during a 1-lane closure scenario in Table 3. Although the delay is reduced by just 1.75%, this decrease is considered significant relative to the overall traffic across the network.
- A small percentage of connected vehicles is enough to gain the benefits of Queue Warning. Simulation results show that just 10% penetration is enough. In fact, having more connected vehicles can even make Queue Warning less effective, causing more vehicle delays.
- The existing road sensing infrastructure with detectors is sufficient to support Queue Warning deployment. While additional BSM data can expedite vehicle queue detection, its impact on reducing vehicle delay is minimal.

We ran simulations with a longer communications range of 2460 feet. However, the results are similar to those with the default range and are not included here.

Table 3. Queue Warning Simulation Results for the Scenario of 1-Lane Closure.

10-Mile 4-Lane Freeway Section with a Speed Limit of 65mph															
Scenario: 1-Lane Closure for One Hour (Communications Range: 1640 feet)		Recommended Speed Limits: (i) 45mph within First Mile from the End of Queue, (ii) 60mph in the Rest of the Queue Warning Zone													
		0% CV		10% CV		20% CV		30% CV		40% CV		50% CV			
Demand Level	Data Collection Method	Network Flow (veh/hr)	Delay (sec/mile)	Delay (sec/mile)	Delay Changes (%)	Delay (sec/mile)	Delay Changes (%)	Delay (sec/mile)	Delay Changes (%)	Delay (sec/mile)	Delay Changes (%)	Delay (sec/mile)	Delay Changes (%)	Delay (sec/mile)	Delay Changes (%)
7200 veh/hr (Mainline)	Detector Only	7002.40	9.47	9.76	-3.06	9.84	-3.91	9.99	-5.49	9.89	-4.44	9.99	-5.49		
	Detector + BSM	7002.40	9.47	9.71	-2.53	9.69	-2.32	9.76	-3.06	9.81	-3.59	9.91	-4.65		
8000 veh/hr (Mainline)	Detector Only	7451.00	17.19	16.89	1.75	17.07	0.70	17.38	-1.11	17.60	-2.39	17.83	-3.72		
	Detector + BSM	7451.00	17.19	16.95	1.40	17.13	0.35	17.41	-1.28	17.86	-3.90	17.91	-4.19		

Table 4. Queue Warning Simulation Results for the Scenario of 2-Lane Closure

10-Mile 4-Lane Freeway Section with a Speed Limit of 65mph													
Scenario: 2-Lane Closure for One Hour (Communications Range: 1640 feet)		Recommended Speed Limits: (i) 45mph within First Mile from the End of Queue, (ii) 60mph in the Rest of the Queue Warning Zone											
		0% CV		10% CV		20% CV		30% CV		40% CV		50% CV	
Demand Level	Data Collection Method	Network Flow (veh/hr)	Delay (sec/mile)	Delay (sec/mile)	Delay Changes (%)	Delay (sec/mile)	Delay Changes (%)	Delay (sec/mile)	Delay Changes (%)	Delay (sec/mile)	Delay Changes (%)	Delay (sec/mile)	Delay Changes (%)
6400 veh/hr (Mainline)	Detector Only	5207.80	32.87	32.96	-0.27	32.86	0.03	33.01	-0.43	33.09	-0.67	33.12	-0.76
	Detector + BSM	5207.80	32.87	32.54	1.00	32.67	0.61	32.57	0.91	32.60	0.82	32.76	0.33
7200 veh/hr (Mainline)	Detector Only	5235.20	42.53	42.77	-0.56	42.63	-0.24	42.71	-0.42	42.29	0.56	42.43	0.24
	Detector + BSM	5235.20	42.53	42.17	0.85	42.57	-0.09	42.40	0.31	42.38	0.35	42.76	-0.54

3.4 Discussion

While it is intuitive that Queue Warning can improve traffic safety by alerting drivers about vehicle queues downstream, realizing its mobility benefits is challenging. A key element of Queue Warning is the suggested strategies, which include recommended speed limits, lane changes, or detours. The simulation results above show that the effectiveness of speed limit recommendations can only be achieved under certain conditions. It may disrupt network traffic during light congestion and offers only minimal improvements during severe congestion.

For Infrastructure Operations Owners (IOO) like Caltrans, leveraging specific platforms such as the Queue Warning platform developed in this project is crucial for evaluating potential impacts when speed recommendations are given to connected vehicles along with queue information.

Therefore, during severe traffic congestion when demand significantly exceeds the reduced capacity, it is crucial to reroute traffic from freeways to local arterials using detour recommendations, which falls under Integrated Corridor Management (ICM) and is out of the project scope.

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4 Speed Harmonization

Speed Harmonization aims to determine speed recommendations based on traffic conditions and other factors (such as weather conditions) and use connected vehicle technologies to help align vehicle speeds with these recommendations. It can be applied in situations like traffic congestion, bottlenecks, incidents, special events, and other scenarios that disrupt flow. This approach will assist in maintaining traffic flow, minimizing unnecessary stops and starts, and ensuring consistent speeds. Therefore, it is expected to improve the efficiency, resilience, and reliability of the transportation system by reducing travel delays and their variability, as well as lowering energy consumption and emissions. Smoother traffic flow is also expected to improve safety within the transportation system by reducing the likelihood of crashes and injuries.

As illustrated in the physical diagram[11] in Figure 18, there are two communications approaches for Speed Harmonization: (i) direct communications via RSU; and (ii) network communications through the Transportation Information Center (TIC). However, given the scope of this project, we will only investigate the performance of Speed Harmonization under the direct communications approach using RSUs.

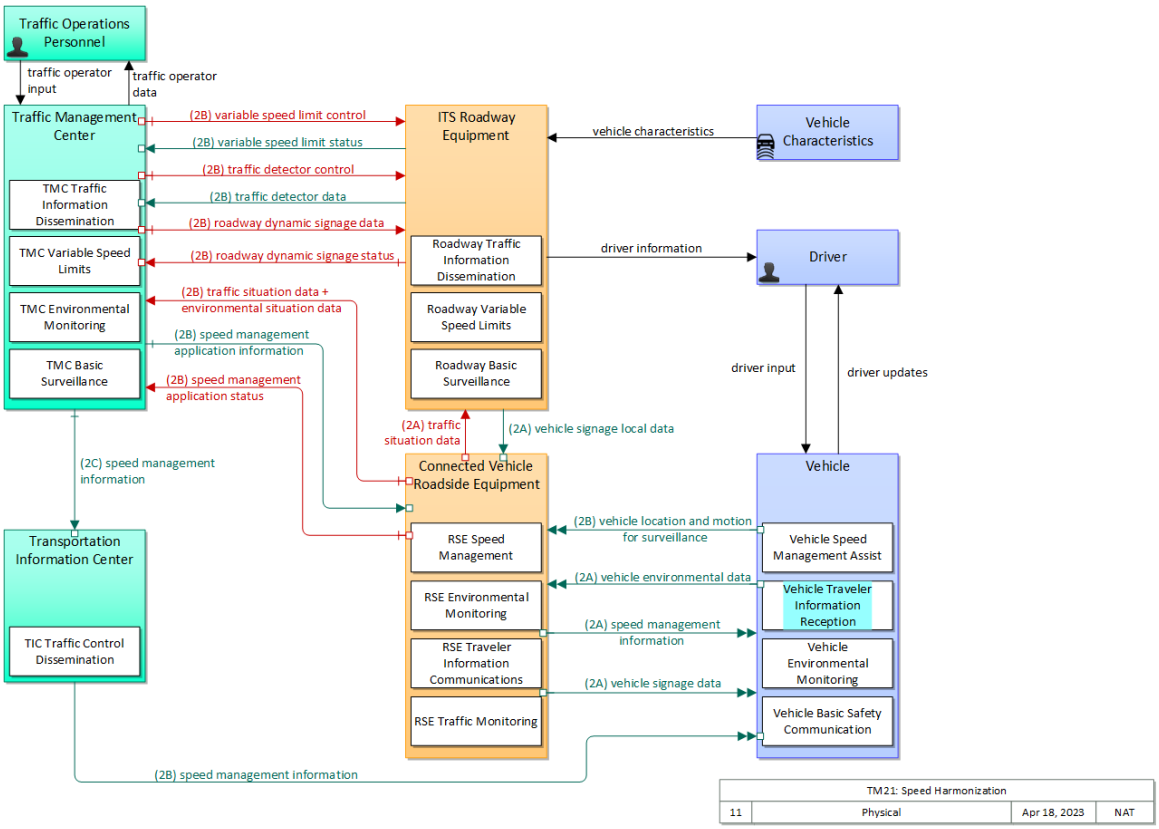

Figure 18. Physical diagram of the Speed Harmonization application.

[11] Speed Harmonization in ARC-IT 9.2. https://www.arc-it.net/html/servicepackets/sp68.html#tab-3

For the implementation in the integrated simulation framework in Aimsun, we further simplify the modeling framework for Speed Harmonization, which is illustrated in Figure 19. To simplify, we combine ITS Roadway Equipment, Traffic Management Center (TMC), Traffic Information Center (TIC), and RSU into one entity, removing the modeling of explicit data flows among them.

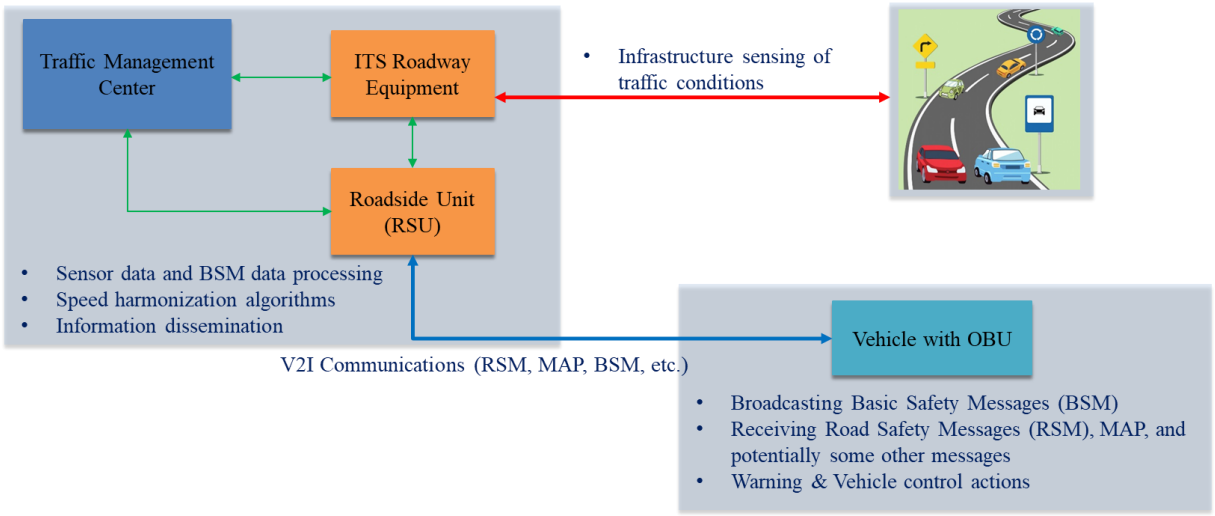

Figure 19. Proposed modeling framework for Speed Harmonization in Aimsun.

4.1 System Design

The implementation of Speed Harmonization in this project aims to help IOOs use real-time data from various sources to detect traffic congestion and set appropriate speed limits for approaching connected vehicles. This approach seeks to help maintain traffic flow, reduce unnecessary stops and starts, and ensure consistent speeds.

Figure 20 illustrates the system design of Speed Harmonization in Aimsum. The implemented workflow is described as follows:

- Connected vehicles in the downstream send BSMs to the RSU.
- The edge computing unit collects real-time data from detectors and BSMs from connected vehicles through the RSU.
- The edge computing unit executes speed harmonization algorithms and generates the recommended speed values.
- The RSU sends recommended speeds to approaching connected vehicles via RSMs.
- A connected vehicle receives recommended speeds via RSMs and takes necessary actions to smooth traffic.

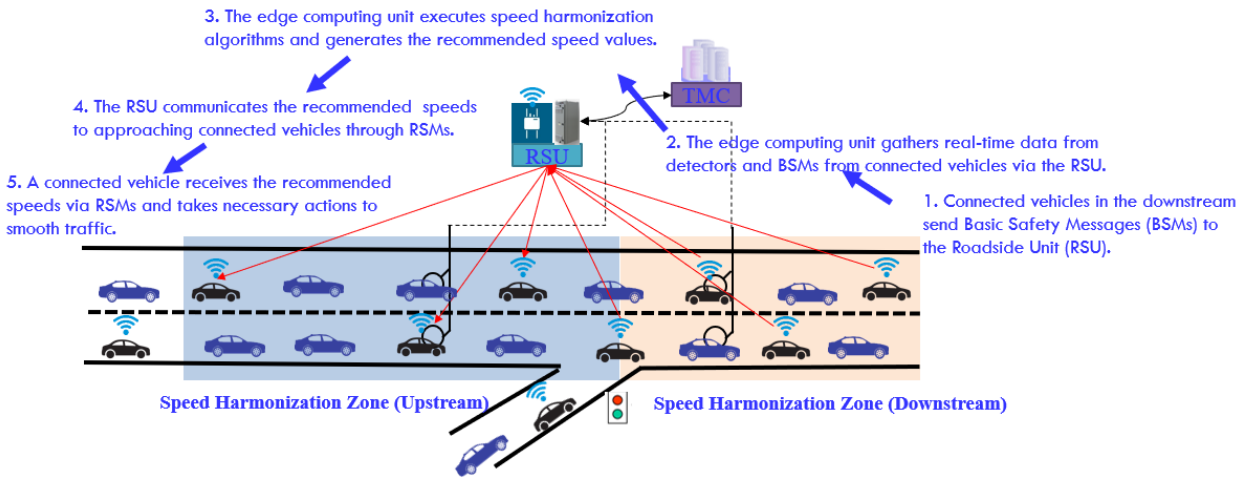

Figure 20. System design of Speed Harmonization in Aimsun.

4.1.1 Speed Harmonization Zone

As shown in Figure 20, there is a user-defined speed harmonization zone. This zone consists of two parts: a downstream segment that collects traffic data to support the decision of recommended speeds, and an upstream section where the recommended speeds are broadcast via RSUs.

Specifically, when applying Speed Harmonization to a freeway weaving section, data collection is done on the downstream segment beyond the merging gore, while message dissemination occurs on the upstream segment. The lengths of these segments are specified by the user and are closely related to the RSU's communications range.

4.1.2 Speed Harmonization Algorithms

Two different data sources can be used to support the determination of recommended speeds:

- 5-minute averages of traffic measurements, such as occupancy, flow, and speed, collected from downstream loop detectors.
- BSMs from connected vehicles located in the downstream area of the speed harmonization zone.

In the literature, several speed harmonization algorithms have been proposed, including a rule-based speed harmonization algorithm[12], a Cooperative Variable Speed Limit (C-VSL) algorithm[13], and a Variable Speed Limit – Variable Speed Advisory (VSL-VSA) algorithm[14,15]. The VSL-VSA algorithm aims to delay traffic

[12] Talebpour, A., Mahmassani, H. S., & Hamdar, S. H. (2013). Speed harmonization: Evaluation of effectiveness under congested conditions. Transportation research record, 2391(1), 69-79.
[13] Grumert, E., Ma, X., & Tapani, A. (2015). Analysis of a cooperative variable speed limit system using microscopic traffic simulation. Transportation research part C: emerging technologies, 52, 173-186.
[14] Lu, X. Y., Shladover, S. E., Jawad, I., Jagannathan, R., & Phillips, T. (2015). Novel algorithm for variable speed limits and advisories for a freeway corridor with multiple bottlenecks. Transportation Research Record, 2489(1), 86-96.
[15] Hale, D., Phillips, T., Raboy, K., Ma, J., Su, P., Lu, X. Y., & Dailey, D. J. (2016). Introduction of cooperative vehicle-to-infrastructure systems to improve speed harmonization (No. FHWA-HRT-16-023).

congestion and improve throughput at a bottleneck by performing two actions: suggesting lower speed limits upstream to decrease incoming flow and recommending higher speeds at the bottleneck to boost outgoing flow. This algorithm has been implemented in the Speed Harmonization application with minor revisions:

- At the bottleneck location, speed (v_m) is weighted between the speed measurement (v_{det}) from infrastructure sensors such as loop detectors and the one (v_{BSM}) from BSMs collected from connected vehicles.
    - $v_m=(1-\alpha)\ v_{det} + \alpha\ v_{BSM}$, where α is a coefficient between 0 and 1.

  Occupancy (Occ_m) is measured using infrastructure sensors like loop detectors.
- At the immediate upstream, a lower speed limit, v_{up}, is recommended if the observed occupancy (Occ_m) exceeds a user-defined threshold (Occ_{th}). Occ_{th} is chosen as the occupancy at which traffic is near capacity flow.
    - $v_{up} = \beta\ v_m$, where β is a user-defined ratio less than 1.

  No speed limit is recommended if the observed occupancy Occ_m is less than Occ_{th}.
- At the bottleneck location, no speed recommendations are provided. Vehicles may be able to accelerate slightly because of the extra space created by the reduced ingress flow upstream of the bottleneck.

4.2 Test Networks and Scenario Design

4.2.1 Test Networks

To support a more comprehensive performance analysis of Speed Harmonization, we use the same artificial test networks created for Queue Warning. While both Speed Harmonization and Queue Warning can provide speed recommendations to approaching connected vehicles, their targeted locations differ. Queue Warning focuses on connected vehicles upstream of the identified End of Queue, which can shift based on downstream traffic congestion. Speed Harmonization is better suited for bottleneck locations, especially those with high weaving flows (e.g., on-ramps). By temporarily reducing the incoming flow from upstream, it allows weaving vehicles to enter or exit the freeway more easily and quickly, potentially delaying traffic bottleneck formation and improving system performance with higher average flows and fewer travel delays.

Figure 21 illustrates the test network used to assess the performance of Speed Harmonization. It consists of a 10-mile, 4-lane freeway segment with 10 weaving sections. Each weaving section is 1 mile apart and contains an on-ramp and an off-ramp. The posted speed limit is 65mph. The distance between the on-ramp and the off-ramp is set at 1000 feet. Two Vehicle Detector Stations (VDSs) are installed upstream and downstream of the merging gore. The distance from the upstream VDS to the merging gore is 500 feet, and from the downstream VDS to the merging gore is 1000 feet. An RSU is located near the merging gore at each weaving section, with a default communications range of 1640 feet (500 meters). Consequently, a total of 10 RSUs are installed in the test network. To ensure consistency with real-world conditions, a ramp meter is placed at the on-ramp in each weaving section to regulate vehicle entry onto the freeway.

