STATE OF CALIFORNIA • DEPARTMENT OF TRANSPORTATION

TECHNICAL REPORT DOCUMENTATION PAGE

TR0003 (REV 10/98)

1. REPORT NUMBER	2. GOVERNMENT ASSOCIATION NUMBER	3. RECIPIENT'S CATALOG NUMBER
CA24-3919	N/A	N/A

4. TITLE AND SUBTITLE Targeted Warning Messages to Protect Moving and Stationary Maintenance Lane Closures	5. REPORT DATE 03/31/2024 6. PERFORMING ORGANIZATION CODE AHMCT Research Center, UC Davis
7. AUTHOR D. Gao, D. Shi, A. Ghafourian, E. Kazemi, K. Yen, I. Soltani	8. PERFORMING ORGANIZATION REPORT NO. UCD-MAR-24-03-31-3919
9. PERFORMING ORGANIZATION NAME AND ADDRESS AHMCT Research Center UCD Dept. of Mechanical & Aerospace Engineering Davis, California 95616-5294	10. WORK UNIT NUMBER N/A 11. CONTRACT OR GRANT NUMBER 65A0749 Task 3919 13. TYPE OF REPORT AND PERIOD COVERED Final Report 01/01/2022 – 03/31/2024
12. SPONSORING AGENCY AND ADDRESS California Department of Transportation P.O. Box 942873, MS #83 Sacramento, CA 94273-0001	14. SPONSORING AGENCY CODE Caltrans

15. SUPPLEMENTARY NOTES

Revised - 05/08/2025

16. ABSTRACT

This report details the development and evaluation of an innovative component in a traffic management system aimed at enhancing safety in work zones through targeted warning messages. The primary objective of the system is to improve the rates of driver compliance with work zone guidelines presented on signages and message boards, which our studies have shown to be a critical factor in ensuring worker safety near temporary lane closures. By personalizing messages for individual vehicles based on specific characteristics, such as make, model, and color, the system may increase the likelihood of driver adherence to safe speed and driving behavior. Our research evaluated two systems: a custom artificial intelligence-based Vehicle Make and Model Recognition (VMMR) system and a commercial off-the-shelf solution. Both systems underwent extensive field testing, demonstrating promising results in vehicle detection and VMMR accuracy. Based on our findings, we recommend that Caltrans adopt the commercial off-the-shelf camera system for its comprehensive capabilities and support. Additionally, we suggest strategic placement of the camera and message board further from the lane closure, allowing drivers ample time to respond to the targeted warnings, thereby enhancing overall safety and traffic flow.

17. KEY WORDS	18. DISTRIBUTION STATEMENT	
Lane closure, work zone, targeted warning message system, vehicle make/model recognition	No restrictions. This document is available to the public through the National Technical Information Service, Springfield, Virginia 22161.	
19. SECURITY CLASSIFICATION *(of this report)*	20. NUMBER OF PAGES	21. COST OF REPORT CHARGED
Unclassified	83	N/A

DISCLAIMER

Advanced Highway Maintenance and Construction Technology Research Center

Department of Mechanical and Aerospace Engineering
University of California at Davis

Targeted Warning Messages to Protect Moving and Stationary Maintenance Lane Closures

Dechen Gao, Debo Shi, Amin Ghafourian, Ehsan Kazemi, Kin Yen &
Principal Investigator: Iman Soltani

Report Number: CA24-3919
AHMCT Research Report: UCD-MAR-24-03-31-3919
March 31, 2024

California Department of Transportation

Division of Research, Innovation and System Information

Executive Summary

In our collaborative study with the California Department of Transportation (Caltrans), we have developed an advanced targeted warning system to enhance safety and traffic flow near work zones. This system uses real-time vehicle-specific data to generate personalized messages, prompting drivers to merge safely and efficiently. The core of this system lies in automated vehicle detection and Make and Model Recognition (VMMR), which was achieved with both a cost-effective solution with the Milesight camera and a more robust, higher-end Vidar system. The latter offers built-in VMMR capabilities along with continuous updates and support, making it suitable for large-scale implementation despite its higher cost.

Field tests conducted primarily during daylight have validated the reliability of both systems in vehicle detection and attribute extraction. Although these tests did not directly assess the impact of the systems on traffic safety, the results confirm the technical efficacy of our systems. Simulation studies using PTV VISSIM software (a traffic simulation software) further supported the potential of targeted warning messages to improve worker safety by reducing late merges near work zone tapers.

Optimal placement of cameras and message boards was also explored, with simulation results suggesting that positioning these elements far from the lane closure maximizes driver response time and safety. The proposed placements integrate seamlessly with existing Caltrans infrastructure, enhancing the practicality of implementation.

As we move to the next phase of this study, we will focus on field implementation to directly observe the system's effect on traffic behavior and safety, refining our approach based on real-world data.

Major Results and Recommendations

Our comprehensive research and extensive field testing demonstrated the effectiveness of both a custom-developed artificial intelligence-based (AI-based) VMMR system, used in conjunction with a low-cost camera, and the more advanced, commercially available Vidar system. Both systems proved highly capable in accurately detecting vehicles, estimating their speed, and identifying their color, make, and model during daytime conditions. Our traffic simulations underscored the importance of driver compliance in enhancing safety and traffic flow near work zones. These results also indicate that placement of the warning message board far from the lane closure improves traffic flow and safety. Consequently, we recommend placing message boards at strategic locations far from lane closures to allow drivers sufficient time to respond to warnings. While both systems showed promise, our final recommendation is that Caltrans adopt the commercial off-the-shelf Vidar system for its comprehensive functionality, support, and ongoing updates to accommodate ever increasing list of new vehicle makes and models.

Table of Contents

Table of Figures

Tables

Acronyms and Abbreviations

Acronym	Definition
AHMCT	Advanced Highway Maintenance and Construction Technology Research Center
AV	Autonomous Vehicle
AI	Artificial Intelligence
ANPR	Automatic number-plate recognition
Caltrans	California Department of Transportation
CC0	Standstill Distance
CC1	Desired Time Headway
CC2	calculated safety distance
CORRECT_MAKE	Accurate make recognition but incorrect model
DOT	Department of Transportation
DMV	Department of Motor Vehicles
COTS	Commercial off the Shelf
DRISI	Caltrans Division of Research, Innovation and System Information
IR	Infrared
INVISIBLE_LP	Where LPs/MMs were undetectable or unclear even to humans
LAN	Local Area Network
LP	License Plate
LPR	License Plate Recognition

Acronym	Definition
LMT	Late Merge at the Taper
LMTs	Number of vehicles attempting to merge at the proximity of taper
MPH	Miles per Hour
MM	Make and Model
MPR	Market Penetration Rate
MUTCD	Manual on Uniform Traffic Control Devices
NO_LP	Vehicles without a visible LP
PIEV	Perception, Identification, Emotion and Volition
ResNet	Residual Networks
SPV	Seconds per Vehicle
SRF	Safety Reduction Factor
SSAM	Surrogate Safety Assessment Model
TTC	Time to Collision
TWM	Targeted Warning Message
UI	User Interface
VPHPL	vehicles per hour per lane
VMMR	Vehicle Make and Model Recognition
VPM	Vehicle Per Mile
VPH	Vehicle Per Hour
WRONG_RECOG	Visible but incorrectly recognized LPs/MMs

Acknowledgments

The authors thank the California Department of Transportation (Caltrans) for their support, in particular Theresa Drum, Larry Schwartz, Paul Featherstone, Steven Smith, Steven Marker and staff within the Division of Maintenance, and Eemon Amini, Arvern Lofton, Joe Horton, and Justin Unck with the Division of Research, Innovation and System Information. The authors acknowledge the dedicated efforts of the AHMCT team who have made this work possible.

Chapter 1 Introduction

Problem

In today's dynamic traffic environments, a critical problem emerges: ensuring the safety of both workers and drivers while maintaining efficient traffic flow, particularly near temporary lane closures in work zones. Despite the presence of traditional traffic management tools, like arrow boards and signposts, a challenge persists in ensuring driver attention and compliance with such warning message signs. Generic warning signs and instructions are frequently overlooked or misinterpreted by drivers. The resulting delayed reaction or non-compliance can potentially lead to unsafe conditions, including abrupt lane changes, collisions, and near-miss incidents, exacerbating the risk to road workers and other motorists. This problem is particularly pronounced in high-speed traffic conditions where the available response time is limited, and the consequences of errors are potentially severe. The need is for an innovative approach that not only captures the attention of drivers more effectively but also provides them with timely, relevant, and personalized information to guide their actions. Addressing this challenge is important for enhancing the safety and efficiency of highway maintenance operations, especially in the face of increasing traffic volumes and the complex dynamics of modern road networks.

Objectives

Central to the research goal is the development and integration of an advanced vehicle detection system, particularly focusing on vehicle make and model recognition (VMMR). This sophisticated detection capability is important for identifying individual vehicles and their specific characteristics, which forms the foundation of our targeted approach. Building on this foundation, the project aims to utilize the data gathered from vehicle detection to generate personalized and targeted warning messages. These messages are designed to be directly relevant to each driver, thereby increasing the likelihood of compliance with the warning message. By customizing the content and timing of these messages, we anticipate an improvement in driver response, contributing to safer and more orderly traffic flow in and around work zones.

Following development of custom systems or selection of commercial off-the-shelf (COTS) tools, another essential part of our endeavor is the comprehensive evaluation of the system's effectiveness. This evaluation includes extensive field testing and simulation studies to assess the technical performance of both the custom-developed VMMR system and the all-in-one Vidar camera system. These evaluations are intended to provide a clear understanding of the strengths and limitations of each system under real-world conditions.

Another important part of our objectives centers around the use of VISSIM simulation studies to understand the potential impact of driver compliance on safety and traffic flow. These simulations have been instrumental in providing insights into how improved compliance, theoretically influenced by targeted messaging, could enhance overall traffic dynamics and safety within work zones.

In addition, these simulations have also been vital in determining the best placement for camera systems and message boards. By simulating various traffic scenarios and configurations of work zones, we have gained a deeper understanding of where these components can be most effective. This strategic placement is important for maximizing the potential benefits of the targeted warning system, ensuring that drivers receive timely and relevant information.

Finally, the project aims to translate these findings into strategic recommendations for Caltrans. These recommendations cover the optimal placement of message boards and camera systems as well as hardware and software recommendations for field implementation.

Scope

The scope of this project encompasses several key areas, each critical to developing a system and complementary to an existing work zone traffic management solution:

Technology Development and Integration: We focused on developing and integrating advanced vehicle detection technology, including a VMMR system. This process includes custom-developed AI algorithms as well as the assessment of COTS systems. The scope covers the technical development, testing, and refinement of these systems.

Simulation Studies: Part of this research is dedicated to conducting traffic simulation studies. These simulations are important for understanding the theoretical impact of driver compliance on safety and traffic flow as well as determining the optimal placement of the camera system and message boards near lane closures.

Field Testing: The project involves field testing of the vehicle detection systems under various daylight conditions. While these tests primarily assess the technical accuracy of vehicle detection and VMMR, they provide invaluable data for understanding the systems' real-world applicability and performance.

Data Analysis and Recommendations: The scope includes thorough analysis of data gathered from both simulation studies and field tests. Based on this analysis, we will formulate strategic recommendations for Caltrans concerning the implementation of these technologies in actual work zone settings.

Documentation and Reporting: The project entails detailed documentation of all processes, findings, and recommendations, including the preparation of a final report that encapsulates the entire project, from conception to conclusion, offering a comprehensive overview of our research, findings, and guidance for future implementation.

The project is designed to align with Caltrans' current practices and infrastructure, ensuring that the outcomes are not only effective but also practical and feasible for real-world application. By maintaining this scope, we aim to contribute meaningfully to the advancement of traffic management strategies in work zones, enhancing safety and efficiency on California's highways.