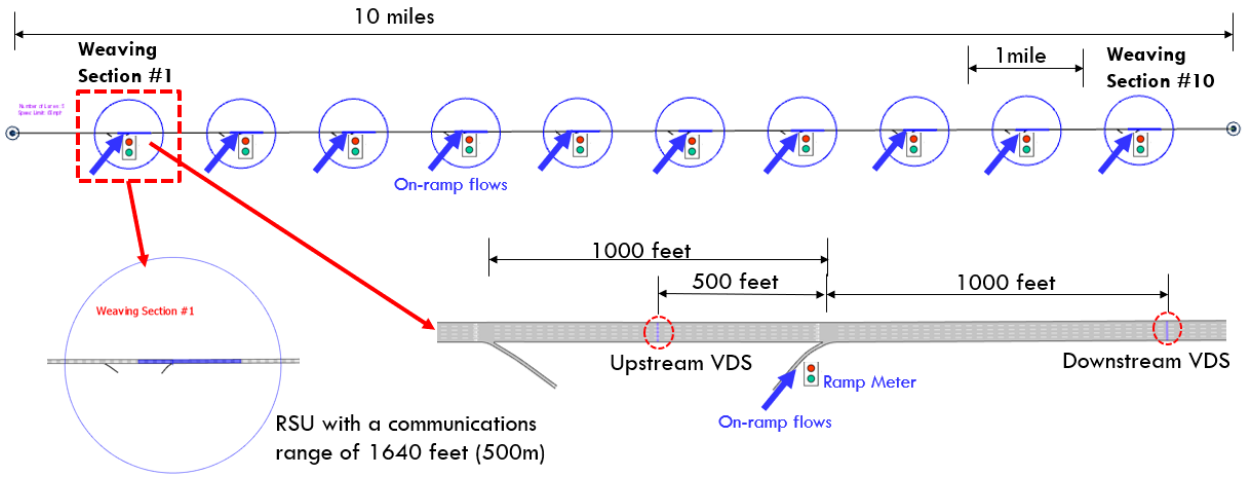

Figure 21. Test network in Aimsun for Speed Harmonization.

4.2.2 Scenario Design

Speed Harmonization is an application designed to improve both safety and mobility. However, since the Surrogate Safety Assessment Model (SSAM) is not suitable for safety evaluations in Aimsun, the assessment will focus on potential mobility improvements instead.

- **Network Settings**

The test network used for performance assessment is a 10-mile 4-lane freeway segment with a speed limit of 65mph, as shown in Figure 21. Since the 65-mph speed limit is commonly used on California freeways, we do not consider other speed limits in our performance assessment. Because each simulation run takes a long time, we also exclude other lane configurations, such as 5 or 3 lanes. However, the implementation framework is flexible and can be easily extended to include other lane setups for performance evaluation.

There are ten weaving sections, numbered one through ten, arranged from the most upstream to the most downstream. A ramp meter is installed at each on-ramp to control the vehicles entering the freeway.

- **Vehicle Reaction to Speed Reduction**

We do not simulate Dynamic Message Signs (DMS) in Aimsun because simulated vehicles do not comply with the regulations or recommendations posted on the DMS. However, connected vehicles will strictly follow the speed limits received from the RSUs via RSMs. Due to a 100% compliance rate, the penetration rate of connected vehicles in the network can be regarded as the "effective" penetration rate of those that adhere to the speed recommendations.

- **Detector Coverage**

The detector coverage follows the settings in Figure 21. We assume that all detectors are functioning properly and provide accurate traffic measurements of flow, speed, and occupancy.

- **Settings of Direct Communications**

We do not consider the impact of communications latency in this application because the aggregation interval in the data used for detecting traffic congestion is much longer than the communication latency. We also do not account for the effect of packet loss rate because Speed Harmonization is not a safety-critical application requiring immediate driver actions.

However, the communications range will impact the collection of BSMs from connected vehicles downstream of the Speed Harmonization zone. It will also affect connected vehicles upstream of the zone, encouraging them to follow the new speed limits recommended by the TMC/RSUs. Therefore, this study will explore two different communications ranges: a default range of 1640 feet (500 meters) and an extended range of 2460 feet (750 meters).

- **Data Collection**

In the current implementation, we consider two sources for data collection: (i) traffic measurements (such as flow, speed, and occupancy) from loop detectors, and (ii) BSMs (with speed information) from connected vehicles.

Since the data collection interval for loop detectors is usually longer than that for BSMs, the speed inputs for the speed harmonization algorithm are obtained by combining measurements from both sources. The coefficient α is set at 0.1. This approach uses reliable speed data from loop detectors, which provide point-based detection with a 100% observation rate, while also integrating high-frequency speed measurements from BSMs to better capture traffic dynamics.

Occupancy data from loop detectors are directly used as inputs for the speed harmonization algorithm.

- **Generation of Traffic Congestion**

To create a traffic bottleneck, we increased the on-ramp flow at weaving section #10, which is illustrated in the Figure 22 and is often the cause of traffic jams in real-world situations.

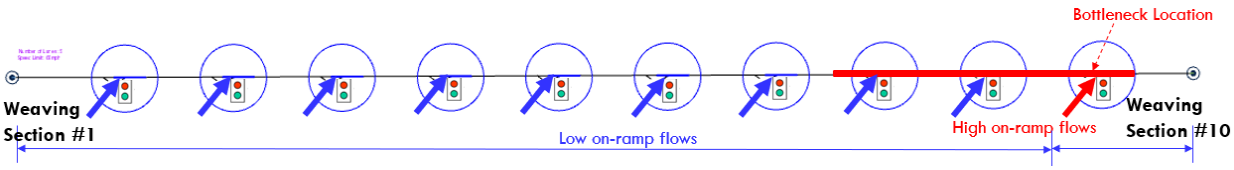

Figure 22. Example of the generation of traffic bottlenecks for Speed Harmonization.

- **Traffic Demand**

We analyze three different levels of traffic demand on the mainline: (i) high demand (8000 vehicles per hour), (ii) medium demand (7000 vehicles per hour), and (iii) low demand (6000 vehicles per hour).

The demand for ramp flows stays steady across different simulation scenarios. We use low on-ramp flows at weaving sections #1 to #9, set at 300 vehicles per hour. At weaving section #10, we increase the on-ramp flow to 900 vehicles per hour. This higher flow will cause weaving section #10 to become a bottleneck in the test network. Traffic congestion will develop and move upstream as on-ramp vehicles merge onto the freeway.

- **Ramp Metering**

The ramp metering rates remain fixed throughout the entire simulation period and stay consistent across different scenarios. The metering rates at weaving sections #1 to #9 are set at 450 vehicles per hour, which exceeds the on-ramp demands simulated. At weaving section #10, the ramp metering rate is set at 900 vehicles per hour, aligning with the simulated on-ramp demand.

- **Penetration Rate of Connected Vehicles**

We have observed that the simulation speed in Aimsun significantly slows down as the number of connected vehicles in the network increases. Due to the size of the test networks, we only run simulations with CV penetration rates of 0%, 10%, 20%, 30%, 40%, and 50%.

- **Random Seed and Number of Replications**

The random seed in microsimulations influences factors such as vehicle generation and release into the simulation network. Considering the simulation duration for each scenario and the potential effects of different random seeds, we have decided to run three replications with three distinct random seeds for each scenario.

- **Speed Reduction Ratio β**

The ratio β shows how aggressive the Speed Harmonization algorithm is at controlling the upstream ingress flow. A smaller β value results in a more aggressive algorithm, which greatly reduces the ingress flow's speed and harms the transportation system's mobility, leading to longer travel delays. Conversely, when β is near 1, the algorithm is less effective. Therefore, three different β values—0.95, 0.9, and 0.85—will be tested to find the best setting.

Therefore, the scenario design for Speed Harmonization can be summarized as follows:

- A 10-mile, 4-lane freeway segment with a speed limit of 65 mph.
- Ramp meters are installed at every on-ramp.
- Full detector coverage with both upstream and downstream VDSs at merging sections.
- A 100% compliance rate of CVs with speed limit recommendations.
- Three levels of mainline demand: high demand (8000 vehicles per hour), medium demand (7000 vehicles per hour), and low demand (6000 vehicles per hour).
- The demand for on-ramps is 300 vehicles per hour at weaving sections #1 to #9, while the ramp metering rate is 450 vehicles per hour. At weaving section #10, the demand is 900 vehicles per hour, and the ramp metering rate is set at 900 vehicles per hour.
- Six different CV penetration rates: 0%, 10%, 20%, 30%, 40%, and 50%.
- Two different communications ranges of RSUs: 1640 ft (500 meters) and 2460 ft (750 meters)..
- Two data sources: (i) from loop detectors, and (ii) from BSMs.
- The coefficient α is set at 0.1.
- Three different β values: 0.95, 0.9, and 0.85.
- 3 replications for each of the scenarios above.

4.3 Performance Evaluation Results

4.3.1 Simulation Parameter Settings

The settings listed below are used for the simulation scenarios described above..

- **Simulation Settings**

The simulation period is 1 hour, from 8:00 AM to 9:00 AM. The warm-up period is 15 minutes.

- **RSU Settings**

All RSUs are positioned near the merging gore at each weaving section. The default communication range for RSUs is 1640 feet (500 meters). They broadcast RSMs at a frequency of 0.1 Hz (once every 10 seconds) when Speed Harmonization is active. They will continue broadcasting until Speed Harmonization is turned off (indicating no traffic congestion).

- **Connected Vehicle Settings**

Connected vehicles are allowed to send BSMs at a frequency of 10 Hz (one message every 0.1 seconds). They maintain a 100% compliance rate and will adjust their speeds to follow the recommended speed limits provided by nearby RSUs via RSMs. They will maintain the current speed limit for 10 seconds. Afterward, they either revert to their normal vehicle control modes or change their speeds to a new speed limit received from nearby RSUs.

- **Speed Harmonization Zone Settings**

In each weaving section, the speed harmonization zone is divided into two parts. The first part is a 2,000-foot freeway segment downstream of the merging gore, used to collect BSMs from connected vehicles. The second part is another 2,000-foot freeway segment upstream of the merging gore, used to send recommended speed limits to approaching connected vehicles.

- **Penetration Rates of Connected Vehicles**

The simulated penetration rates of connected vehicles are 0%, 10%, 20%, 30%, 40%, and 50%. To reduce the total simulation time, and since a 50% penetration rate is already quite high, rates above 50% are not included.

- **Data Collection**

The interval for collecting BSM data is every 30 seconds, while the interval for collecting detector data is 5 minutes. The median speed measurement (i.e., 50th percentile) is used for the speeds obtained from the BSMs. In contrast, the mean speed and occupancy are used for the measurements collected from the detectors within the same VDS. The coefficient α is set at 0.1 to combine the speed measurements from the BSMs with those from loop detectors.

- **Speed Harmonization Algorithm Settings β**

The occupancy threshold Occ_{th} is set at 20%, and the speed reduction ratio β can have three different values: 0.95, 0.9, and 0.85.

- **Traffic Demand Settings**

To better assess the impact of Speed Harmonization, the following traffic demands are proposed:

- Three different levels of mainline demand
  - A high demand of 8000 vehicles per hour, a medium demand of 7200 vehicles per hour, and a low demand of 6000 vehicles per hour.
- Low on-ramp flow rates of 300 vehicles per hour at weaving sections #1 through #9.
- A high on-ramp flow rate of 900 vehicles per hour at weaving section #10.

4.3.2 Simulation Results

Table 5 to Table 7 summarize the Speed Harmonization simulation results with different values of β: 0.85, 0.9, and 0.95. The communications range is set at 1640 feet, and the occupancy threshold is set at 20%. Table 8 further shows the simulation results when β is 0.95 with the communications range extended to 2640 feet.

Based on the simulation results, we observe the following findings:

- Regardless of the value of the speed reduction ratio β and the level of traffic congestion, the current Speed Harmonization algorithm does not improve mobility in the transportation system. This also indicates that reducing the ingress flow at traffic bottlenecks may not create enough space to harmonize downstream weaving flows. Instead, it could potentially increase the average vehicle delay.
- Since the Speed Harmonization algorithm currently used is ineffective, expanding the communications range does not provide any extra mobility benefits.

4.4 Discussion

The simulation results show that achieving the mobility benefits of Speed Harmonization at traffic bottlenecks is difficult. Lowering the ingress flow just upstream of a traffic bottleneck may not provide enough space for downstream weaving flows to exit more quickly and efficiently. This is also supported by the Queue Warning simulation results, which aim to alert drivers of vehicle queues further upstream but only lead to mobility improvements when traffic demand slightly exceeds capacity.

Therefore, for traffic congestion caused by heavy weaving flows, alternative traffic management strategies should be used, such as rerouting the on-ramp flows at the bottleneck to the upstream or downstream on-ramps.

Table 5. Speed Harmonization Simulation Results with β=0.85 and Communications Range =1640ft.

10-Mile 4-Lane Freeway with 10 Weaving Sections	Average Delay with Occupancy Threshold = 20% & β= 0.85 & Communications Range = 1640ft											
	0% CV		10% CV		20% CV		30% CV		40% CV		50% CV	
Demand Level	Network Flow (veh/hr)	Delay (sec/mile)	Delay (sec/mile)	Delay Changes (%)	Delay (sec/mile)	Delay Changes (%)	Delay (sec/mile)	Delay Changes (%)	Delay (sec/mile)	Delay Changes (%)	Delay (sec/mile)	Delay Changes (%)
9600 veh/hr (6000 Mainline + 3600 On-Ramp)	9651.67	13.18	13.29	-0.83	13.21	-0.23	13.27	-0.68	13.38	-1.52	13.50	-2.43
10600 veh/hr (7000 Mainline + 3600 On-Ramp)	10198.67	28.04	27.88	0.57	28.12	-0.29	28.08	-0.14	28.21	-0.61	28.27	-0.82
11600 veh/hr (8000 Mainline + 3600 On-Ramp)	10286.33	45.23	45.04	0.42	45.52	-0.64	45.32	-0.20	45.30	-0.15	45.89	-1.46

Table 6. Speed Harmonization Simulation Results with β=0.9 and Communications Range =1640ft.

10-Mile 4-Lane Freeway with 10 Weaving Sections	Average Delay with Occupancy Threshold = 20% & β= 0.9 & & Communications Range = 1640ft											
	0% CV		10% CV		20% CV		30% CV		40% CV		50% CV	
Demand Level	Network Flow (veh/hr)	Delay (sec/mile)	Delay (sec/mile)	Delay Changes (%)	Delay (sec/mile)	Delay Changes (%)	Delay (sec/mile)	Delay Changes (%)	Delay (sec/mile)	Delay Changes (%)	Delay (sec/mile)	Delay Changes (%)
9600 veh/hr (6000 Mainline + 3600 On-Ramp)	9651.67	13.18	13.48	-2.28	13.07	0.83	13.26	-0.61	13.21	-0.23	13.16	0.15
10600 veh/hr (7000 Mainline + 3600 On-Ramp)	10198.67	28.04	28.53	-1.75	28.34	-1.07	28.03	0.04	28.37	-1.18	27.96	0.29
11600 veh/hr (8000 Mainline + 3600 On-Ramp)	10286.33	45.23	45.03	0.44	45.43	-0.44	45.16	0.15	45.26	-0.07	45.18	0.11

Table 7. Speed Harmonization Simulation Results with β=0.95 and Communications Range =1640ft.

10-Mile 4-Lane Freeway with 10 Weaving Sections	Average Delay with Occupancy Threshold = 20% & β = 0.95 & Communications Range = 1640ft											
	0% CV		10% CV		20% CV		30% CV		40% CV		50% CV	
Demand Level	Network Flow (veh/hr)	Delay (sec/mile)	Delay (sec/mile)	Delay Changes (%)	Delay (sec/mile)	Delay Changes (%)	Delay (sec/mile)	Delay Changes (%)	Delay (sec/mile)	Delay Changes (%)	Delay (sec/mile)	Delay Changes (%)
9600 veh/hr (6000 Mainline + 3600 On-Ramp)	9651.67	13.18	13.32	-1.06	13.17	0.08	13.39	-1.59	13.04	1.06	13.30	-0.91
10600 veh/hr (7000 Mainline + 3600 On-Ramp)	10198.67	28.04	28.29	-0.89	27.84	0.71	28.06	-0.07	28.95	-3.25	27.53	1.82
11600 veh/hr (8000 Mainline + 3600 On-Ramp)	10286.33	45.23	45.10	0.29	45.08	0.33	45.12	0.24	45.38	-0.33	45.15	0.18

Table 8. Speed Harmonization Simulation Results with β=0.95 and Communications Range =2460ft.

10-Mile 4-Lane Freeway with 10 Weaving Sections	Average Delay with Occupancy Threshold = 20% & β = 0.95 & Communications Range = 2460ft											
	0% CV		10% CV		20% CV		30% CV		40% CV		50% CV	
Demand Level	Network Flow (veh/hr)	Delay (sec/mile)	Delay (sec/mile)	Delay Changes (%)	Delay (sec/mile)	Delay Changes (%)	Delay (sec/mile)	Delay Changes (%)	Delay (sec/mile)	Delay Changes (%)	Delay (sec/mile)	Delay Changes (%)
9600 veh/hr (6000 Mainline + 3600 On-Ramp)	9651.67	13.18	13.49	-2.35	13.25	-0.53	13.46	-2.12	13.72	-4.10	13.44	-1.97
10600 veh/hr (7000 Mainline + 3600 On-Ramp)	10198.67	28.04	27.48	2.00	28.25	-0.75	27.99	0.18	28.20	-0.57	27.82	0.78
11600 veh/hr (8000 Mainline + 3600 On-Ramp)	10286.33	45.23	45.05	0.40	45.30	-0.15	44.98	0.55	45.28	-0.11	45.02	0.46

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5 Intersection Safety Warning and Collision Avoidance

Intersection Safety Warning and Collision Avoidance[16] aims to enable connected vehicles to receive information from the infrastructure as they approach an instrumented intersection. This information may include the signal timing and geometry of the intersection. Vehicles can use this data to assess whether they can safely pass through without violating traffic rules or risking collisions with other vehicles or vulnerable road users (VRUs). If it is unsafe to proceed, a warning will be issued to the driver. Collision avoidance measures will be taken based on the vehicle's level of automation. Additionally, a warning about an imminent unsafe vehicle infringement at the intersection—potentially threatening other vehicles or pedestrians—will be broadcast to alert approaching connected vehicles and/or nearby connected personnel devices.