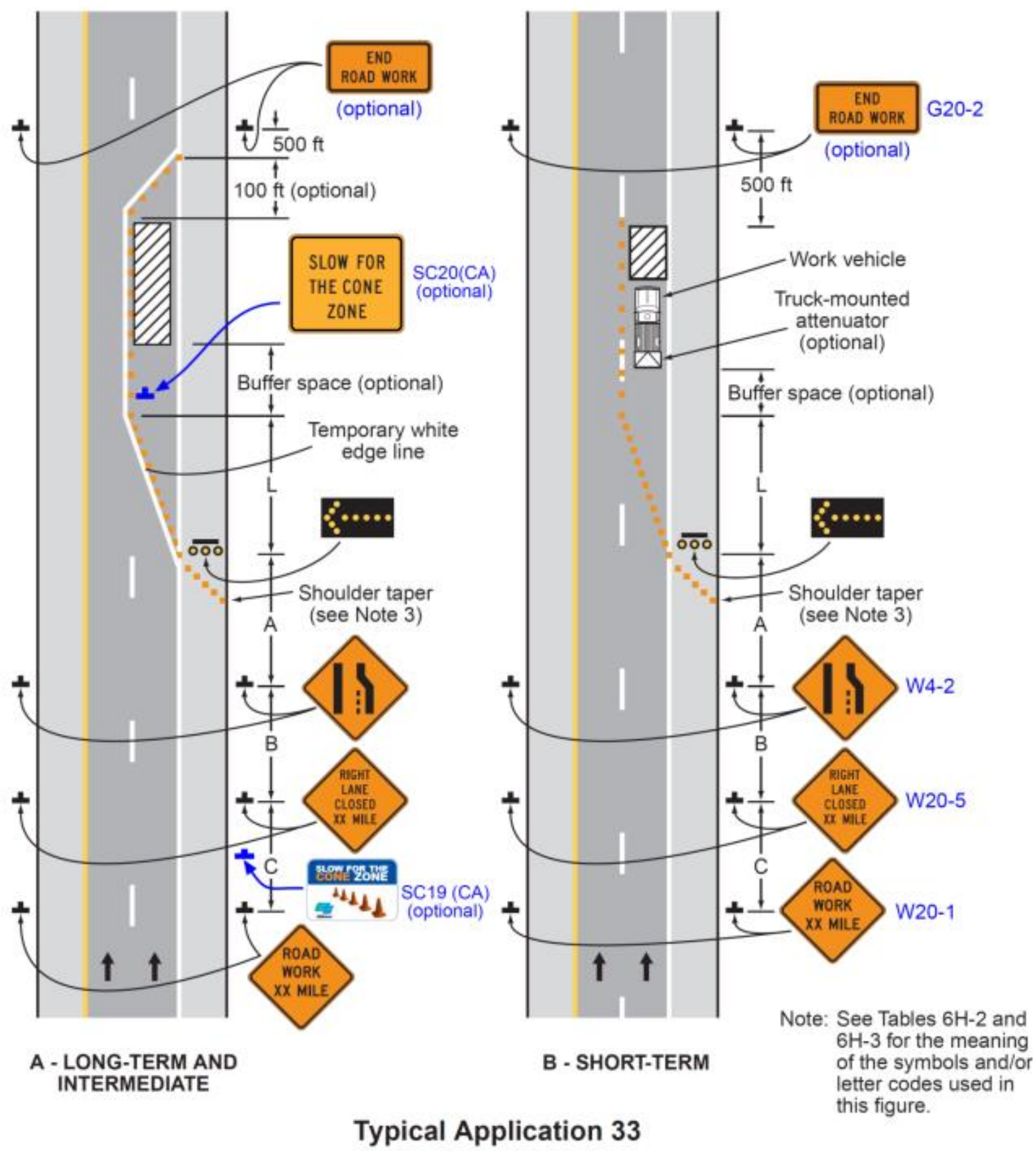


Figure 1.1: Work zone arrangement involving lane closure [1].

Background

The motivation for this project lies in the ongoing challenges faced in work zone traffic management, especially in the context of temporary lane closures for highway maintenance and construction. Historically, managing traffic near work zones has been a complex task, balancing the need for road maintenance with the safety of workers and the uninterrupted flow of traffic. Traditional approaches have relied on standard traffic control devices like cones, barriers, signboards, and arrow boards. Figure 1.1 shows existing work zone guidelines regarding the placement of warning message boards and signages. However, these measures have often proven inadequate in ensuring driver compliance, leading to potentially unsafe scenarios and traffic inefficiencies.

A notable issue, particularly in scenarios involving lane closures, is the phenomenon of "leapfrogging." This situation occurs when traffic builds up in the open lanes, prompting some drivers in the closed lane to take advantage of the thinning traffic, accelerate and leapfrog ahead, seeking to merge further down, closer to the lane closure. This behavior not only exacerbates congestion but also significantly increases the risk of collisions. Drivers attempting to leapfrog tend to make sudden, unpredictable maneuvers, disrupting the flow of traffic and creating unsafe conditions for themselves and others on the road. This issue is especially concerning in high-speed traffic environments, such as highways, where the consequences of such maneuvers can be severe. Addressing leapfrogging behavior is an important aspect of improving traffic safety and efficiency in work zones, necessitating a solution that effectively guides driver behavior in these situations.

Advancements in technology have opened new avenues for addressing such situations. The integration of artificial intelligence and machine learning in traffic management systems has the potential to enhance safety and operational efficiency. This project builds upon these technological advancements, aiming to leverage artificial intelligence-driven (AI-driven) vehicle detection and targeted messaging to address the specific issues around work zones.

Warning messages targeting specific vehicles that indicate unsafe driving patterns, such as delayed merging, can potentially reduce the number of such cases. Our background research indicates a gap in existing work zone traffic management systems regarding personalized driver communication. Most current systems do not account for individual driver behavior or vehicle characteristics, which can be pivotal in influencing driver decisions and actions in work zones.

Additionally, the rapid evolution of vehicle technology and the increasing complexity of traffic patterns, due to a mixture of autonomous and manual vehicles, necessitate a more sophisticated approach to work zone traffic management. This project aims not only to develop a solution that addresses current challenges but also to be adaptable enough to meet future demands in traffic safety and management.

In summary, this project is rooted in the need for more effective traffic management solutions in work zones. By understanding the limitations of traditional methods and harnessing the power of modern technology, this project aims to contribute to the field of work zone traffic management and road safety.

Research Methodology

Our research methodology adopted a two-pronged approach with each prong tailored to evaluate distinct, yet complementary, components of work zone traffic management solutions.

The first approach focused on integrating cost-effective commercial technologies with custom-developed AI techniques. We selected a commercial camera system based on specific criteria: cost-effectiveness, vehicle detection, license plate recognition, and speed measurement capabilities. Our team then developed AI algorithms capable of extracting vehicle-specific information, such as make and model, from the visual data captured by these cameras.

The second approach sought to assess an all-in-one commercial solution, a system inherently equipped to perform the functions of the camera system but with added VMMR capabilities. This advanced system was designed to detect vehicles, read their license plates, measure their speed, and identify vehicle-specific information, such as make, model, and color.

In our research, we carefully selected two distinct COTS systems for evaluation: Milesight and VIDAR. Milesight offers capabilities in detecting vehicles, recognizing license plates, and measuring their speed. This system was chosen for its cost-effectiveness and fundamental features necessary for work zone traffic management. This system needs to be paired with custom AI-based make and model recognition software for adoption in targeted warning generation. VIDAR represents a more comprehensive solution. It not only encompasses all the capabilities of Milesight but also extends to the detection of vehicle-specific information, such as make, model, and color.

The selection of these two systems was strategic; Milesight allowed us to explore the feasibility of pairing basic vehicle detection with our custom-developed AI for enhanced functionality at a lower cost, while VIDAR offered an all-in-one solution that could potentially streamline the process by integrating all desired features into a single, albeit more expensive, package. This distinction between the two systems was pivotal in our methodology, allowing for a comparative analysis of a modular versus an integrated approach in work zone traffic management technology.

Both systems underwent rigorous field testing to quantify their performance across various parameters. We evaluated their performance in vehicle detection, license plate recognition, speed measurement, and the extraction of make, model, and color data. These field tests were important in comparing the efficacy of the custom AI-enhanced low-cost system versus the comprehensive capabilities of the all-in-one commercial solution.

In parallel with the field testing of these systems, our research relied on traffic simulation studies using VISSIM software. These simulations served two critical purposes: firstly, to gain a deeper understanding of the role of driver compliance in safe and efficient merging near lane closures, and secondly, to ascertain the optimal placement of targeted message boards. By simulating various traffic scenarios, we were able to analyze the potential impact of different message board locations on driver behavior and overall traffic flow.

Additionally, our methodology encompassed a continuous process of data analysis and refinement. Based on the insights gained from both field tests and simulations, we iteratively improved our systems and strategies. This approach ensured that our recommendations are grounded in empirical evidence and tailored to the nuances of real-world work zone traffic management challenges.

Overall, our research methodology combined practical field tests with simulations, creating a robust framework for decision making and design selection. This comprehensive approach aimed to not only address the immediate challenges of work zone traffic management but also to contribute insights for future advancements in the field.

Additional Considerations:

Data Privacy and Ethics: In developing and implementing our systems, we adhered to strict data privacy guidelines, ensuring that all collected data were anonymized and used solely for research purposes.

Experimental Conditions: Our experimental evaluations predominantly focused on daytime conditions, recognizing that the adopted technologies are vision-based and rely on the clear visibility of vehicles. This decision was also driven by the fact that most temporary lane closures take place during the day. Concurrently, with a forward-looking perspective, we developed a simpler, license plate-based method tailored for nighttime use. This method was designed to address the inherent visibility challenges of nighttime conditions, leveraging the relative reliability of license plate recognition in low-light environments. It's important to clarify that while this nighttime-oriented approach was developed, its experimental evaluation was not within the scope of our current study. We prioritized a thorough investigation of daytime conditions, thereby ensuring depth and precision in our findings. However, the inclusion of this nighttime-focused technique serves as a foundational step, informing Caltrans of viable options for future expansion into nighttime adoption of targeted warning systems. This dual approach underscores our commitment to providing Caltrans with comprehensive, adaptable solutions.

Overview of Research Results and Benefits

Our research yielded promising results that have important implications for traffic management in work zones. The two systems we evaluated, Milesight and VIDAR, demonstrated distinct strengths in their respective areas of application.

Milesight System: This system, complemented by our custom AI algorithms for VMMR, proved effective in vehicle detection, license plate recognition, and speed measurement. While it required additional development for VMMR, its cost-effectiveness makes it a viable option for wide-scale implementation where budget constraints are a consideration.

VIDAR System: As an all-in-one solution, VIDAR excelled in not only performing the basic functions of vehicle and license plate detection and speed measurement but also in accurately identifying vehicle-specific details like make, model, and color. The higher cost of this system is offset by its comprehensive capabilities and reduced need for additional development.

Both systems demonstrated high accuracy during daylight field tests in their respective functionalities. In light of our research and evaluations, we recommend the VIDAR system for traffic management in work zones, particularly in scenarios where budgetary constraints are less restrictive. The recommendation for VIDAR is anchored in its more robust design and the comprehensive nature of its capabilities. Unlike the Milesight system, which requires additional development for VMMR, VIDAR offers an all-encompassing solution that seamlessly integrates vehicle detection, license plate recognition, speed measurement, and the identification of specific vehicle attributes like make, model, and color.

A critical advantage of the VIDAR system is its ability to continuously update and accommodate new vehicle models and makes. This feature is particularly important given the rapid evolution of vehicle designs and technology, ensuring that the system remains relevant and effective over time. Additionally, the support and service provided by the manufacturers of VIDAR add a layer of reliability and assurance, making it an attractive option for long-term implementation in work zone traffic management scenarios.

The recommendation to adopt the VIDAR system is thus based not only on its current performance but also on its potential for adaptability and sustained effectiveness in the dynamic landscape of road traffic and vehicle technology.

Our VISSIM simulation studies played an important role in understanding the dynamics of traffic flow and safety in work zones. These simulations illuminated the importance of driver compliance and timely merging in ensuring efficient traffic movement and reducing safety risks near lane closures. We observed that driver response to merge warnings significantly impacts the occurrence of unsafe conditions, such as late merges at the taper, which can lead to near-miss incidents or collisions. This insight underscores the potential impact of the proposed targeted warning system. By providing personalized, relevant information to drivers through this system, we anticipate an improvement in driver compliance with the warning signs. Such an enhancement in driver compliance is expected to contribute to smoother traffic flow and heightened safety in work zones. Therefore, the targeted warning system, as suggested by our research, could be an effective tool in improving current work zone traffic management practices.

Chapter 2 Commercial Off the Shelf Camera System Selection

The cornerstone of effective targeted message generation lies in the strategic selection of the camera system. The ability to generate precise and relevant messages hinges on leveraging license plate recognition (LPR), vehicle make and model recognition (VMMR), and vehicle speed detection capabilities.