Note that if we only focus on the actions of connected vehicles, this application has a similar physical diagram to the one defined for the application of Vulnerable Road User Safety[17] (known as "Pedestrian in Signalized Crosswalk Warning" in previous versions of ARC-IT) in ARC-IT Version 9.3.

With timely warnings from the infrastructure and collision avoidance actions taken by vehicles and drivers, this application is expected to improve the safety of the transportation system for both motorized and non-motorized users. Additionally, this application could enhance the efficiency, resilience, and reliability of the transportation system, potentially leading to fewer crashes and injuries.

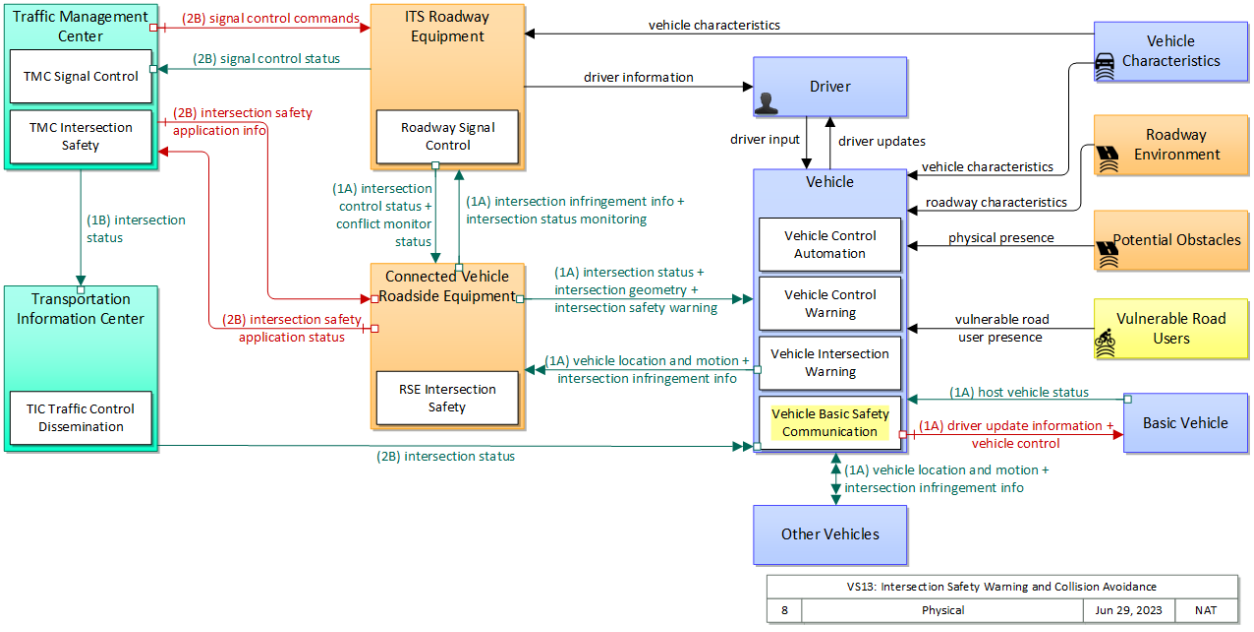


Figure 23. Physical diagram of the Intersection Safety Warning and Collision Avoidance application.

[16] Intersection Safety Warning and Collision Avoidance in ARC-IT 9.3. https://www.arc-it.net/html/servicepackets/sp57.html#tab-3

[17] Vulnerable Road User Safety in ARC-IT 9.3. https://www.arc-it.net/html/servicepackets/sp50.html#tab-3

As illustrated in the physical diagram in Figure 23, there are two communications approaches for implementing Intersection Safety Warning and Collision Avoidance: (i) direct communications via RSUs, and (ii) network communications through the Transportation Information Center (TIC). However, given the scope of this project, we will focus on evaluating the performance of Intersection Safety Warning and Collision Avoidance using the direct communications approach with RSUs.

For the implementation in the integrated simulation framework in Aimsun, we further simplify the modeling framework for Intersection Safety Warning and Collision Avoidance, as illustrated in Figure 24. To simplify, we combine ITS Roadway Equipment, Traffic Management Center (TMC), Traffic Information Center (TIC), and RSU into one entity, removing the need to model explicit data flows between them.

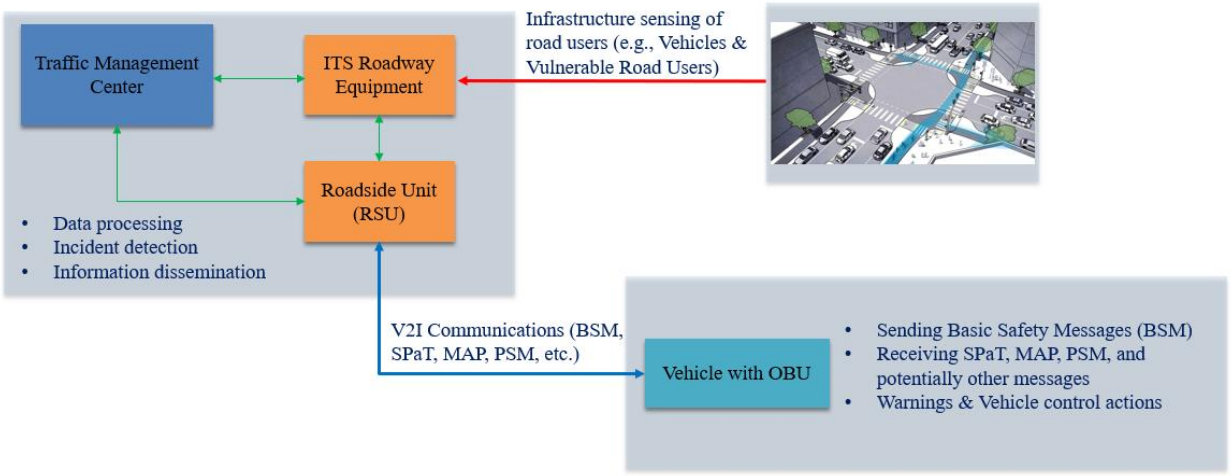


Figure 24. Proposed modeling framework for Intersection Safety Warning and Collision Avoidance in Aimsun.

The application of Intersection Safety Warning and Collision Avoidance can support the deployment of multiple sub-use cases, for example, Red Light Violation Warning [18] and Pedestrian in Signalized Crosswalk Warning[17]. In this study, we aim to implement these two sub-use cases within the integrated simulation framework in Aimsun and assess their safety and mobility performance. Detailed implementations are provided in the following sections.

5.1 Red Light Violation Warning

5.1.1 System Design

Figure 25 illustrates the system design of Red Light Violation Warning. The workflow for notifying vehicles running red lights is outlined below:

- The RSU collects real-time SPaT data from the traffic signal controller.
- The RSU broadcasts SPaT and MAP messages to nearby connected vehicles.
- A connected vehicle receives real-time SPaT and MAP messages and takes necessary actions to prevent running a red light.

[18] Red Light Violation Warning in CVRIA: https://local.iteris.com/cvria/html/applications/app57.html#tab-3

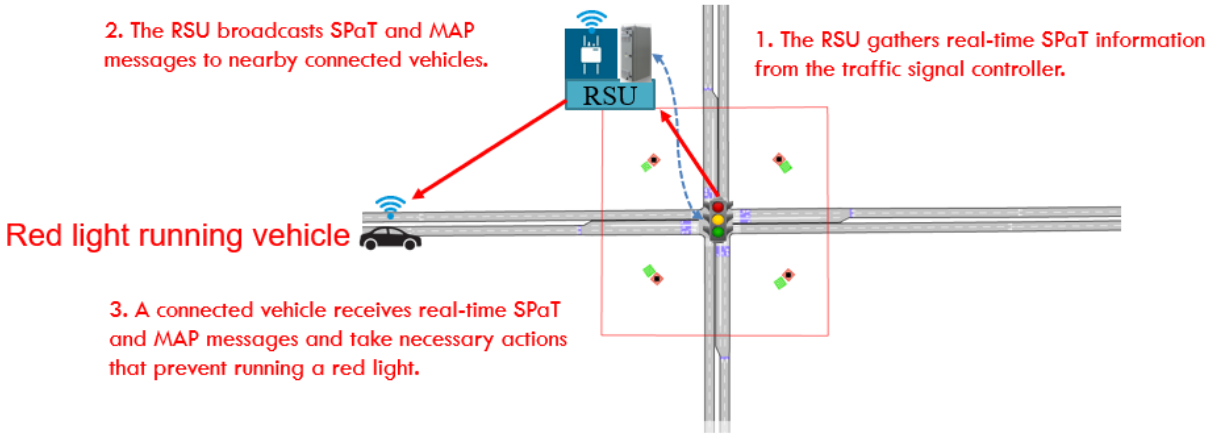


Figure 25. System design for Red Light Violation Warning.

5.1.1.1 Identification of a Potential Red-Light Runner

A key part of implementing Red Light Violation Warning is detecting a potential red-light runner. Using real-time SPaT and MAP messages from the intersection, a connected vehicle compares its current location and speed with the signal status to figure out if it might run the red light.

A potential red-light runner occurs only when: (i) the vehicle is too close to the intersection, (ii) it is traveling at high speed, and (iii) there is no leader in front.

There are two scenarios in which the vehicle is identified as a potential red-light runner:

- When the current traffic light is red,
  - It cannot completely stop before the stop bar at its maximum deceleration rate before the light turns green.
- When the current traffic light is green or yellow,
  - It cannot pass the stop bar at its current speed before the light turns red.

5.1.1.2 Modeling a Red-Light Runner in Aimsun

Following Aimsun's Technical Support recommendations, we modeled the behavior of red-light running using the following two steps:

- Define a signal group that applies solely to a user class of compliant vehicles.
- Introduce the demand for certain vehicles that don't belong to that class. These are the potential red-light running vehicles that go through the intersection without regard for traffic signals.

5.1.1.3 Proposed Algorithm to Avoid Red-Light Running

When a connected vehicle detects a potential red light violation, it will follow the algorithm outlined below to prevent it from occurring:

- There are three distance thresholds (L_{th1}, L_{th2}, and L_{th3}) that divide the space between the connected vehicle and the intersection stop bar into three zones, each with different deceleration rates.
- These three distance thresholds are defined or calculated as follows:
    - L_{th1} is a fixed value, for example, 32.8 feet (or 10 meters).
    - L_{th2} is a dynamic value calculated as a ratio (e.g., 3 times) of the vehicle's braking distance at its current speed v_{avg}, using a normal deceleration rate d_{normal}.
    - L_{th3} is also a dynamic value, calculated as a higher multiple (e.g., 5 times) of the vehicle's braking distance at its current speed v_{avg}, using a normal deceleration rate d_{normal}.
- The connected vehicle will carry out different actions within these three zones.
    - Zone #1 (Emergency Braking Zone): The connected vehicle within this zone must perform emergency braking with a very high deceleration rate, e.g., four times of d_{normal}.
    - Zone #2 (High Deceleration Rate Zone): The connected vehicle within this zone will decelerate at a high rate, e.g., two times of d_{normal}.
    - Zone #3 (Normal Deceleration Rate Zone): The connected vehicle within this zone will decelerate at its normal rate, d_{normal}.
- The proposed algorithm will not activate if the connected vehicle is beyond Zone #3.

The implied logic of the control algorithm is: when a connected vehicle detects it might run a red light but is still some distance from the intersection (in Zone 3), it begins to decelerate at a normal rate. As it approaches the intersection (in Zone 2), it starts to decelerate more rapidly if it still has the potential to run the red light. When it enters the Emergency Braking Zone (Zone 1), it applies emergency braking if the traffic light is red or about to turn red.

But note that it is possible for a vehicle not to come to a complete stop before or at the stop bar, even with the proposed algorithm. In this case, the vehicle will run the red light.

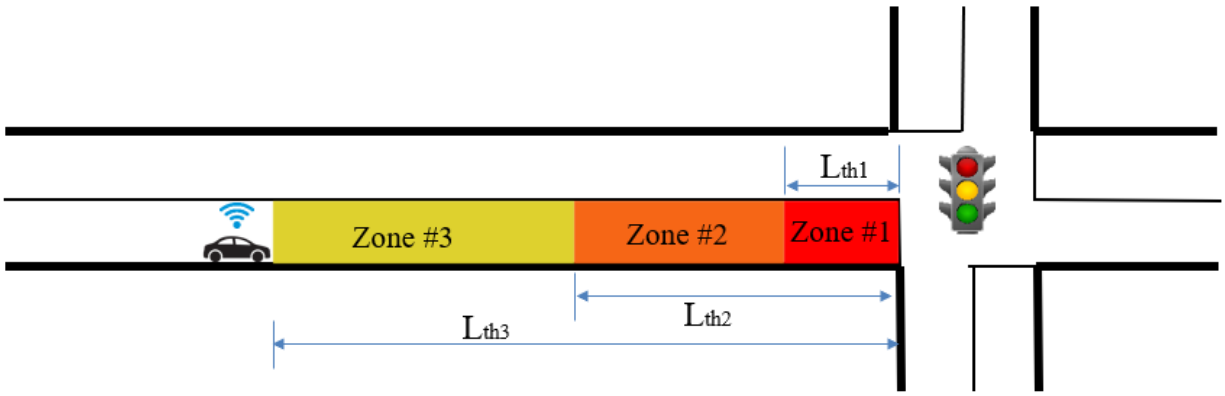


Figure 26. Three deceleration zones defined in the proposed algorithm to prevent red light violations.

5.1.2 Test Networks and Scenario Design

5.1.2.1 Test Networks

To support more comprehensive performance analysis, we create artificial test networks in Aimsun that match the design of signalized intersections in the field. Based on typical settings such as the number of

lanes, speed limits, and cycle lengths in arterial networks, we develop the following three test networks to evaluate the performance of Red Light Violation Warning.

- **Test Network #1:** A two-lane signalized intersection with a speed limit of 40 mph and a cycle length of 120 seconds.
- **Test Network #2:** A two-lane signalized intersection with a speed limit of 40 mph and a cycle length of 90 seconds.
- **Test Network #3:** A two-lane signalized intersection with a speed limit of 35 mph and a cycle length of 90 seconds.

Figure 27 provides an example of test networks in Aimsun for Red Light Violation Warning. As shown in the figure, an RSU is installed at the intersection with a default communications range of 1640 feet (500 meters). At the intersection, both stopbar and advance detectors are placed at each approach to monitor traffic arrivals and assist with the actuated traffic control.

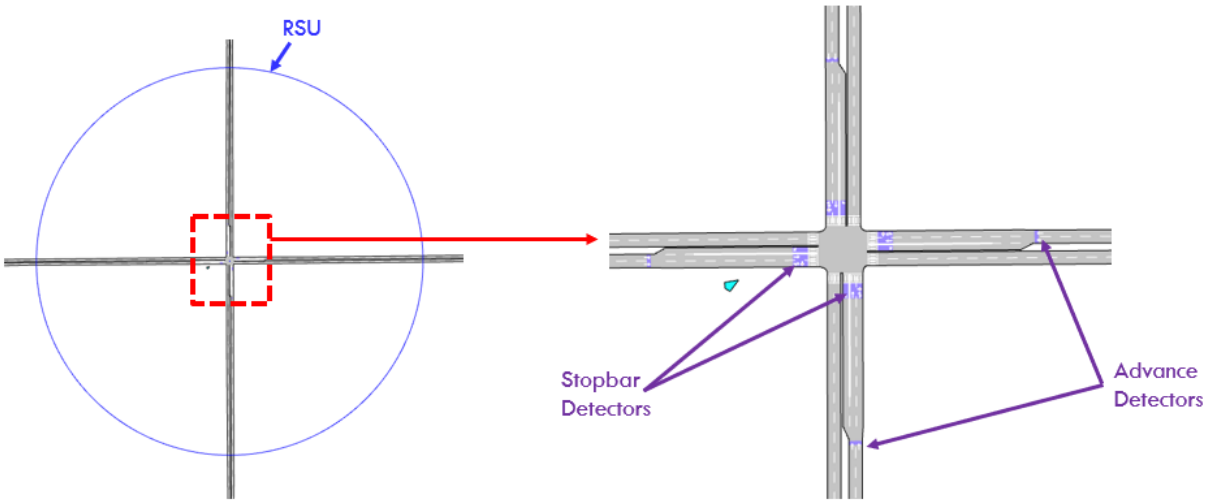


Figure 27. Example of test networks in Aimsun for Red Light Violation Warning.

5.1.2.2 Scenario Design

Since Red Light Violation Warning is a safety-related application, the scenario design will focus on: (i) the benefits, such as safety improvements, of detecting traffic violations and providing real-time alerts to affected road users (e.g., connected vehicles); and (ii) how various V2I communications settings, like communications delay and packet loss rate, influence overall performance.

- **Network Settings**

We focus on 2-lane arterials with speed limits of 35 mph and 40 mph, and cycle lengths of 90 seconds and 120 seconds, in this performance assessment because they are typical arterial road settings in the field. However, the implementation framework is flexible enough and can easily be adapted to other arterial networks for performance evaluation.

- **Settings of Direct Communications**

We do not model the impact of communications range because a default range of 1640 feet (i.e., 500 meters) is sufficient to cover the entire intersection.

However, communications latency and packet loss rates will affect the accuracy of the signal information sent from the signalized intersection, which could reduce the effectiveness of the proposed algorithm in preventing red-light running. Therefore, this study will analyze different levels of communications latency and packet loss rates.

  - Communications latency: 0 seconds, 0.1 seconds, 0.2 seconds, and 0.5 seconds.
  - Packet loss rates: 0%, 5%, 10%, and 15%.

- **Traffic Demand**

We set a fixed traffic demand of 500 vehicles per hour for the three test networks. For each approach, there are 15 left-turn vehicles, 10 right-turn vehicles, and 100 through vehicles. All left-turn and right-turn vehicles strictly follow traffic rules. However, for through vehicles, we consider an extreme scenario where none obey traffic rules and they are potential red-light runners. Therefore, for performance assessment, the baseline scenario assumes 100% of the through vehicles are potential red-light runners. The alternative scenario is x% of the through vehicles are connected vehicles regulated by the proposed algorithm to prevent red-light running.

- **Penetration Rate of Connected Vehicles**

Given the size of the test networks, we will run simulations with CV penetration rates ranging from 0% to 100% in 10% increments: 0%, 10%, 20%, 30%, 40%, 50%, 60%, 70%, 80%, 90%, and 100%.

- **Random Seed and Number of Replications**

The random seed in microsimulations affects various factors, such as vehicle generation and release into the simulation network. Considering the simulation duration for each scenario and the possible effects of different random seeds, we chose to run ten replications with ten distinct random seeds for each scenario.