Reliable and timely LPR is important when selecting an appropriate product as it produces the vital data necessary to construct targeted messages. Moreover, license plates enable the retrieval of other vehicle information from web (e.g., Department of Motor Vehicle [DMV] application programming interfaces (APIs)), which is particularly useful when VMMR is unavailable in camera or VMMR fails to function in low-light conditions. The capability to measure vehicle speed is equally valuable, enabling the generation of deceleration prompts for vehicles that are approaching too quickly before merging. Additionally, the inclusion of VMMR is a significant advantage as it allows for the creation of messages that incorporate make and model information, which tends to be more readily identifiable and comprehensible for drivers since it is not reasonable to expect all drivers to remember their license plate information.

Given the significant cost associated with cameras equipped with VMMR, our exploration of solutions was twofold. Firstly, we considered a cost-effective approach that leverages cameras with basic LPR capabilities, circumventing the need for an expensive VMMR module. Secondly, we evaluated the feasibility of deploying a comprehensive camera system that includes an VMMR module, acknowledging its higher acquisition cost but recognizing the simplicity and potential efficiency it brings to system setup.

In our quest to find the most suitable camera systems for targeted warning message (TWM), we narrowed down our choices to two distinct solutions: the Milesight camera for its cost-effectiveness and essential functionality, and the VIDAR camera for its comprehensive features and straightforward deployment. These selections were made after a meticulous evaluation of available products with a focus on their potential to enhance traffic safety and efficiency through advanced detection and messaging capabilities.

This chapter provides an in-depth look at the Milesight and VIDAR cameras, detailing their specifications, core functionalities, and the rationale behind their selection. While the specifics of our field tests will be discussed in a later chapter, it's important to note that these cameras were chosen based on preliminary assessments that underscored their suitability for extensive real-world deployment and testing on freeways and highways.

Milesight Camera System

Product Introduction:

In our search for a cost-effective camera product, we selected the *Radar AI LPR 4x/12x Pro Bullet Plus Network Camera* from Milesight. This choice was motivated by the camera's LPR capabilities and its integrated radar features, for vehicle detection and speed measurement, making it a viable component of our cost-effective solution.

Sensor Capabilities:

The camera's radar system enhances its tracking capability, supporting the detection of multiple targets—up to 32 vehicles—across one to four lanes. Its speed detection range is extensive, from 5 km/h to 200 km/h with an accuracy of ±0.36 km/h, ensuring speed measurements under a wide variety of traffic conditions. It can be installed at heights ranging from 2 to 7 m.

The Milesight camera features 1/2.8" Progressive Scan CMOS sensors with minimum illumination requirements as low as 0.001 Lux for color and 0.00 Lux with Infrared on, ensuring clarity in low-light conditions. It supports 140 dB Super WDR Pro, ensuring image quality in diverse lighting. The cameras allows for rapid shutter times of 1/100000 s, and IR distances reaching up to 180m, facilitating night vision. Lens specifications include 12x optical zoom capabilities, with focus control being either automatic or manual. The aperture ranges from F1.6-F1.7 to F1.6-F2.8, and iris control is automated.

Automatic Recognition Capabilities:

The Milesight camera is capable of recognizing vehicles traveling at speeds up to 200 km/h and can simultaneously capture up to four distinct regions.

Beyond LPR, speed, and direction detection, the camera is equipped to recognize vehicle types. The vehicle type information is not detailed enough, only including high level categories such as trucks or cars. The camera is also capable of providing color information, which can be used to compile a targeted warning message.

Figure 2.1: Radar AI LPR 4x/12x Pro Bullet Plus Network Camera from Milesight.

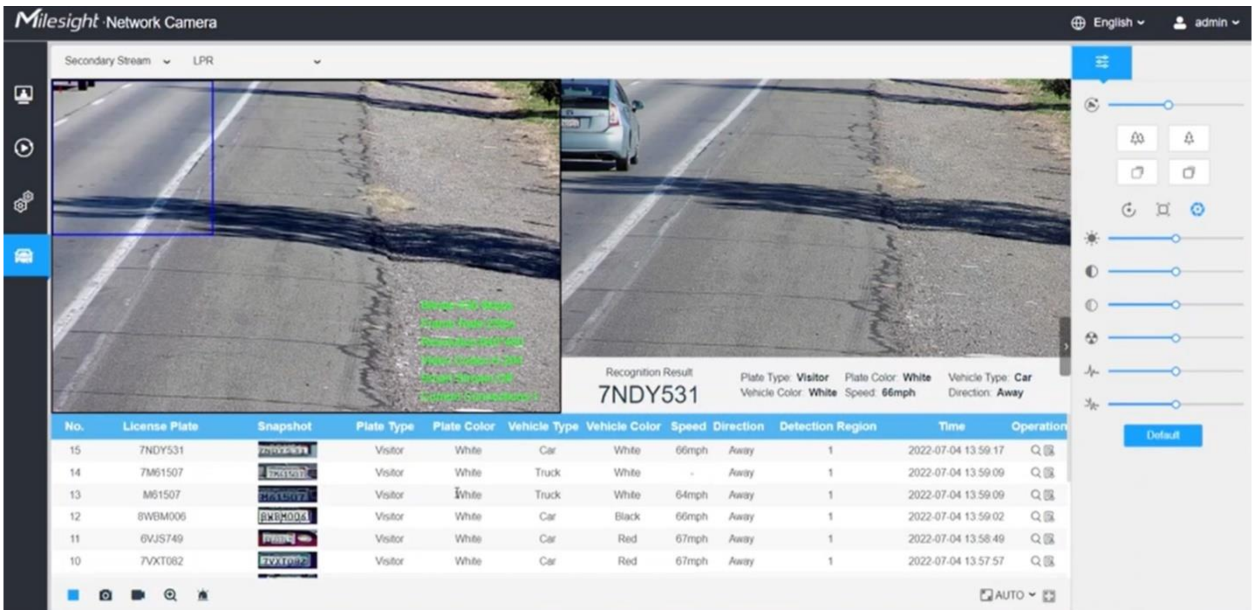


Figure 2.2: An example UI of Milesight camera. A single region of interest (blue rectangle on the left) is defined in our application.

The basic functionality of the Milesight camera, including vehicle detection, LPR, color, and speed measurement, makes it a reasonable choice for our cost-effective targeted warning message (TWM) solution.