Therefore, the scenario design for Red Light Violation Warning can be summarized as follows:

- Three 2-lane signalized intersections, varying in speed limits and cycle lengths: (i) 40 mph with a 120-second cycle, (ii) 40 mph with a 90-second cycle, and (iii) 35 mph with a 90-second cycle.
- There is a fixed traffic demand of 500 vehicles per hour. Each approach has 100 through vehicles, 15 left-turn vehicles, and 10 right-turn vehicles. All left-turn and right-turn vehicles strictly obey traffic laws, while all through vehicles are potential red-light runners.
- Eleven penetration rates for CVs are listed: 0%, 10%, 20%, 30%, 40%, 50%, 60%, 70%, 80%, 90%, and 100%. All connected vehicles will follow the proposed algorithm to prevent red-light running.
- A default communications range for RSUs: 1640 ft (i.e., 500 meters).
- Four different communications latency values: 0 seconds, 0.1 seconds, 0.2 seconds, and 0.5 seconds.
- Four different packet loss rates: 0%, 5%, 10%, and 15%.
- 10 repetitions for each of the scenarios above.

5.1.3 Performance Evaluation Results

5.1.3.1 Simulation Parameter Settings

The settings listed below are used in the simulation scenarios mentioned above.

- **Simulation Settings**

The simulation lasts for 1 hour, from 8:00 AM to 9:00 AM. The warm-up period lasts for 5 minutes.

- **Settings for the Proposed Algorithm to Prevent Red-Light Running**

L_{th1} is set at 32.8 feet (approximately 10 meters). The ratio used to calculate L_{th2} is 3, and the ratio for L_{th3} is 5. The normal deceleration rate d_{normal} is assigned by Aimsun when a vehicle enters the network. The deceleration rate is 4 times d_{normal} at Zone 1, 2 times d_{normal} at Zone 2, and 1 time d_{normal} at Zone 3.

- **RSU Settings**

The communications range for the RSU is 1640 feet (about 500 meters). It broadcasts MAP messages at a rate of 1 Hz (once per second) and SPaT messages at a rate of 10 Hz (every 0.1 seconds). The interval for checking timing plan changes is every 60 seconds.

Simulations will be conducted with different communications latency levels (0 seconds, 0.1 seconds, 0.2 seconds, and 0.5 seconds) and packet loss rates (0%, 5%, 10%, and 15%).

- **Connected Vehicle Settings**

Connected vehicles are permitted to send BSMs at a frequency of 10 Hz (i.e., every 0.1 seconds). They follow the proposed algorithm to prevent red-light running. The vehicle's speed is retrieved every 0.1 seconds, and a smoothing window of 5 is used to compute the running average of vehicle speeds.

- **Penetration Rates of Connected Vehicles**

The simulated penetration rates of connected vehicles range from 0% to 100% in 10% increments: 0%, 10%, 20%, 30%, 40%, 50%, 60%, 70%, 80%, 90%, and 100%.

- **Traffic Demand Settings**

Each intersection approach has 100 through vehicles, 15 left-turn vehicles, and 10 right-turn vehicles. All left-turn and right-turn vehicles strictly obey traffic laws, while all through vehicles are potential red-light runners.

5.1.3.2 Simulation Results

Simulation results of the average number of red light violations in the test network with a speed limit of 40 mph and a cycle length of 120 seconds are provided in Table 9. The corresponding changes in red light

violations compared to the baseline scenario with zero delay and zero packet loss rate are included in Table 10.

Similarly, the simulation results are shown in Table 11 and Table 12 for the test network with a speed limit of 40 mph and a cycle length of 90 seconds, and in Table 13 and Table 14 for the test network with a speed limit of 35 mph and a cycle length of 90 seconds.

Based on the simulation results, here are our findings:

- Under ideal conditions with zero communications latency and packet loss rate, the proposed algorithm effectively prevents red light running across various speed limits and cycle lengths.
- Both communications latency and packet loss rate can impact the performance of the proposed algorithm. As either latency or packet loss increases, the algorithm's performance decreases more substantially, particularly when the penetration of connected vehicles is low.
- Communications latency is generally more critical than packet loss rate. Even when the latency (delay) is zero, the proposed algorithm still performs well across various packet loss rates and penetration rates of connected vehicles.
- Higher penetration rates of connected vehicles generally stabilize transportation systems more, reducing the impact of degraded V2X communications with non-zero latency and packet loss rates. This is especially evident when penetration rates are very high, as demonstrated in the simulation results at 90% and 100%.

5.1.4 Discussion

The simulation results demonstrate that effective algorithms can be developed to utilize real-time signal phase and MAP information to prevent red light running. This highlights the potential of connected vehicle technology to improve intersection safety. The findings also highlight the need for high-quality V2X communications, as high latency and packet loss can significantly weaken the performance of algorithms for Red Light Violation Warning. Moreover, the results demonstrate that high penetration rates of connected vehicles can help stabilize the performance of the Red Light Violation Warning system. Therefore, it is essential for transportation agencies like Caltrans to work with the private sector and explore practical solutions to expand V2X communications on a larger scale.

Table 9. Average Number of Red Light Violations with Speed Limit 40mph and Cycle Length 120s.

A 2-lane 40mph Intersection with a Cycle Length of 120s	Red Light Violation Statistics: Averaged Number of Red Light Violations (10 Replications)															
CV Penetration Rate	0s Delay 0% Loss	0s Delay 5% Loss	0s Delay 10% Loss	0s Delay 15% Loss	0.1s Delay 0% Loss	0.1s Delay 5% Loss	0.1s Delay 10% Loss	0.1s Delay 15% Loss	0.2s Delay 0% Loss	0.2s Delay 5% Loss	0.2s Delay 10% Loss	0.2s Delay 15% Loss	0.5s Delay 0% Loss	0.5s Delay 5% Loss	0.5s Delay 10% Loss	0.5s Delay 15% Loss
0%	252															
5%	236	236	236	236	237	237	236	237	237	237	237	237	237	237	236	237
10%	234	234	234	234	234	234	234	234	234	234	234	234	234	234	234	234
20%	198	198	198	197	198	198	198	198	198	198	198	198	198	198	198	198
30%	168	168	168	168	169	169	169	169	168	168	168	168	169	169	169	170
40%	148	148	148	148	148	148	148	148	149	149	149	149	149	149	149	148
50%	116	116	116	116	116	116	116	116	116	116	116	116	116	116	116	116
60%	93	93	93	93	93	93	93	93	93	93	93	93	94	94	94	94
70%	67	67	67	67	67	67	67	67	67	67	67	67	67	67	67	67
80%	50	50	50	50	50	50	50	50	50	50	50	50	49	49	49	49
90%	24	24	24	24	24	24	24	24	24	24	24	24	24	24	24	24
100%	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0

Table 10. Percentage of Changes in Red Light Violations with Speed Limit 40mph and Cycle Length 120s.

A 2-lane 40mph Intersection with a Cycle Length of 120s	Red Light Violation Statistics: Percentage of Changes in Red Light Violations (10 Replications)															
Penetration Rate	0s Delay 0% Loss	0s Delay 5% Loss	0s Delay 10% Loss	0s Delay 15% Loss	0.1s Delay 0% Loss	0.1s Delay 5% Loss	0.1s Delay 10% Loss	0.1s Delay 15% Loss	0.2s Delay 0% Loss	0.2s Delay 5% Loss	0.2s Delay 10% Loss	0.2s Delay 15% Loss	0.5s Delay 0% Loss	0.5s Delay 5% Loss	0.5s Delay 10% Loss	0.5s Delay 15% Loss
0%	0.00															
5%	0.00	0.00	0.00	0.00	0.42	0.42	0.00	0.42	0.42	0.42	0.42	0.42	0.42	0.42	0.00	0.42
10%	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
20%	0.00	0.00	0.00	-0.51	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
30%	0.00	0.00	0.00	0.00	0.60	0.60	0.60	0.60	0.00	0.00	0.00	0.00	0.60	0.60	0.60	1.19
40%	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.68	0.68	0.68	0.68	0.68	0.68	0.68	0.00
50%	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
60%	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	1.08	1.08	1.08	1.08
70%	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
80%	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	-2.00	-2.00	-2.00	-2.00
90%	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
100%	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00

Table 11. Average Number of Red Light Violations with Speed Limit 40mph and Cycle Length 90s.

A 2-lane 40mph Intersection with a Cycle Length of 90s	Red Light Violation Statistics: Averaged Number of Red Light Violations (10 Replications)															
CV Penetration Rate	0s Delay 0% Loss	0s Delay 5% Loss	0s Delay 10% Loss	0s Delay 15% Loss	0.1s Delay 0% Loss	0.1s Delay 5% Loss	0.1s Delay 10% Loss	0.1s Delay 15% Loss	0.2s Delay 0% Loss	0.2s Delay 5% Loss	0.2s Delay 10% Loss	0.2s Delay 15% Loss	0.5s Delay 0% Loss	0.5s Delay 5% Loss	0.5s Delay 10% Loss	0.5s Delay 15% Loss
0%	255															
5%	245	245	245	245	246	246	246	246	246	246	246	246	246	246	246	246
10%	230	230	230	230	230	230	230	230	230	230	230	230	232	232	232	232
20%	202	202	202	202	202	202	201	201	202	202	202	202	202	202	202	202
30%	178	178	177	177	177	177	177	178	178	177	178	178	178	178	178	178
40%	156	156	156	156	156	156	157	156	156	156	156	157	156	156	156	156
50%	125	126	126	126	126	126	126	126	126	126	126	126	126	125	125	126
60%	98	98	98	98	98	98	98	98	99	98	99	99	99	99	99	99
70%	71	71	71	71	71	71	71	71	71	71	71	71	71	71	71	71
80%	46	46	46	46	46	46	46	46	46	46	46	46	46	46	46	46
90%	23	23	23	23	23	23	23	23	23	23	23	23	23	23	23	23
100%	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0

Table 12. Percentage of Changes in Red Light Violations with Speed Limit 40mph and Cycle Length 90s.

A 2-lane 40mph Intersection with a Cycle Length of 90s	Red Light Violation Statistics: Percentage of Changes in Red Light Violations (10 Replications)															
CV Penetration Rate	0s Delay 0% Loss	0s Delay 5% Loss	0s Delay 10% Loss	0s Delay 15% Loss	0.1s Delay 0% Loss	0.1s Delay 5% Loss	0.1s Delay 10% Loss	0.1s Delay 15% Loss	0.2s Delay 0% Loss	0.2s Delay 5% Loss	0.2s Delay 10% Loss	0.2s Delay 15% Loss	0.5s Delay 0% Loss	0.5s Delay 5% Loss	0.5s Delay 10% Loss	0.5s Delay 15% Loss
0%	0.00															
5%	0.00	0.00	0.00	0.00	0.41	0.41	0.41	0.41	0.41	0.41	0.41	0.41	0.41	0.41	0.41	0.41
10%	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.87	0.87	0.87	0.87
20%	0.00	0.00	0.00	0.00	0.00	0.00	-0.50	-0.50	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
30%	0.00	0.00	-0.56	-0.56	-0.56	-0.56	-0.56	0.00	0.00	-0.56	0.00	0.00	0.00	0.00	0.00	0.00
40%	0.00	0.00	0.00	0.00	0.00	0.00	0.64	0.00	0.00	0.00	0.00	0.64	0.00	0.00	0.00	0.00
50%	0.00	0.80	0.80	0.80	0.80	0.80	0.80	0.80	0.80	0.80	0.80	0.80	0.80	0.00	0.00	0.80
60%	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	1.02	0.00	1.02	1.02	1.02	1.02	1.02	1.02
70%	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
80%	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
90%	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
100%	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00

Table 13. Average Number of Red Light Violations with Speed Limit 35mph and Cycle Length 90s.

A 2-lane 35mph Intersection with a Cycle Length of 90s	Red Light Violation Statistics: Averaged Number of Red Light Violations (10 Replications)															
CV Penetration Rate	0s Delay 0% Loss	0s Delay 5% Loss	0s Delay 10% Loss	0s Delay 15% Loss	0.1s Delay 0% Loss	0.1s Delay 5% Loss	0.1s Delay 10% Loss	0.1s Delay 15% Loss	0.2s Delay 0% Loss	0.2s Delay 5% Loss	0.2s Delay 10% Loss	0.2s Delay 15% Loss	0.5s Delay 0% Loss	0.5s Delay 5% Loss	0.5s Delay 10% Loss	0.5s Delay 15% Loss
0%	259															
5%	246	246	246	246	247	247	247	247	246	246	246	246	246	246	246	246
10%	237	237	237	237	237	237	237	237	238	238	238	238	238	238	238	238
20%	203	203	203	203	203	203	203	203	203	203	203	203	204	204	204	204
30%	174	174	174	174	175	175	175	175	175	175	175	175	175	175	175	175
40%	149	149	149	149	149	149	149	149	149	149	149	149	150	150	150	151
50%	126	126	126	126	127	127	127	127	127	127	127	127	127	127	127	127
60%	99	99	99	99	99	99	99	99	99	99	99	99	99	99	99	99
70%	74	74	74	74	74	75	75	75	75	75	75	75	74	75	75	75
80%	47	47	47	47	48	48	48	48	47	47	47	47	47	47	47	47
90%	24	24	24	24	24	24	24	24	24	24	24	24	24	24	24	24
100%	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0

Table 14. Percentage of Changes in Red Light Violations with Speed Limit 35mph and Cycle Length 120s.

A 2-lane 35mph Intersection with a Cycle Length of 90s	Red Light Violation Statistics: Percentage of Changes in Red Light Violations (10 Replications)															
CV Penetration Rate	0s Delay 0% Loss	0s Delay 5% Loss	0s Delay 10% Loss	0s Delay 15% Loss	0.1s Delay 0% Loss	0.1s Delay 5% Loss	0.1s Delay 10% Loss	0.1s Delay 15% Loss	0.2s Delay 0% Loss	0.2s Delay 5% Loss	0.2s Delay 10% Loss	0.2s Delay 15% Loss	0.5s Delay 0% Loss	0.5s Delay 5% Loss	0.5s Delay 10% Loss	0.5s Delay 15% Loss
0%	0.00															
5%	0.00	0.00	0.00	0.00	0.41	0.41	0.41	0.41	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
10%	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.42	0.42	0.42	0.42	0.42	0.42	0.42	0.42
20%	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.49	0.49	0.49	0.49
30%	0.00	0.00	0.00	0.00	0.57	0.57	0.57	0.57	0.57	0.57	0.57	0.57	0.57	0.57	0.57	0.57
40%	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.67	0.67	0.67	1.34
50%	0.00	0.00	0.00	0.00	0.79	0.79	0.79	0.79	0.79	0.79	0.79	0.79	0.79	0.79	0.79	0.79
60%	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
70%	0.00	0.00	0.00	0.00	0.00	1.35	1.35	1.35	1.35	1.35	1.35	1.35	0.00	1.35	1.35	1.35
80%	0.00	0.00	0.00	0.00	2.13	2.13	2.13	2.13	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
90%	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
100%	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00

5.2 Pedestrian in Signalized Crosswalk Warning

5.2.1 System Design

Figure 28 illustrates the system design of Pedestrian in Signalized Crosswalk Warning. The implemented workflow is described below:

- The edge computing unit collects real-time SPaT data from the traffic signal controller and detects road users using advanced sensors.
- The edge computing unit transmits both signal data and pedestrian presence information to the RSU.
- The RSU broadcasts PSMs containing pedestrian information, along with SPaT and MAP messages, to nearby connected vehicles.
- A nearby connected vehicle receives messages from the RSU and takes necessary actions to prevent potential collisions with pedestrians.

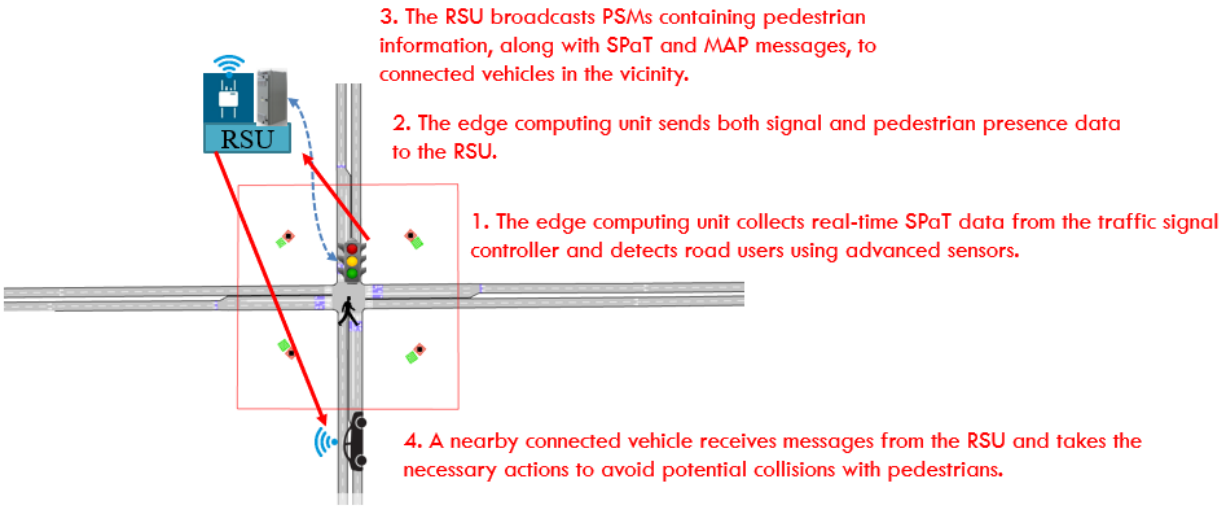


Figure 28. System design of Pedestrian in Signalized Crosswalk Warning.

5.2.1.1 Modeling of Pedestrian Red Light Violations

In reality, pedestrians can be seen in signalized crosswalks during the red light because of (i) insufficient walking time or (ii) pedestrian red light violations. Using real-time road user information (such as speed and location) from advanced sensors and signal phase data from the traffic controller, pedestrians in signalized crosswalks during the red phase can be identified based on the following criteria:

- Pedestrians are in the crosswalks.
- The phase for the crosswalks is red.

We follow the instructions in Aimsun's Technical Notes #48[19] and #51[20] and model pedestrians explicitly in the simulation models. However, due to limitations in Aimsun's API functions, it is not possible to equip OBUs on pedestrians to enable communication with other connected objects such as infrastructure/RSU, connected vehicles, and VRUs with connectivity. Additionally, since pedestrians in Aimsun simulations strictly follow crosswalk paths, we do not model jaywalking behavior.

Similar to modeling red light running, we can simulate pedestrian red light violations through these steps: (i) define a signal group that includes only compliant pedestrians, and (ii) introduce the demand for some pedestrians outside this group who cross the intersection without paying attention to the traffic light.

Limited API functions in Aimsun hinder modifying signal phase settings, such as dynamic green or all-red time extensions, during simulations that replicate real-time signal changes in the field. Consequently, we do not include dynamic signal adjustments to meet requests from VRUs.

5.2.1.2 Detection of Pedestrians in Crosswalks

Aimsun API functions are available to provide pedestrians' real-time location and speed, simulating output from advanced sensors like cameras or LiDAR. Algorithms have been developed to map pedestrians to the corresponding crosswalks and road sections. Since the Pedestrian Simulator and the V2X SDK are two separate modules that do not communicate directly, this real-time pedestrian data is output to an external file. The V2X module reads the latest information from this file. We verified that the pedestrian data output using Aimsun API functions occurs earlier than the loading process in the V2X module, indicating that no additional delay is caused by the connection between the Pedestrian Simulator and the V2X SDK.

5.2.1.3 Proposed Algorithm to Avoid Vehicle-Pedestrian Collision

A vehicle-pedestrian collision happens when a pedestrian runs a red light, but the vehicle has the right of way. The vehicle might be moving quickly (for straight crossing) or slowly (for turning left or right). Therefore, we use the following criteria to identify a possible vehicle-pedestrian collision:

- The estimated travel time for the connected vehicle to reach the crosswalk at its current speed is less than the time it takes for the pedestrian to cross the street.

To prevent potential collisions, we believe it is more appropriate for connected vehicles rather than pedestrians to take proactive actions for the following reasons:

- It is more appropriate for a vehicle to brake immediately to avoid serious injury in a collision.
- It is easier to warn drivers than pedestrians about potential collisions because vehicles are equipped with more advanced sensors and communication devices. Consequently, drivers can respond faster than pedestrians.

[19] Aimsun Technical Note #48: How to use the new in-house Pedestrian Simulator in Aimsun Next. https://www.aimsun.com/technical-notes/how-to-use-the-in-house-pedestrian-simulator/

[20] Aimsun Technical Note #51: How to model pedestrian crossings in Aimsun Next. https://www.aimsun.com/technical-notes/how-to-model-pedestrian-crossings-in-aimsun-next/

When a connected vehicle detects a potential vehicle-pedestrian collision, it will follow the algorithm outlined below to prevent it from happening:

- As shown in Figure 29, there are two distance thresholds (S_{th1} and S_{th2}) that split the space between the connected vehicle and the pedestrian into two zones, each with different deceleration rates.
- These two distance thresholds are defined/calculated as below:
  - S_{th1} is a dynamic value calculated as a ratio (e.g., 3 times) of the vehicle's braking distance at its current speed v_{avg}, using a normal deceleration rate d_{normal}.
  - S_{th2} is also a dynamic value, calculated as a higher multiple (e.g., 6 times) of the vehicle's braking distance at its current speed v_{avg}, using a normal deceleration rate d_{normal}.
- The connected vehicle will perform various actions within these two zones.
  - Zone #1 (High Deceleration Zone): The connected vehicle within this zone will need to decelerate at a high rate, e.g., 2 times of d_{normal}.
  - Zone #2 (Normal Deceleration Rate Zone): The connected vehicle within this zone will decelerate at a normal rate, e.g., d_{normal}.
- The proposed algorithm will not activate if the connected vehicle is outside of Zone #2.

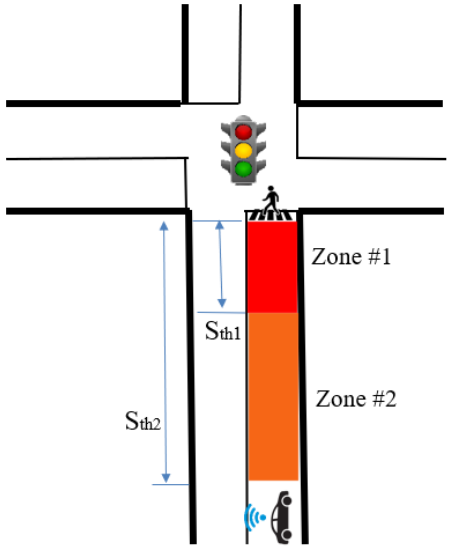


Figure 29. Two deceleration zones defined in the proposed algorithm to prevent vehicle-pedestrian collisions.

5.2.1.4 Modeling Limitations

We need to highlight the modeling limitations in Aimsun that prevent a more thorough safety assessment for Pedestrian in Crosswalk Warning.

Aimsun is a "collision-free" model. When an actual collision occurs between two objects (e.g., vehicle-vehicle or vehicle-pedestrian), Aimsun's internal collision avoidance algorithm: (i) applies an unrealistic deceleration to the vehicle, causing it to stop within one or two simulation time steps; and (ii) shifts one of the objects (e.g., the vehicle) away from the other to create enough space for them to move in the next time step.

When Aimsun's internal collision avoidance algorithm activates, it overrides the proposed algorithm and takes control of the vehicle. Since the parameters and settings of Aimsun's internal collision avoidance algorithm are unknown, predicting its activation to prevent interference with the proposed algorithm is difficult. As a result, it is challenging to use quantitative measures to assess the safety improvements of the proposed algorithm. Therefore, in this study, we focus on evaluating the impact of the proposed algorithm on individual vehicle-pedestrian collisions.

5.2.2 Test Networks and Scenario Design

5.2.2.1 Test Networks

Figure 30 provides the test network in Aimsun for Pedestrian in Crosswalk Warning. The test network closely resembles the one in Figure 27, but with a pedestrian simulation area and pedestrian origins and destinations added. The pedestrian simulation area defines the active zone for pedestrians. Pedestrian origins and destinations are generated to allow the simulation engine to assign pedestrians traveling from one point to another.

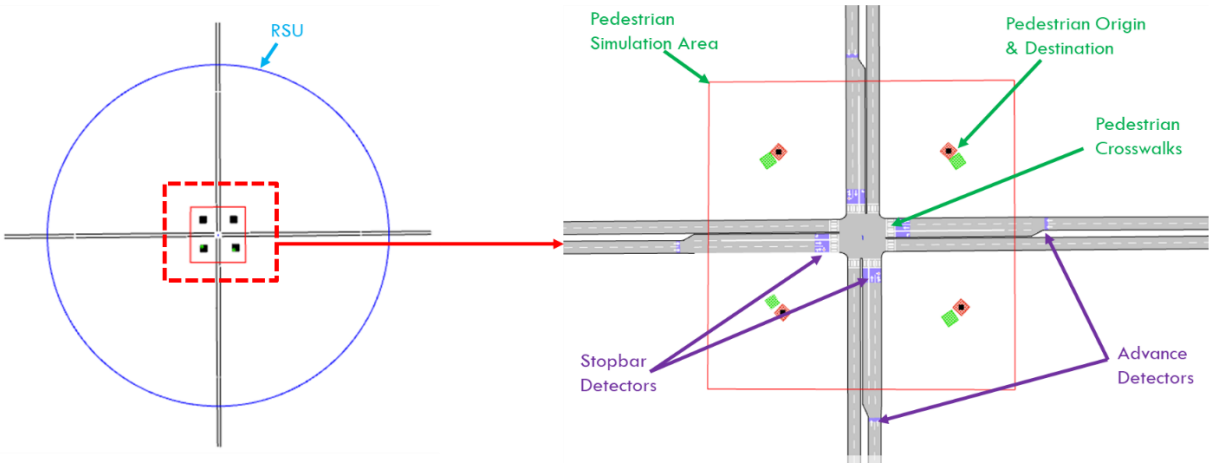


Figure 30. The test network in Aimsun for Pedestrian in Crosswalk Warning.

5.2.2.2 Scenario Design

The scenario design will focus on creating multiple potential vehicle-pedestrian collisions to assess the effectiveness of the proposed algorithm for Pedestrian in Crosswalk Warning.

- **Network Settings**

We focus on a 2-lane arterial with a speed limit of 35 mph and a cycle length of 90 seconds. However, the implementation framework is flexible enough and can easily be adapted to other arterial networks for performance assessment.

- **Traffic Demand**

Traffic demand settings are provided in Figure 31. There is a demand for 300 vehicles per hour from Centroid A to Centroid B, including 25 left-turn vehicles, 250 through vehicles, and 25 right-turn vehicles. Additionally, there is a demand for 50 vehicles per hour from Centroid C to Centroid D to prevent the traffic phases in the AB direction from remaining green solely under the actuated signal control. We assign a high pedestrian demand to ensure we can identify multiple vehicle-pedestrian collision scenarios for analysis. Therefore, there is a demand for 40 pedestrians per hour from Pedestrian Centroid E to Centroid F, and another demand of 40 pedestrians per hour from Centroid F to Centroid E.

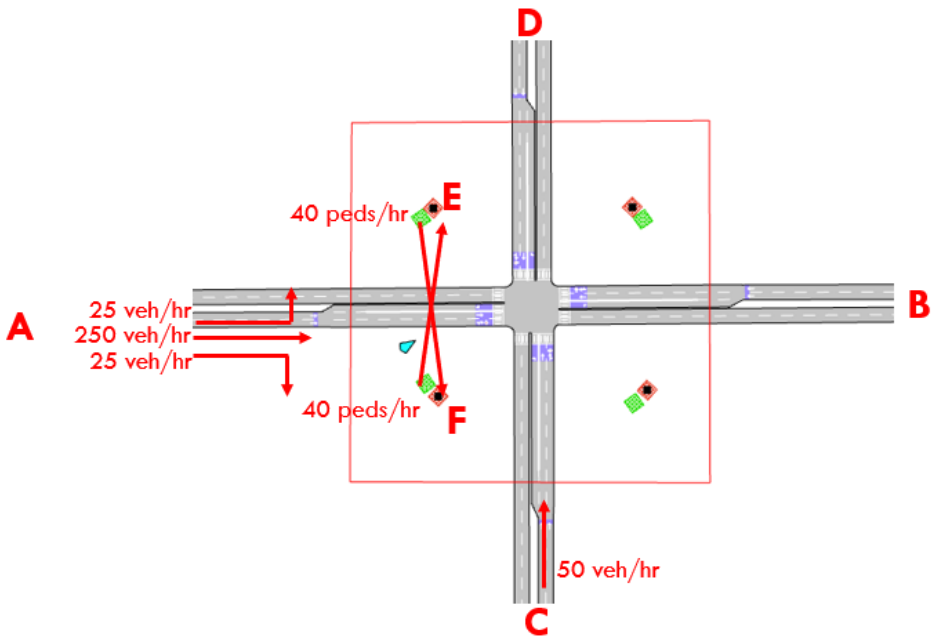


Figure 31. Traffic demand settings for Pedestrian in Crosswalk Warning.

- **Penetration Rate of Connected Vehicles**

We assume a 100% penetration rate, meaning all simulated vehicles are connected vehicles. A connected vehicle can choose to activate (the alternative scenario) or not activate (the baseline scenario) the Pedestrian in Crosswalk Warning application.

- **Processing Delay in Pedestrian in Crosswalk Detection**

The edge computing unit might face delays when processing data from advanced video or LiDAR sensors and in detecting pedestrians in crosswalks. This could impact the performance of the proposed algorithm because connected vehicles may need to slow down or delay their actions to avoid potential collisions with pedestrians.

Considering there might be a communications delay in transmitting pedestrian information to nearby connected vehicles, we combine the processing delay and the communications delay into a single delay for performance assessment.

- **Settings of Direct Communications**

We do not model the impact of communications range because a default range of 1640 feet (i.e., 500 meters) is sufficient to cover the entire intersection.

However, communications latency and packet loss rates will impact the accuracy of the signal and pedestrian information sent from the signalized intersection, which could weaken the effectiveness of the proposed algorithm in preventing vehicle-pedestrian collisions.

Therefore, this study will analyze different levels of processing and communications latency, along with packet loss rates.

- Processing and communications delays (seconds): 0, 0.1, 0.2, 0.3, 0.4, and 0.5.
- Packet loss rates: 0%, 5%, 10%, 15%, and 20%.

5.2.3 Performance Evaluation Results

5.2.3.1 Simulation Parameter Settings

The following settings are used for the simulation scenarios described above.

- **Simulation Settings**

The simulation lasts for 1 hour, from 8:00 AM to 9:00 AM. The warm-up period is 5 minutes.

- **Settings for the Proposed Algorithm to Prevent Vehicle-Pedestrian Collisions**

The ratio used to calculate S_{th1} is 3, and the ratio for S_{th2} is 6. The normal deceleration rate d_{normal} is assigned by Aimsun when a vehicle enters the network. The deceleration rate is twice as high as d_{normal} at Zone 1 and equal to d_{normal} at Zone 2.

- **Settings for the Detection of Pedestrians in Crosswalks**

The interval for checking pedestrians in crosswalks is 0.1 seconds. Once a pedestrian's presence is detected, this information will be immediately sent to the RSU.

- **RSU Settings**

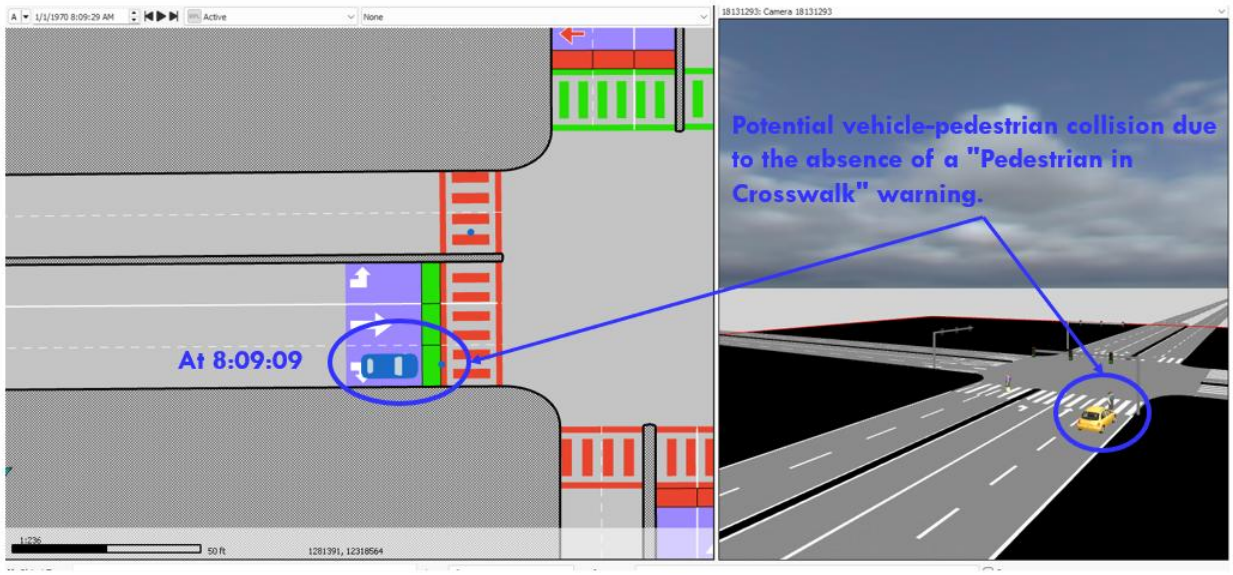
The RSU's communications range is 1640 feet (approximately 500 meters). It broadcasts MAP messages at 1 Hz (once per second), SPaT messages at 10 Hz (every 0.1 seconds), and PSM messages at 10 Hz (every 0.1 seconds). The interval for checking timing plan changes is every 60 seconds.

Simulations will be run with varying processing and communications delays (0, 0.1, 0.2, 0.3, 0.4, and 0.5 seconds) and packet loss rates (0%, 5%, 10%, 15%, and 20%).

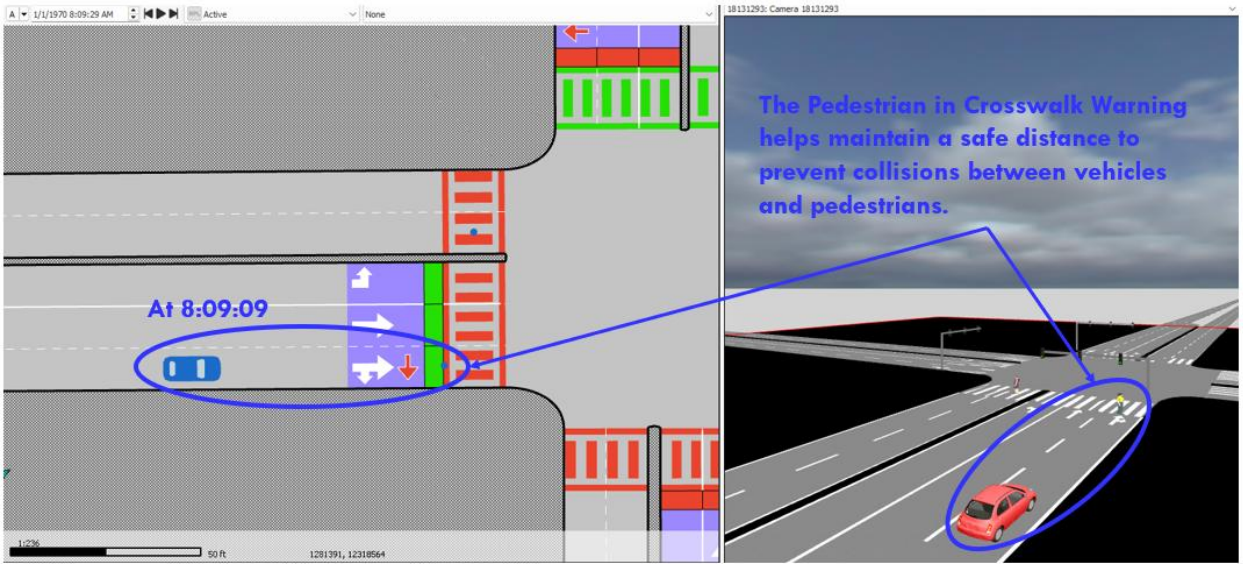
5.2.3.2 Simulation Results

Using the above simulation settings, we identified several potential vehicle-pedestrian collisions. Figure 32 shows an example of a potential vehicle-pedestrian collision and demonstrates how Pedestrian in Crosswalk Warning can effectively prevent it. Without warning, the connected vehicle only manages to stop just before

the crosswalk. However, controlled by the Pedestrian in Crosswalk Warning algorithm, the vehicle can successfully maintain a safe distance to prevent a collision.