Figure 2.1 shows the Milesight Camera/Radar system. It has a relatively small footprint and can be mounted on a post as was done in our experiments. Figure 2.2 shows the UI of the Milesight camera extracted during a field test. As seen in this figure, the camera system provides a list of detected vehicles with information about their license plate, plate type, plate color, vehicle type, vehicle color, speed, direction and detection region. Detection region is only used when multiple regions in the field of view of the camera are defined as regions of interest. In our use-case examined a single lane (closed lane), and hence, a single region of interest was defined.

VIDAR Camera System

Product Introduction:

The VIDAR camera represents a high-end product choice for TWM, complete with integrated LPR and VMMR. It is supported by dual high-resolution sensors and radar. This integration negates the need for developing a separate VMMR module, streamlining deployment, albeit at a higher cost point than the Milesight camera.

It also features an intuitive user interface (UI) that significantly enhances interaction, allowing for fine-tuned control over camera, radar, and a myriad of settings to adapt to various road conditions. Users can effortlessly customize triggering distances, specific areas, and lane settings to suit the dynamic needs of traffic flow. This level of customization ensures that the VIDAR camera excels in accurately identifying and tracking vehicles across different lanes, which is particularly useful for targeted messaging in traffic scenarios where attention is focused on specific lanes.

Sensor Capabilities:

The imaging specifications include a high-resolution sensor of 2432 x 2048, which, combined with color and global shutter technology, ensures detailed image capture. It operates with a maximum frame rate of 45 FPS at 3 MP on sensor 1 and 120 FPS at 720 p on sensor 2, accommodating various traffic speeds and conditions. The camera offers a motorized zoom lens with remote focus and zoom adjustability, featuring an optical zoom up to 18x and a variable focal length between 4.8 to 84.6 mm.

Enhanced radar capabilities of the VIDAR camera system enable precise vehicle speed and direction detection, which is important for speed enforcement and safety analysis.

The camera provides a wide field of view (Tele: 8.1° x 6.1° to Wide: 25.1° x 21.3°) for extensive area coverage. Automatic number-plate recognition (ANPR) capabilities are designed to function optimally within a distance range of 10 to 20 m in ambient light and up to 50 m in total darkness or reflective license plates, handling vehicle speeds ranging from 0 km/h to over 320 km/h. This VIDAR model ensures coverage for road widths up to 10 m.

Figure 2.3: VIDAR speed from Adaptive Recognition.

Automatic Recognition Capabilities:

The VIDAR camera features on-board intelligence with capabilities for LPR and VMMR. The VIDAR camera's built-in models are designed to provide accurate detection across a wide range of light (either day or night mode) and road conditions (freeway or highway). Its advanced sensors and detection algorithms ensure reliable identification. Beyond LPR and VMMR, VIDAR provides other information, such as vehicle type, color, speed, and direction.

A standout feature of the VIDAR system is its dedication to maintaining reliable performance through bi-annual updates to its AI detection models. This commitment ensures that the camera remains effective over time by recognizing the latest vehicle makes and models.

Figure 2.3 shows the camera system. Figure 2.4 provides an example UI. For each detected vehicle the camera system provides information about country, state, speed, lane, make, model, category (e.g., van), and color, etc.

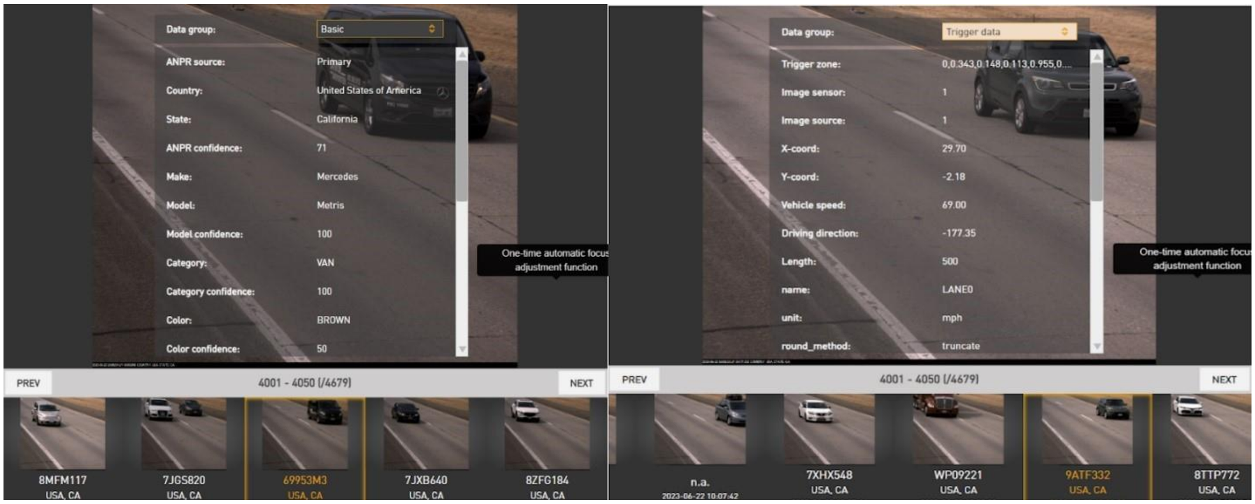


Figure 2.4: VIDAR speed example user interface.

Chapter 3 Make and Model Recognition

Custom AI-Based Vehicle Make and Model Recognition

The inception of our custom AI-based VMMR algorithm was driven by the specific need to augment the capabilities of the Milesight camera within our TWM system. While the Milesight camera offered robust LPR and basic vehicle detection functionalities, it lacked the intrinsic ability to identify vehicle makes and models. Recognizing the significance of this feature in delivering precise and relevant TWMs, we embarked on developing a custom AI solution. This chapter discusses our journey in creating a VMMR algorithm that seamlessly integrates with the Milesight camera, bridging the gap between basic vehicle detection and the nuanced recognition of vehicle specifics.

This chapter delves into the details of the machine learning method we devised, the dataset used in the training process, and our performance evaluation results.

Our approach to VMMR leveraged latest developments in deep learning, specifically through a visual classifier built upon a residual network (ResNet) architecture [2]. ResNet is a revolutionary neural network architecture that allows for training extremely deep networks. Its key innovation is the introduction of "residual blocks", which use skip connections to jump over some layers. These connections perform identity mapping, and their outputs are added to the outputs of the stacked layers. Importantly, this design significantly improves the flow of gradients throughout the network, enabling the training of networks that are much deeper than was previously feasible. ResNets, with their deep yet efficient architecture, have demonstrated remarkable performance in a variety of visual recognition tasks. Figure 3.1 shows the residual block and a sample ResNet architecture.