(a) Without Pedestrian in Crosswalk Warning



(b) With Pedestrian in Crosswalk Warning

Figure 32. Simulation snapshots with and without Pedestrian in Crosswalk Warning.

Figure 33 also shows the vehicle's speed and distance to the crosswalk as it approaches the intersection in the example of the vehicle-pedestrian collision mentioned above. As illustrated, at the 50-foot threshold, the connected vehicle's speed without warning remains high—around 25 mph—posing a serious risk of hitting the pedestrian. However, with Pedestrian in Crosswalk Warning, the connected vehicle starts slowing down earlier and keeps a relatively low speed, about 15 mph, as it nears the intersection. Therefore,

even when the pedestrian is in the same lane as the vehicle, the distance between them remains enough—50 feet—to prevent a collision.

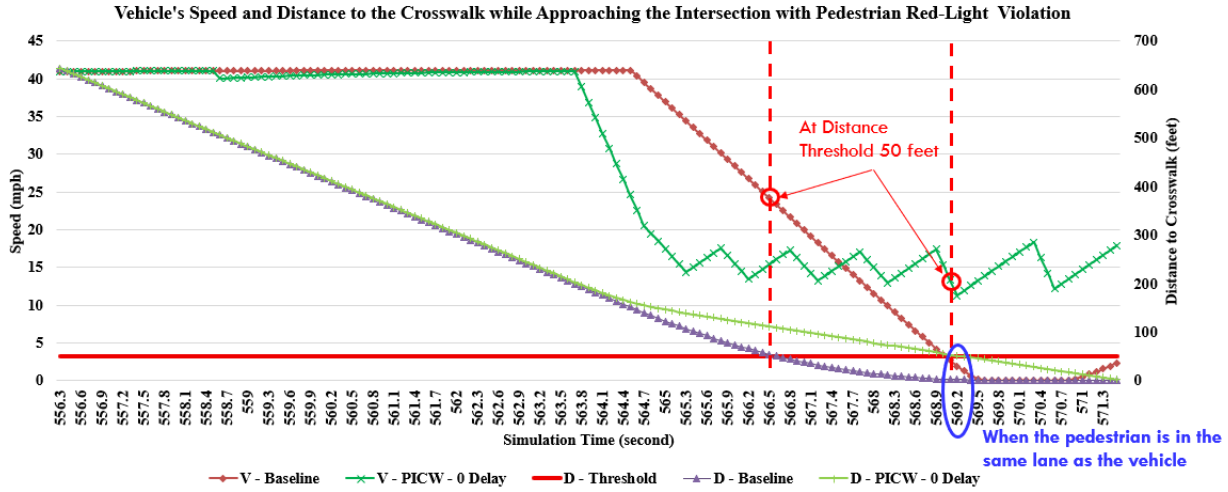


Figure 33. Vehicle's speed and distance to the crosswalk with and without Pedestrian in Crosswalk Warning.

Furthermore, Figure 34 illustrates the impact of processing and communications delays on the performance of the proposed algorithm for Pedestrian in Crosswalk Warning. As shown in the figure, the impact on the proposed algorithm is minimal. Although it delays the start of the speed reduction process, the connected vehicle can still maintain a sufficient distance to avoid hitting the pedestrian. This suggests that if we begin alerting connected vehicles at a sufficiently long distance, such as when they enter the intersection approach, and send pedestrian information frequently, the processing and communications delays will not affect the performance of the Pedestrian in Crosswalk Warning application.

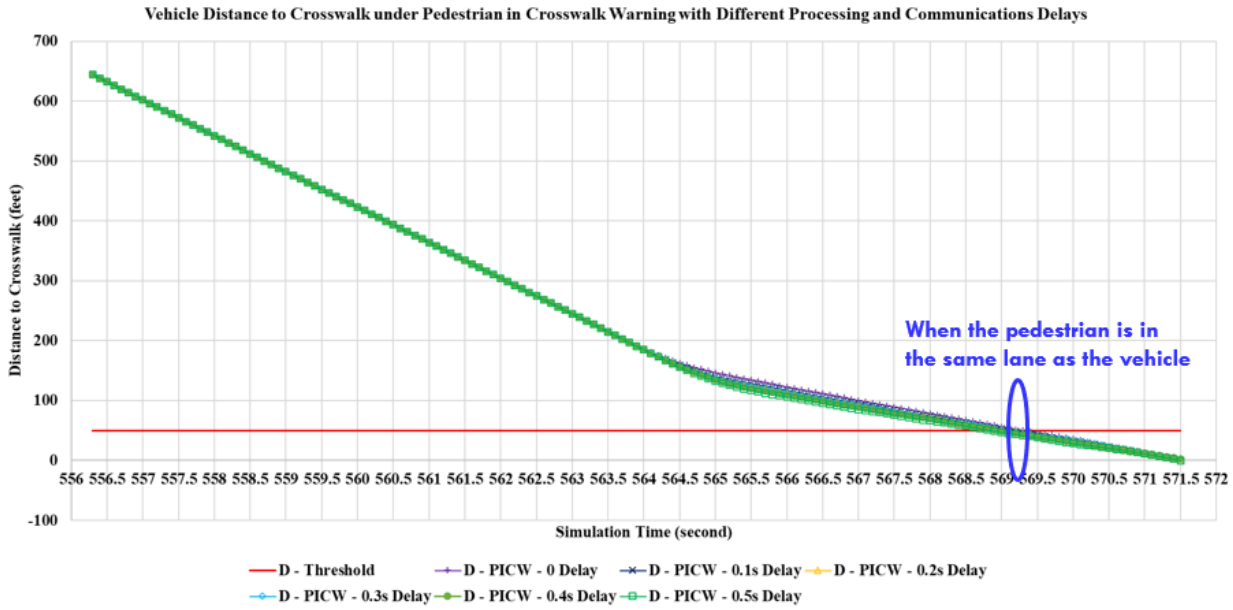
Additionally, we ran simulations with different packet loss rates. However, we found that these do not affect the performance of the proposed algorithm for Pedestrian in Crosswalk Warning. This is because pedestrian information is detected and broadcast at a high frequency to connected vehicles over a long upstream distance, so missing one or two messages does not impact the control actions of the proposed algorithm.

5.2.4 Discussion

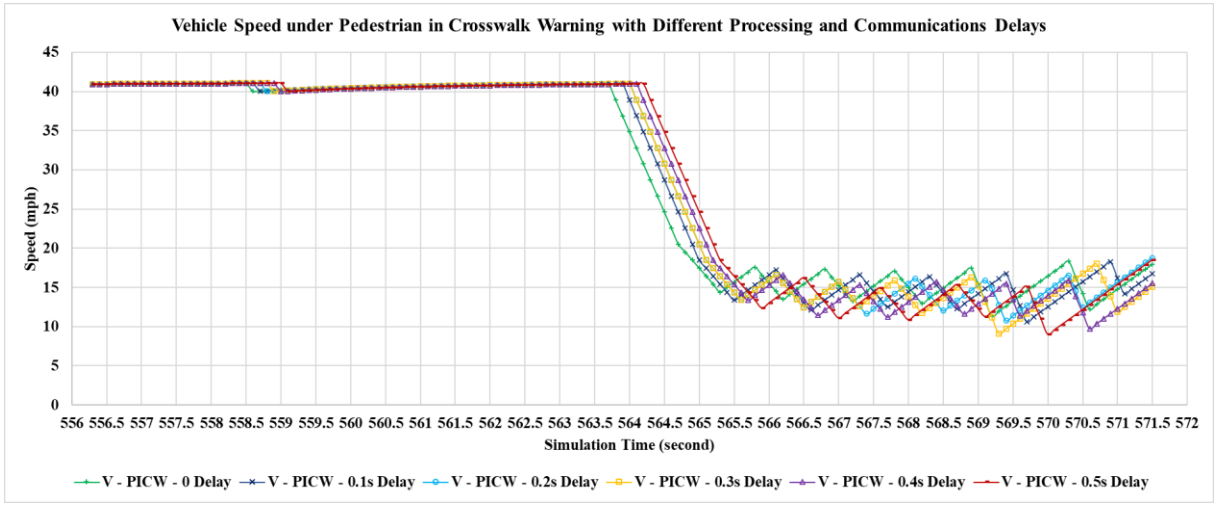
Although we cannot perform a more comprehensive analysis of Pedestrian in Crosswalk Warning like other CV applications, we have gained some valuable insights from examining individual potential vehicle-pedestrian collisions.

- It is recommended that detecting pedestrians' presence on crosswalks and broadcasting this information at a high frequency is a key factor in ensuring the effectiveness and robustness of Pedestrian in Crosswalk Warning.
- It is also recommended that maintaining a sufficiently long V2X communications range is important to ensure connected vehicles can receive alerts earlier upstream, allowing them to start decelerating and prevent potential collisions.

- With a high frequency of detecting and broadcasting pedestrians' presence in crosswalks and a sufficiently long V2X communications range, the impact of processing and communications delays and packet loss rates on Pedestrian in Crosswalk Warning is minimal.



(a) Vehicle Distance to Crosswalk



(b) Vehicle Speed

Figure 34. Impact of processing and communications delays on Pedestrian in Crosswalk Warning.

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6 Eco-Approach and Departure at Signalized Intersections

The application of Eco-Approach and Departure (EAD) at Signalized Intersections aims to assist connected vehicles in leveraging V2X communications to gather data from the infrastructure and nearby connected vehicles to facilitate their "green" approaches to and departures from signalized intersections. The collected information may include geometry and signal phase data from the intersections via V2I communications. It can also include data from nearby connected vehicles through V2V communications. This application will analyze the gathered data and offer speed recommendations to the driver. The driver can then adjust the vehicle's speed to pass the next traffic signal on green or slow down to a stop in the most eco-friendly way.

This application, supported by extensive data from infrastructure and nearby connected vehicles, is expected to help protect the environment and improve system efficiency by reducing fuel and energy consumption, emissions, travel delays, and more.

As illustrated in the physical diagram in Figure 35[21], there are two communications approaches for the application of Eco-Approach and Departure at Signalized Intersections: (i) direct communications via RSUs and (ii) network communications through the Transportation Information Center (TIC). However, considering the scope of this project, we only investigate the performance of Eco-Approach and Departure at Signalized Intersections under the direct communications approach using RSUs.

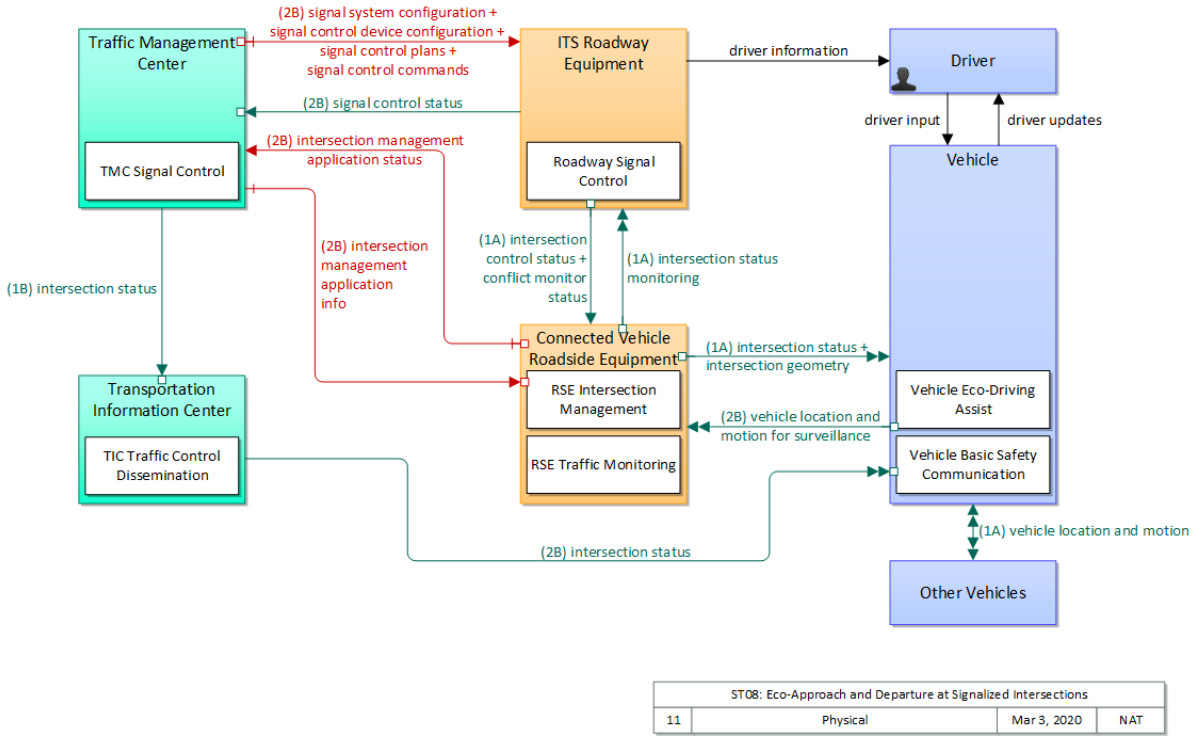


Figure 35. Physical diagram of the Eco-Approach and Departure at Signalized Intersections application.

[21] Eco-Approach and Departure at Signalized Intersections in ARC-IT 9.2. https://www.arc-it.net/html/servicepackets/sp66.html#tab-3

For the implementation in the integrated simulation framework in Aimsun, we further simplify the modeling framework for the application of Eco-Approach and Departure at Signalized Intersections, as illustrated in Figure 36. For simplicity, we combine ITS Roadway Equipment, the Traffic Management Center (TMC), the Traffic Information Center (TIC), and RSU into a single entity, eliminating the need to model explicit data flows between them. Additionally, we do not model the presence of VRUs crossing the streets.

In the implementation, we only consider the scenario where the infrastructure (i.e., Intersection & RSU) broadcasts real-time SPaT and MAP messages to nearby connected vehicles. Regarding signal control, we focus on signalized intersections under coordinated actuated control, the most common control strategy in the United States. Furthermore, we examine various left-turn settings, such as permitted versus protected, as well as different road geometry configurations, including those with or without left-turn pockets, along with major versus minor arterials.

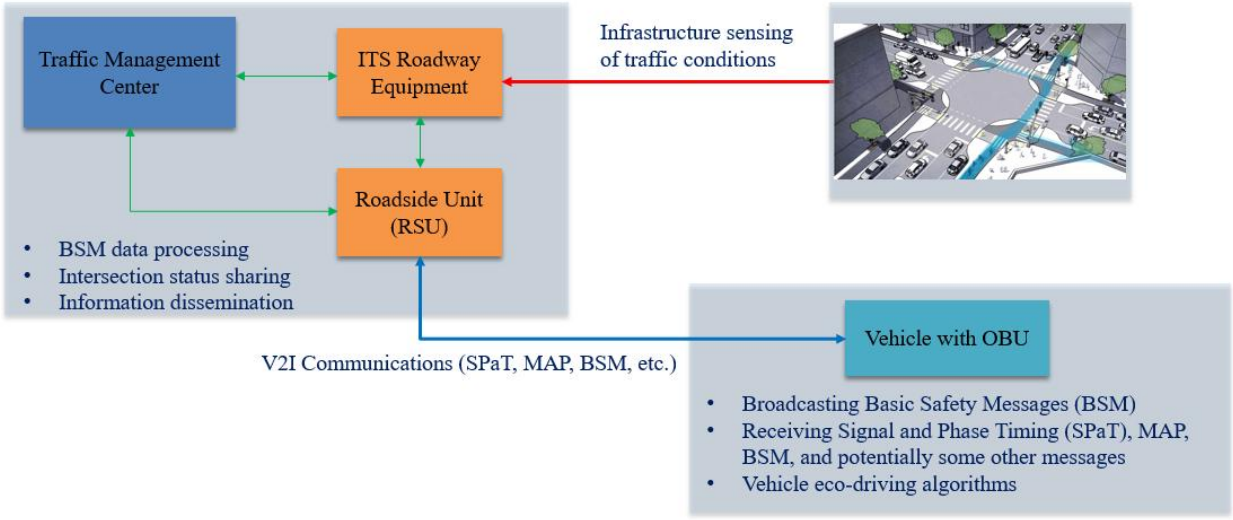


Figure 36. Proposed modeling framework for Eco-Approach and Departure at Signalized Intersections in Aimsun.

6.1 System Design

Figure 37 illustrates the system design of Eco-Approach and Departure at Signalized Intersections in Aimsun. According to the figure, the current implementation focuses on a traditional approach that broadcasts only SPaT and MAP messages. The implemented workflow is described as follows:

- The RSU collects real-time SPaT data directly from the traffic signal controller.
- The RSU broadcasts SPaT and MAP messages to nearby connected vehicles.
- A connected vehicle receives real-time SPaT and MAP messages and adjusts its speeds based on the Eco-Approach and Departure algorithms.

Note that support from advanced sensors like video and LiDAR sensors has not been implemented but offers a potential option for future upgrades.

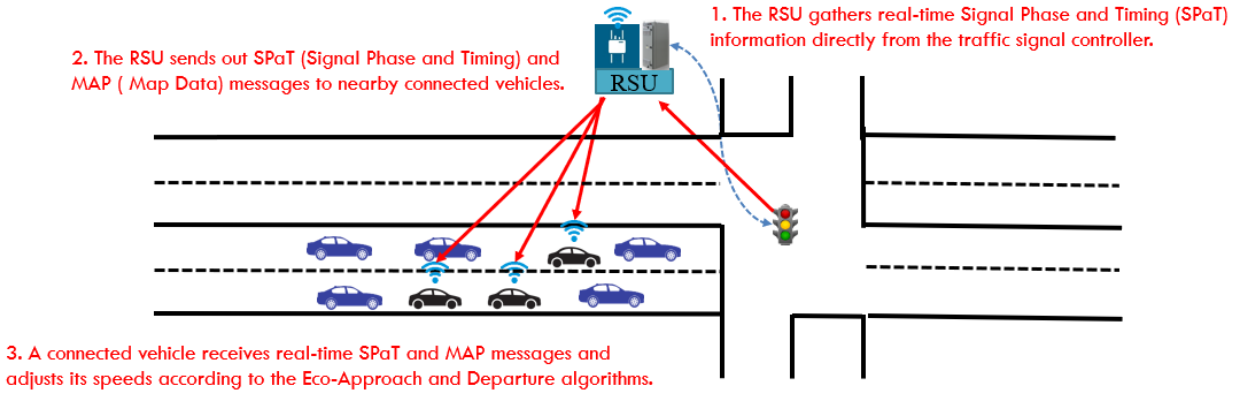
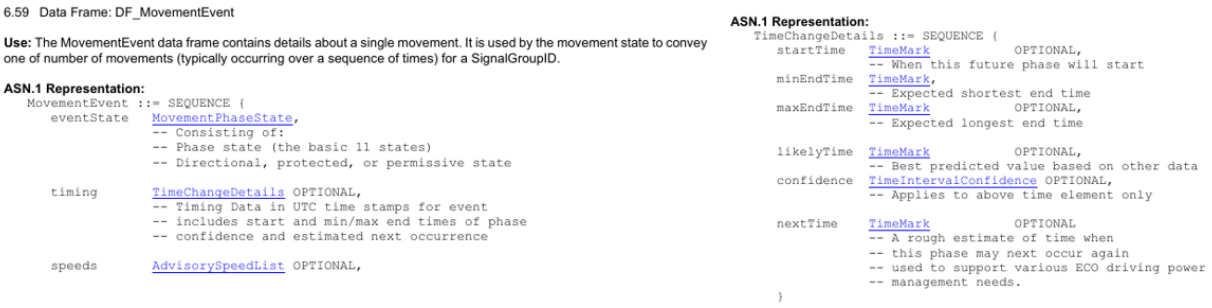


Figure 37. System design of Eco-Approach and Departure at Signalized Intersections.

In the literature, many algorithms, such as the Green Light Optimized Speed Advisory (GLOSA) application[22], have been proposed for the Eco-Approach and Departure (EAD) application. Refer to the final report for Caltrans Task 3712 for more details[23]. However, many of these algorithms assume that the signal phase information received from the infrastructure is 100% accurate, with no uncertainty involved. While this assumption is valid for fixed-time signal control, it becomes incorrect when the intersection uses actuated signal control. In this case, the duration of a phase is uncertain: it can end earlier with no vehicle actuation (i.e., Gap-Out), or it can reach its maximum green time when traffic demand is high (i.e., Max-Out). As shown in Figure 38, the attribute "TimeChangeDetails" in the SPaT Message includes the elements "startTime", "minEndTime", and "maxEndTime", which are essential inputs for the EAD algorithms. However, due to Gap-Out and Max-Out in actuated signal control, the values in the attribute "TimeChangeDetails" are estimates with some level of uncertainty. Therefore, it is not appropriate to implement many existing EAD algorithms in the literature, as this may pose safety risks due to the uncertainty in the SPaT messages.



6.59 Data Frame: DF_MovementEvent

Use: The MovementEvent data frame contains details about a single movement. It is used by the movement state to convey one of number of movements (typically occurring over a sequence of times) for a SignalGroupID.

ASN.1 Representation:

```
MovementEvent ::= SEQUENCE {
   eventState    MovementPhaseState,
                 -- Consisting of:
                 -- Phase state (the basic 11 states)
                 -- Directional, protected, or permissive state

   timing        TimeChangeDetails OPTIONAL,
                 -- Timing Data in UTC time stamps for event
                 -- includes start and min/max end times of phase
                 -- confidence and estimated next occurrence

   speeds        AdvisorySpeedList OPTIONAL,
```

ASN.1 Representation:

```
TimeChangeDetails ::= SEQUENCE {
   startTime     TimeMark            OPTIONAL,
                 -- When this future phase will start
   minEndTime    TimeMark,
                 -- Expected shortest end time
   maxEndTime    TimeMark            OPTIONAL,
                 -- Expected longest end time

   likelyTime    TimeMark            OPTIONAL,
                 -- Best predicted value based on other data
   confidence    TimeIntervalConfidence OPTIONAL,
                 -- Applies to above time element only

   nextTime      TimeMark            OPTIONAL
                 -- A rough estimate of time when
                 -- this phase may next occur again
                 -- used to support various ECO driving power
                 -- management needs.
}
```

Figure 38. The attribute "TimeChangeDetails" in the SPaT Message.

[22] Katsaros, K., Kernchen, R., Dianati, M., & Rieck, D. (2011). Performance study of a Green Light Optimized Speed Advisory (GLOSA) application using an integrated cooperative ITS simulation platform. In 2011 7th International Wireless Communications and Mobile Computing Conference (pp. 918-923). IEEE.

[23] System impact of connected and automated vehicles: An application to the 1-210 Connected Corridors pilot. Final Report. https://dot.ca.gov/-/media/dot-media/programs/research-innovation-system-information/documents/final-reports/ca22-task3712-a11y.pdf

Instead, we adopted the following simple EAD control strategy intended to promote connected vehicles to travel through the intersection at a faster speed.

- For safety reasons, the EAD control strategy is not activated if the distance to the leader or the intersection stop bar is less than a user-defined threshold, such as 50 feet.
- When the targeted signal is red,
    - If the remaining red time is less than a connected vehicle's free-flow travel time to the intersection stop bar, the vehicle will accelerate at its maximum rate to reach the posted speed limit.
    - If the remaining red time is less than a connected vehicle's travel time to the intersection stop bar at its current speed, averaged over the past one or two seconds, the vehicle will accelerate normally to reach a higher, yet permissible, speed. This speed is lower than the posted speed limit but faster than the current speed.
- If the targeted signal is green,
    - If the remaining green time exceeds a connected vehicle's free-flow travel time to the intersection stop bar, the vehicle will accelerate at its maximum rate to reach the posted speed limit.

6.2 Test Networks and Scenario Design

6.2.1 Test Networks

In this project, we aim to evaluate the performance of Eco-Approach and Departure at Signalized Intersections across various road networks and traffic signal configurations. Specifically, we want to understand whether this application can offer mobility benefits for arterial corridors under coordination. For our performance assessment, we use the subnetworks (i.e., coordinated arterial intersections) generated from the I-210 Corridor Network (Figure 2) for the following reasons: (i) it is challenging to create artificial networks with the correct offsets that align with traffic demands along the coordinated traffic directions; (ii) it is difficult to estimate or develop suitable traffic demands and routes to produce realistic traffic congestion and bottlenecks in artificial networks.

Therefore, as shown in Figure 39, two coordinated arterials in the City of Pasadena have been chosen as test networks:

(a) 6 coordinated intersections along Hill Ave, between Walnut St and Del Mar Blvd.
(b) 14 coordinated intersections along California Blvd, between Hudson Ave and Michillinda Ave.

6.2.2 Scenario Design

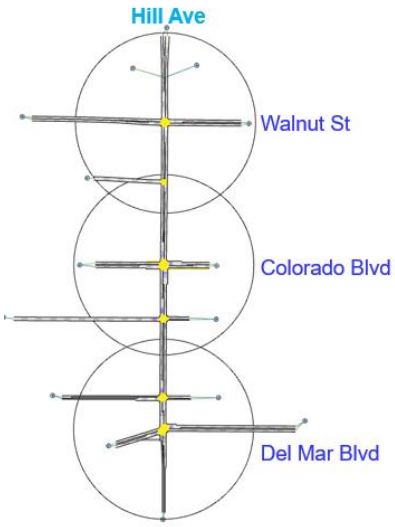
Eco-Approach and Departure at Signalized Intersections is a mobility application designed to provide more accurate traffic information to connected vehicles, helping them pass through intersections more efficiently and effectively. Therefore, the evaluation of this application will focus on potential improvements in mobility.

- **Network Settings**

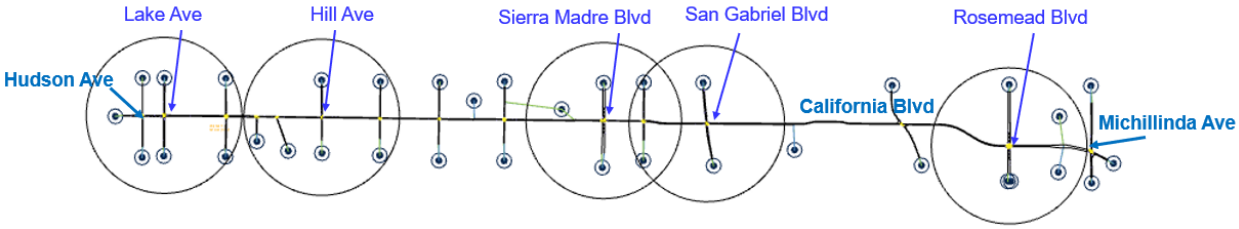
The test network along Hill Ave is an arterial corridor with six coordinated intersections. Most road links have a speed limit of 30 mph, while those on Del Mar Blvd are set to 35 mph. All signalized intersections feature either dedicated left-turn pockets or lanes. This test network includes various left-turn configurations, such as protected versus permitted left-turn phases and lead-lead versus lead-lag left-turn phase stages.

The test network along California Ave is an arterial corridor with 14 coordinated intersections. The speed limit on California Ave is 30 mph between Hudson Ave and Allen Ave, while it increases to 35 mph for the remaining intersections. All side streets have a uniform speed limit of 25 mph. Like the test network along Hill Ave, all major streets have dedicated left-turn pockets, but the side streets do not. This test network also features various left-turn configurations, such as protected versus permitted left-turn phases and lead-lead versus lead-lag left-turn phase stages.

Therefore, the selected test networks are sufficiently representative for performance evaluation.



(a) Hill Ave between Walnut St and Del Mar Blvd.



(b) California Blvd between Hudson Ave and Michillinda Ave

Figure 39. Two test networks in Aimsun for Eco-Approach and Departure at Signalized Intersections.

- **Installation of RSUs**

Considering the road topologies of these two test networks, RSUs have been installed at the following key intersections, which are illustrated as circles in Figure 39:

- The test network along Hill Ave: @Walnut St, @Colorado Blvd, and @Del Mar Blvd.
- The test network along California Blvd: @Lake Ave, @Hill Ave, @Sierra Madre Blvd, @San Gabriel Blvd, and @Rosemead Blvd.

- **Settings of Direct Communications**

We do not model the impact of communications latency and packet loss rate in this application because it is not a safety-critical application that requires drivers' immediate actions.

Furthermore, because the signalized intersections are closely spaced, the default communications range of 1640 feet (500 meters) is sufficient to cover an entire intersection. Therefore, we do not explore the potential mobility benefits of longer ranges.

- **Penetration Rate of Connected Vehicles**

For the two test networks, we will run simulations with CV penetration rates ranging from 0% to 100%, increasing in 10% steps: 0%, 10%, 20%, 30%, 40%, 50%, 60%, 70%, 80%, 90%, 100%.

- **Random Seed and Number of Replications**

The random seed in microsimulations will influence various factors, such as the generation and release of vehicles into the simulation network. Considering the simulation time for each scenario and the potential effects of different random seeds, we decided to run five replications with five distinct random seeds for each scenario.

- **Traffic Demand**

To better capture the variations in traffic demand, the following time periods have been chosen for the two test networks:

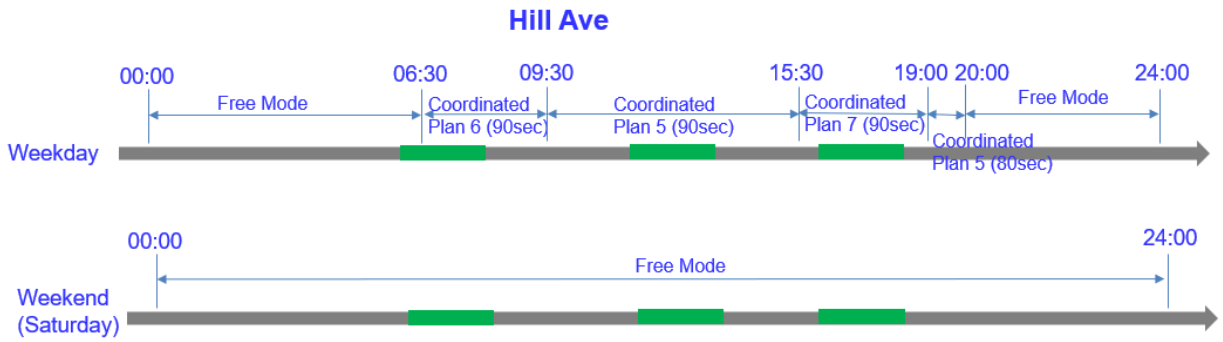
- The test network along Hill Ave
  - Weekday & Weekend (Saturday): 06:00 – 08:00, 11:00 – 13:00, 16:00 – 18:00
- The test network along California Blvd
  - Weekday & Weekend (Saturday): 06:00 – 08:00, 11:00 – 13:00, 17:00 – 19:00

For the selected time periods, the corresponding coordination settings are illustrated in Figure 40. In the test network along Hill Ave, all three time periods on Weekend (Saturday) are in free mode. On Weekday, the first 30 minutes in the morning period (i.e., 06:00 – 06:30) are in free mode. The rest of the time periods are coordinated with different timing plans. Note that the timing plan id is the actual plan id provided in the timing sheet and implemented in the field traffic controller. Similarly, in the test network along California Blvd, all three time periods on Weekday are coordinated with different timing plans. On Weekend (Saturday), all three time periods are coordinated with the same timing plan.

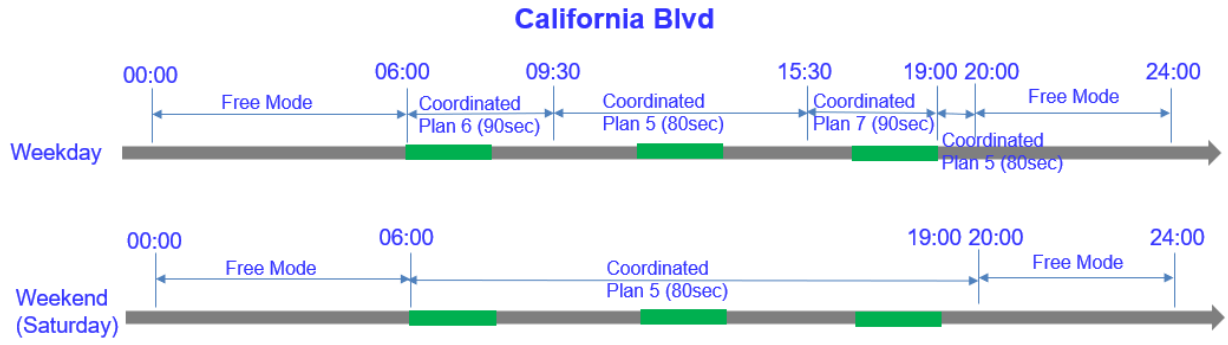
Therefore, the scenario design for Eco-Approach and Departure at Signalized Intersections can be summarized as follows:

- Two test networks: one along Hill Ave with six coordinated intersections and the other along California Blvd with fourteen coordinated intersections.

- Eleven different penetration rates of CVs: 0%, 10%, 20%, 30%, 40%, 50%, 60%, 70%, 80%, 90%, and 100%.
- Three RSUs have been installed in the test network along Hill Ave, and five RSUs have been installed in the test network along California Blvd.
- A default communications range of 1640 feet (i.e., 500 meters) with no communications latency and a zero packet loss rate for all RSUs.
- Five replications for each of the scenarios above.
- Six two-hour demand profiles have been chosen for each test network.



(a) Hill Ave between Walnut St and Del Mar Blvd.



(b) California Blvd between Hudson Ave and Michillinda Ave

Figure 40. Coordination settings in the two test networks.

6.3 Performance Evaluation Results

6.3.1 Simulation Parameter Settings

The settings listed below are used for the simulation scenarios described above.

- **Simulation Settings**

The simulation runs for 2 hours, including a 5-minute warm-up period.

- **RSU Settings**

All RSUs have a communications range of 1640 feet (i.e., 500 meters). They broadcast SPaT messages at a frequency of 10 Hz (once every 0.1 seconds) and MAP messages at 1 Hz (once every second). There is no communications delay, and the packet loss rate is zero. The interval for checking potential changes in the timing plan for a signalized intersection is set at 60 seconds.

- **Connected Vehicle Settings**

The interval for updating a connected vehicle's position is set at 0.1 seconds. The interval for updating a connected vehicle's speed with the latest signal information is 0.5 seconds. The distance threshold to deactivate the EAD algorithm is 50 feet. The vehicle's speed is collected every 0.1 seconds, and a 2-second time window is used to calculate the running averages of the vehicle's speed.

- **Penetration Rates of Connected Vehicles**

The simulated penetration rates of connected vehicles are 0%, 10%, 20%, 30%, 40%, 50%, 60%, 70%, 80%, 90%, and 100%.

- **Traffic Demand Settings**

For the network along Hill Ave, the following time periods are chosen for simulations:

  - Weekday & Weekend (Saturday): 06:00 – 08:00, 11:00 – 13:00, 16:00 – 18:00

For the test network along California Blvd, the following time periods are chosen for simulations:

  - Weekday & Weekend (Saturday): 06:00 – 08:00, 11:00 – 13:00, 17:00 – 19:00

6.3.2 Simulation Results

Table 15 and Table 16 summarize the simulation results for the application of Eco-Approach and Departure at Signalized Intersections. Based on the simulation results, we have the following findings:

- The implemented EAD algorithm provides mobility benefits only during periods of low traffic demand, such as between 6AM and 8AM on Weekend (Saturday). During other times of high traffic demand, it tends to have negative effects, increasing the average vehicle delay.
- During the period when EAD provides mobility improvements, specifically between 6AM and 8AM on Weekend (Saturday), the EAD algorithm tends to perform better when traffic along the arterial corridor is not coordinated, for example, at Hill Ave between Walnut St and Del Mar Blvd.
- During periods when EAD has negative impacts, baseline scenarios with optimal system performance (e.g., Weekday 11:00–13:00 along California Blvd) often face more severe system degradation when the EAD algorithm is active.

Table 15. EAD Simulation Results for Hill Ave between Walnut St and Del Mar Blvd.