We chose the ResNet-50 [2] model; a robust architecture known for its efficacy in visual tasks and especially classification tasks. This network receives an image as input and extracts the most relevant visual features in the form of a feature vector that can then be used in a subsequent task, such as vehicle make and model recognition. Initially, this model was pretrained on the extensive ImageNet dataset [3], providing a solid foundation of visual understanding. We then fine-tuned this pretrained model specifically for the VMMR task, adapting it in a supervised learning [4] setting. The goal was to train the model to accurately classify input images into distinct vehicle make and model categories.

Figure 3.2 illustrates the model outline, highlighting the ResNet-50 based architecture and its adaptation for the VMMR task. This figure provides a visual representation of the model's structure, showcasing how the visual data are classified as a particular make and model.

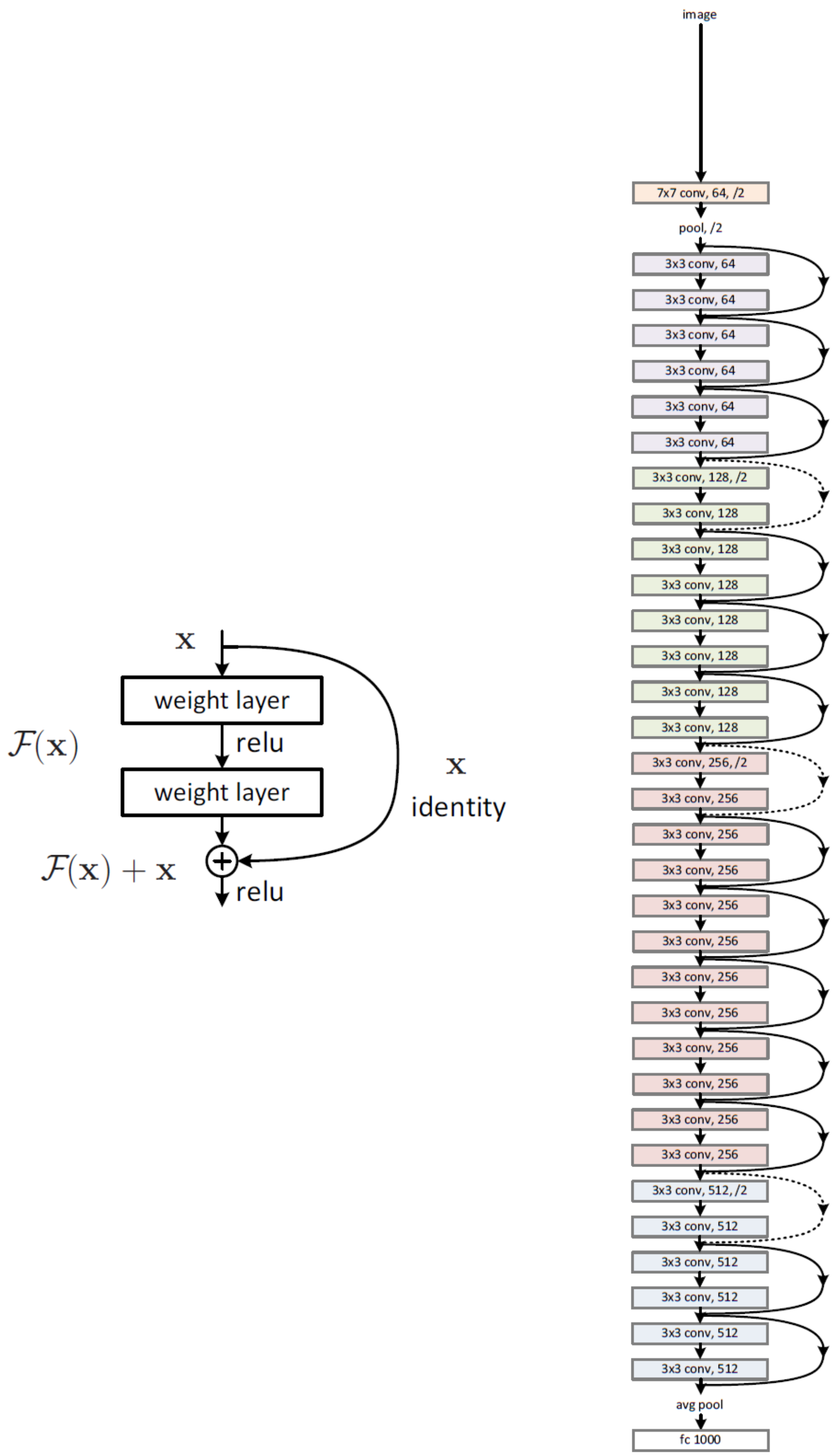


Figure 3.1: Residual block (left) and an example ResNet architecture with 34 parameter layers (right).

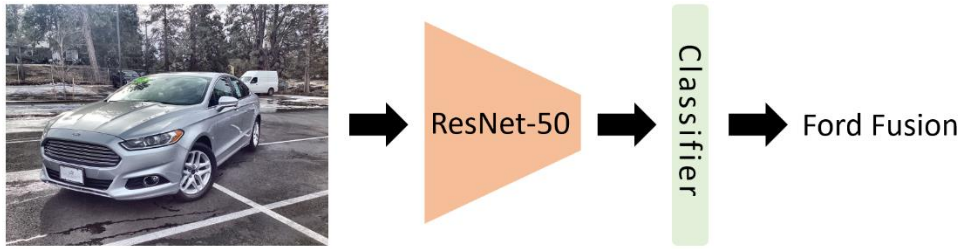


Figure 3.2: Model outline. The ResNet-50 vision model receives an image, and the classifier picks the most probable make and model from among participating vehicle make and model classes.

ImageNet dataset, which is used for pretraining the model, is a large dataset often used for training and evaluating visual recognition models. It consists of over 1.4 million images across 1,000 classes. For the specific VMMR task, we used VMMRdb dataset [5], which consists of nearly 300,000 images across over 9,000 classes corresponding to vehicle makes, models, and manufacturing years between 1950 and 2016. The information was collected by crawling the webpages related to vehicle sales, especially Craigslist and Amazon websites. The labels are generated based on seller title and description.