Hill Ave Between Walnut St and Del Mar Blvd			CV Penetration Rate																			
			0%	10%		20%		30%		40%		50%		60%		70%		80%		90%		100%	
Day of Week	Time Of Day	Total Flow (veh/h)	Average Delay (s)	Average Delay (s)	Delay Change (%)	Average Delay (s)	Delay Change (%)	Average Delay (s)	Delay Change (%)	Average Delay (s)	Delay Change (%)	Average Delay (s)	Delay Change (%)	Average Delay (s)	Delay Change (%)	Average Delay (s)	Delay Change (%)	Average Delay (s)	Delay Change (%)	Average Delay (s)	Delay Change (%)	Average Delay (s)	Delay Change (%)
Weekend (Saturday)	0600-0800	2303.70	60.98	60.98	0.00	60.87	0.18	60.96	0.03	60.63	0.57	60.91	0.11	60.37	1.00	60.37	1.00	60.56	0.69	60.24	1.21	59.97	1.66
	1100-1300	5723.3	85.81	85.73	0.09	85.94	-0.15	85.64	0.20	86.01	-0.23	86.4	-0.68	86.06	-0.29	86.34	-0.62	85.95	-0.16	86.42	-0.71	86.35	-0.63
	1600-1800	4976.8	82.79	82.58	0.25	82.69	0.12	82.73	0.07	82.71	0.10	83.05	-0.31	83.05	-0.31	83.13	-0.41	83.16	-0.45	83.07	-0.34	83.13	-0.41
Weekday	0600-0800	3801.10	75.13	75.15	-0.03	75.12	0.01	75.17	-0.05	75.18	-0.07	75.12	0.01	75.23	-0.13	75.17	-0.05	75.11	0.03	75.08	0.07	75.13	0.00
	1100-1300	6022.2	94.05	94.1	-0.05	94.08	-0.03	94.13	-0.09	94.15	-0.11	94.19	-0.15	94.23	-0.19	94.29	-0.25	94.41	-0.38	94.45	-0.43	94.42	-0.39
	1600-1800	8030.3	89.65	89.84	-0.21	89.86	-0.23	89.87	-0.25	89.87	-0.25	89.92	-0.30	90.11	-0.51	90.15	-0.55	90.06	-0.46	90.14	-0.55	90.15	-0.56

Table 16. EAD Simulation Results for California Ave between Hudson Ave and Michillinda Ave.

California Ave Between Hudson Ave and Michillinda Ave			CV Penetration Rate																			
			0%	10%		20%		30%		40%		50%		60%		70%		80%		90%		100%	
Day of Week	Time Of Day	Total Flow (veh/h)	Average Delay (s)	Average Delay (s)	Delay Change (%)	Average Delay (s)	Delay Change (%)	Average Delay (s)	Delay Change (%)	Average Delay (s)	Delay Change (%)	Average Delay (s)	Delay Change (%)	Average Delay (s)	Delay Change (%)	Average Delay (s)	Delay Change (%)	Average Delay (s)	Delay Change (%)	Average Delay (s)	Delay Change (%)	Average Delay (s)	Delay Change (%)
Weekend (Saturday)	0600-0800	3986.40	34.84	34.88	-0.11	34.77	0.20	34.60	0.69	34.53	0.89	34.49	1.00	34.48	1.03	34.62	0.63	34.62	0.63	34.96	-0.38	34.95	-0.35
	1100-1300	9147.7	49.96	50.07	-0.22	50.17	-0.42	50.28	-0.64	50.09	-0.26	50	-0.08	50.23	-0.54	50.04	-0.16	50.3	-0.68	50.21	-0.50	49.92	0.08
	1700-1900	8758.3	46.28	46.34	-0.13	46.53	-0.54	46.71	-0.93	46.45	-0.37	46.62	-0.73	46.59	-0.67	46.36	-0.17	46.66	-0.82	46.77	-1.06	46.87	-1.27
Weekday	0600-0800	8075.30	55.23	55.29	-0.11	55.59	-0.65	55.55	-0.58	55.39	-0.29	55.37	-0.25	55.56	-0.60	55.46	-0.42	55.66	-0.78	55.51	-0.51	55.64	-0.74
	1100-1300	8803.7	52.68	53.01	-0.63	52.84	-0.30	53.67	-1.88	53.34	-1.25	53.58	-1.71	53.57	-1.69	53.35	-1.27	53.89	-2.30	53.46	-1.48	53.57	-1.69
	1700-1900	12490	71.64	71.96	-0.45	71.68	-0.06	71.92	-0.39	72.3	-0.92	71.86	-0.31	71.58	0.08	71.72	-0.11	71.94	-0.42	72.04	-0.56	72.26	-0.87

6.4 Discussion

The simulation results suggest that applying the Eco-Approach and Departure at Signalized Intersections is not recommended for arterial intersections under coordinated actuated control. The reasons are provided below:

- Under actuated control, the uncertainty in the signal information provided in the SPaT messages significantly limits the scenarios in which an EAD algorithm can operate safely.
- EAD algorithms tend to help vehicles in forming platoons. This vehicle control module functions independently of the intersection coordination control plans, which could negatively impact the performance of existing vehicle platoons. This indicates that if an arterial corridor is well coordinated, there is no need to implement EAD algorithms.

Therefore, new signal control strategies need to be developed to ensure that the information provided in the SPaT messages is reliable. This will improve the effectiveness of an EAD algorithm by expanding its operational domain. Meanwhile, to achieve better mobility improvements, more collaborative control strategies should be developed to synchronize the control actions applied to the signalized intersections and the connected vehicles.

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7 Conclusion

This project developed a V2X Microsimulation Platform in Aimsun that supports comprehensive performance assessments of CV applications to guide future deployment. Five CV applications, including Curve Speed Warning, Queue Warning, Speed Harmonization, Intersection Safety Warning, and Collision Avoidance, as well as Eco-Approach and Departure at Signalized Intersections, were implemented based on the latest physical diagrams provided in ARC-IT 9.3. For Intersection Safety Warning and Collision Avoidance, two sub-use cases were implemented: Red Light Violation Warning and Pedestrian in Crosswalk Warning. Various test networks and scenarios were created to enable thorough performance evaluation across different road layouts, V2X communications configurations, traffic demand levels, and connected vehicle penetration rates. After running numerous simulations, we present the following findings for the five implemented CV applications.

- Curve Speed Warning
  Delay at the curve will increase when the Curve Speed Warning is activated, as this feature aims to encourage vehicles traveling at excessive speeds to slow down when passing through the curve.

  There exists an “optimal” penetration rate for connected vehicles, which balances safety improvements with mobility reduction. This “optimal" rate has little connection to curve settings like the number of lanes and speed limits.

  However, this “optimal” penetration rate is closely linked to traffic demands. As demonstrated in multiple simulation runs, the penetration rates are 10% at 100% traffic demand (at road capacity), 15% at 90% traffic demand, 20% at 80% traffic demand, 25% at 70% traffic demand, and 30% at 60% traffic demand.

  Additionally, Curve Speed Warning is not a latency-sensitive application, as it does not require drivers to take immediate action to avoid potential safety hazards. Therefore, communications latency and packet loss rate are not considered and are set to zero in the simulation settings. However, it is important to ensure that the RSU's communications range covers the entire curve so that connected vehicles can receive timely notifications while passing through it.

- Queue Warning
  Queue Warning provides reasonable mobility benefits only under specific traffic conditions, closely related to the demand-to-capacity ratio and the implemented speed reduction strategies. This benefit is clear in scenarios of high demand during a 1-lane closure, where traffic demand slightly surpasses the reduced capacity.

  For other simulated scenarios, Queue Warning has a negative impact on overall traffic, causing more delays. This is because:
  - Connected vehicles may overreact to light traffic congestion. As a result, the more connected vehicles follow the proposed speed reduction strategy, the longer the vehicle delays will be.

- During heavy traffic congestion when demand far exceeds reduced capacity, although connected vehicles are required to slow down upstream of the queue, it does not create enough space for vehicles in the queue to move faster.

A high percentage of connected vehicles is not needed to realize the mobility benefits of Queue Warning. Simulation results indicate that only a 10% penetration is sufficient for Queue Warning.

Furthermore, simulation results indicate that the current road sensing infrastructure with detectors is sufficient to support Queue Warning deployment. While additional BSM data can enhance the speed of detecting vehicle queues, its impact on reducing vehicle delays remains minimal.

Queue Warning is not a latency-sensitive application because it does not require drivers to take immediate action to prevent safety hazards. As a result, communications latency and packet loss rate are not considered and are set to zero in the simulation settings. Although not included in this report, additional simulation results with an extended communications range of 2460 feet show that the communications range is not the main factor affecting Queue Warning's performance.

While this project assessed the impact of speed recommendations in Queue Warning, other strategies such as lane changes and detours should be examined in future studies. Specifically, during severe traffic congestion when demand greatly exceeds the reduced capacity, redirecting traffic from freeways to local arterials through detour suggestions can lead to greater improvements in mobility and safety.

- Speed Harmonization

  Simulation results indicate that achieving the mobility benefits of Speed Harmonization at traffic bottlenecks is challenging. Reducing the ingress flow just before a traffic bottleneck may not generate enough space for downstream weaving flows to exit more quickly and efficiently. This is also supported by the simulation results of Queue Warning, which aims to alert drivers about vehicle queues further upstream but only improves mobility when traffic demand slightly exceeds capacity.

  Similarly, Speed Harmonization is not a latency-sensitive application because it does not require drivers to take immediate action to avoid safety hazards. Therefore, communications latency and packet loss rate are not considered and are set to zero in the simulation settings. Additional simulations with an extended communications range of 2460 feet show that, since the Speed Harmonization algorithm being used is ineffective, increasing the communications range does not provide any further mobility improvements.

  For traffic bottlenecks caused by heavy weaving flows, alternative traffic management strategies should be used, such as rerouting on-ramp flows at the bottleneck to either upstream or downstream on-ramps.

- Intersection Safety Warning and Collision Avoidance

Two sub-use cases were implemented within the framework of Intersection Safety Warning and Collision Avoidance: Red Light Violation Warning and Pedestrian in Crosswalk Warning.

- Red Light Violation Warning
  Simulation results demonstrated that effective algorithms can be developed to utilize real-time signal phase and MAP information to prevent red light running. This highlights the potential of connected vehicle technology to improve intersection safety.

  Simulation results also highlighted the importance of maintaining high-quality V2X communications, as high latency and packet loss can significantly impair the performance of algorithms for Red Light Violation Warning. The results further showed that communications latency is more critical than the packet loss rate.

  Additionally, simulation results demonstrated that higher penetration rates of connected vehicles tend to stabilize transportation systems more, reducing the impacts of degraded V2X communications with non-zero latency and packet loss rates. Therefore, it is crucial for transportation agencies like Caltrans to work with the private sector and explore practical solutions to expand V2X communications on a larger scale.

- Pedestrian in Crosswalk Warning
  Simulation results showed that effective algorithms can be developed to use real-time data from intersections, such as pedestrians in crosswalks, signal phases, and MAP, to help prevent vehicle-pedestrian crashes. This highlights the potential of connected vehicle technology to enhance intersection safety.

  Simulation results also indicated that detecting pedestrians' presence at crosswalks and broadcasting this information at a high frequency is a key factor in ensuring the effectiveness and reliability of Pedestrian in Crosswalk Warning. Another key factor is maintaining a sufficiently long V2X communications range, which allows connected vehicles to receive alerts earlier upstream, providing them with more time to decelerate and avoid potential collisions.

  Additionally, simulation results demonstrated that with frequent detection and broadcasting of pedestrians' presence at crosswalks and a sufficiently long V2X communication range, the effects of processing and communications delays and packet loss rates on the Pedestrian in Crosswalk Warning are minimal.

- Eco-Approach and Departure at Signalized Intersections
  Simulation results indicated that applying the Eco-Approach and Departure at Signalized Intersections is not recommended for arterial intersections under coordinated actuated control. The implemented EAD algorithm only offers mobility benefits during low traffic demand. During periods of high traffic demand, it tends to have negative effects, increasing the average vehicle delay.

Two main reasons explain the poor performance of the implemented EAD algorithm.

- Under actuated control, uncertainty in the signal information provided by the SPaT messages significantly restricts the scenarios in which an EAD algorithm can operate safely.
- EAD algorithms generally help vehicles form platoons. This vehicle control module operates independently of the intersection coordination plans, which could negatively impact the performance of current vehicle platoons. This suggests that if an arterial corridor is well-coordinated, implementing EAD algorithms may not be necessary.

In addition to the valuable insights mentioned earlier, all test networks (Aimsun ang files) with embedded DLLs are accessible for detailed analysis. Users can configure the simulation parameters based on their deployment needs and run simulations to evaluate the performance of the CV application. All these files are available upon request.

For future research, the following three topics are recommended:

- Development of an open testing platform for CV applications.
  As demonstrated in this project, while it is important for Infrastructure Owner Operators (IOOs) to enable V2X communications and share real-time signal control and traffic management information with connected vehicles, how CV applications are implemented is crucial to ensure they function as intended and do not negatively impact the transportation system.

  Therefore, building on the V2X Microsimulation Platform with integrated CV applications, efforts can focus on developing an open testing platform that allows OEMs and vendors to evaluate the performance of their products.

  As illustrated in Figure 41, vehicle control strategies developed by OEMs can connect to the V2X Microsimulation Platform through a common API. Performance can be assessed by retrieving vehicle-related data from the microsimulation environment and providing vehicle actions back to the environment. For vendors offering traffic management decision tools to the TMCs to support CV applications, their tools can also connect to the V2X Microsimulation Platform via the common API. Performance can be assessed by retrieving TMC-related data from the microsimulation environment and providing traffic management recommendations back to the environment.

  This open testing platform enables IOOs like Caltrans to assess vendors' solutions before deployment. It also promotes public-private partnerships to make the deployment of CV applications more measurable, collaborative, and effective.

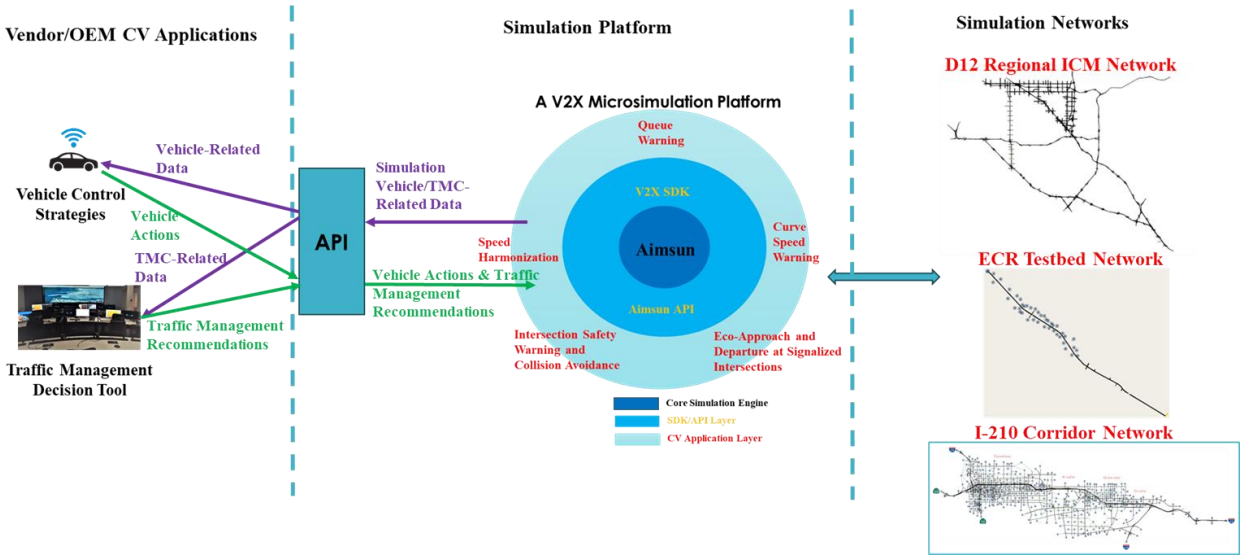

Figure 41. Proposed open testing platform for CV Applications.

- Feasibility analysis of adaptive fixed-time control to accelerate the deployment of CV technologies. As explained in the application of Eco-Approach and Departure at Signalized Intersections, existing coordinated actuated control introduces uncertainty in the signal information provided by the SPaT messages, which significantly limits the scenarios in which an EAD algorithm can operate safely.

  This issue can be addressed by switching to adaptive fixed-time control. In this approach, multiple pre-defined timing plans can be used to satisfy the user's needs. Infrastructure sensors (such as loop detectors and video/Lidar sensors) or third-party data providers can supply real-time or near-real-time traffic data. Heuristic or mathematical techniques will be employed to choose the best timing plan based on the traffic measurements. The selected timing plan will be implemented at the intersection and will stay in effect until the next interval, such as 15 or 30 minutes.

  As illustrated in Figure 42, this approach will promote center-to-center communications and facilitate data sharing. It will reduce the installation and maintenance costs of communications devices like RSUs for Infrastructure Owner Operators (IOOs). It will also lessen the need for automakers to install devices such as OBUs. Therefore, it has great potential to support large-scale deployment of CV applications.

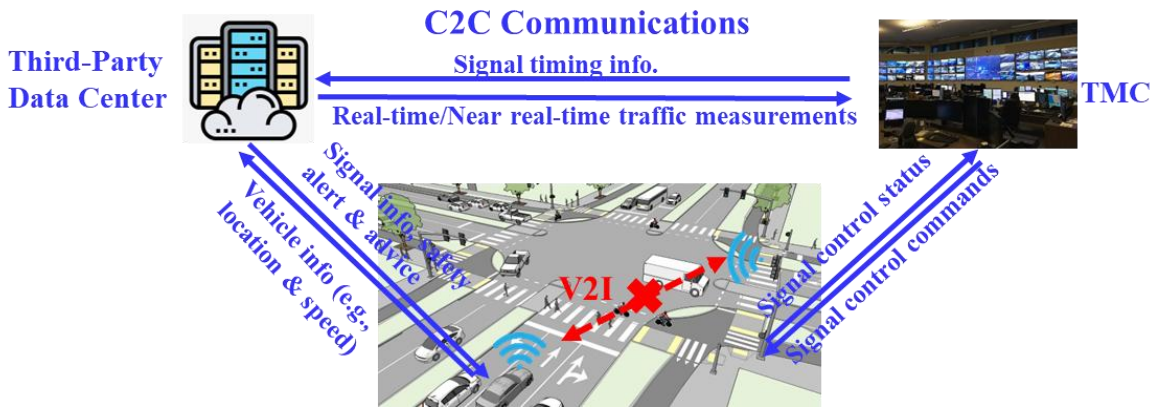

Figure 42. Proposed communications framework under adaptive fixed time control.

Given the potential benefits mentioned above, it is recommended to conduct a feasibility study of adaptive fixed-time control within a microsimulation environment. If successful, a pilot project could be launched either at the Richmond Field Station at UC Berkeley or in the California Connected Vehicle Testbed along El Camino Real (State Route 82) in Palo Alto, CA.

- Training courses on CV applications.
  While it is crucial to train Caltrans engineers on how to install and maintain connected devices like RSUs and roadside processors, it is also vital to provide training courses on the CV applications relevant to Caltrans's interests.

  Building on the deliverables from this project, efforts can focus on creating training courses for CV applications, which will include: (i) the minimum system hardware and software components, along with potential implementation approaches based on the physical diagrams outlined in ARC-IT 9.3; (ii) development of microsimulation scenarios to evaluate application performance under various CV penetration rates, communications ranges and latencies, traffic demands, and traffic control settings.