Considering the 2016 cutoff and noting that the newest makes and models may not be adequately covered in the VMMRdb dataset given their then recent availability, we complemented this dataset through our own data collection effort, which spanned vehicle makes and models that were available in the United States for the 2015 to 2022 period. To accomplish this objective, we automated the internet image search for each model. The search phrase would consist of vehicle make, model, year, and the term "exterior" as we found better quality search results when narrowing to vehicle exteriors. We downloaded the first 60 image results for nearly all of the make/model/year searches. This resulted in a combined dataset size of over 436,303 images across 11,535 classes.

The performance of the trained model was evaluated on a dataset of 42 actual roadside images from one of our recordings where each image is presented to the model and its predicted make and model is recorded. To assess the accuracy of the label prediction, ground-truth make and model is obtained via searching the license plate online. For a few vehicles with missing, illegible, or custom license plates, true make and model was obtained through visual identification and possibly using the actual network output as guidance.

Notably, for evaluation, only make and model information was considered and information on year was dismissed. This decision was made to avoid the inherent ambiguity in predicting the year among the same makes and models from several different consecutive years since manufacturers rarely update the exterior design (at least in a significant way) in all consecutive products of the same make and model. Nevertheless, if the year interval is of interest, a lookup table can be constructed that lists time intervals associated with similar designs for each make and model. Then, by finding the interval that spans the predicted year, that information can also be retrieved.

Figure 3.3: Top – ambiguous test image that is potentially misclassified. Bottom left- predicted label (Chevrolet Tahoe). Bottom right – presumed true label (Chevrolet Silverado).

Out of the 42 vehicle images, the make and model of 41 vehicles were correctly identified, resulting in an approximate 98% accuracy. Further, the only misidentified vehicle looks ambiguous even to the human eye. Figure 3.3 shows the image of this sample and the true and predicted makes and models for it. Considering the visual resemblance and the fact that this is among the vehicles with no license plate, the true label remains uncertain, and 98% is a conservative estimate of performance on the evaluated dataset where the alternative is 100% accuracy. Still, the first few predictions for this sample are all the same two makes and models from different years. For instance, while the first prediction is a 1995 Chevrolet Tahoe, the second and third most likely predictions are, respectively, a 1998 and 1997 Chevrolet Silverado, and the fourth and fifth are a 1998 and 1999 Chevrolet Tahoe.

Finally, we note that even though the current result is favorable, it can be negatively impacted by various factors. For instance, all evaluated vehicle images are captured in daytime with good visibility. Further, although some of the vehicles, and particularly older models, did show signs of discoloration and wear-and-tear, none of the vehicles' appearances are heavily modified or reflect signs of heavy damage, which presumably facilitate the classification. The code associated with this make and model recognition effort is available at: https://github.com/Soltanilara/Caltrans-VMMR

Web-Based Vehicle Make and Model Extraction Under Low Visibility Conditions Using License Plate Information

In addition to our AI-based VMMR system, we explored a web-based approach, particularly valuable under low visibility conditions, such as nighttime. This method capitalizes on the observation that license plates typically reflect near-infrared light effectively, a feature well-detected by both VIDAR and Milesight cameras. At night or in other low visibility scenarios, while other vehicle details become obscure, license plate recognition (LPR) remains reliable, which opens up the possibility of using license plate data to access the DMV or other databases for extracting vehicle make and model information.

Proof of Concept and Limitations:

It is important to emphasize that this web-based approach serves primarily as a proof of concept. We experimented with existing publicly available and free websites, such as findbyplate.com, to demonstrate the feasibility of this method. However, we acknowledge that reliance on such public platforms is not viable for field deployment due to the absence of guarantees for continuous access to these servers. This approach, at its current stage, is intended to illustrate the potential of integrating web-based data retrieval with LPR technologies.

Collaboration Needs:

Realizing this concept in a practical, field-ready format necessitates a collaborative effort between Caltrans and the DMV. Such a partnership would address the comprehensive compliance requirements around privacy, security, and data handling that accessing DMV databases entails. This collaboration is key to unlocking the full potential of web-based VMMR in enhancing work zone traffic management systems.

Technical Implementation and Latency:

Our team developed Python scripts (available through GitHub repositories https://github.com/Soltanilara/CalTransTWM) that automate the process of receiving license plate information and communicating with the web-based service for vehicle data retrieval. Preliminary tests indicate that this process introduces a latency of approximately 1 s from license plate detection to receiving vehicle-specific information. In the context of our TWM system, this latency is deemed acceptable and does not significantly impede the overall response time of the system.

This web-based VMMR approach, while currently a conceptual model, points to a promising direction for enhancing vehicle recognition capabilities in low visibility conditions. Its successful implementation hinges on future developments in data access and collaboration, laying the groundwork for more sophisticated and responsive work zone traffic management solutions.

Chapter 4 Camera System and Targeted Warning Message Board Placement

Traffic Simulations

The first section of this chapter delves into the utilization of traffic simulations in determining the optimal placement of cameras and message boards for our TWM system. Using VISSIM software, these simulations provided a valuable framework for analyzing traffic flow and driver behavior in various work zone scenarios. They enabled us to explore a range of traffic conditions, from varying vehicle speeds to different levels of congestion, giving us insights into how best to position our equipment for maximum effectiveness. Importantly, these simulations also shed light on the role of driver compliance, particularly in merging maneuvers, and its influence on overall traffic safety and flow near lane closures. The data and observations gathered through these simulations have been essential in making informed decisions about the placement of the components of the system, ensuring that it aligns effectively with the real-world constraints and existing guidelines. Furthermore, as discussed in the following, with a forward-looking approach, the simulations consider scenarios in which autonomous vehicles (AV) share the road with human drivers.

Simulation Methodology

In this section, we discuss the methodology, configuration of the work zone, and calibration of the microsimulation model adopted in this study. We further describe our findings and validation of our results.

Configuration of the studied work zone:

Figure 4.1 shows the configuration for a hypothetical work zone area on a typical road segment with a total length of 3,500 ft. We assume a two-to-one lane dropped work zone on a freeway with a speed limit of 60 miles per hour (mph). Additionally, we set the work zone speed limit to 50 mph. The simulated work zone consists of four areas: advanced warning, transition, activity, and termination area. We assume two advisory merge signs placed at 2,500 ft and 1,000 ft from the taper following the guidance from the manual [6] for work zones in freeways. The first sign serves as an early warning to drivers, giving them early notice that they will need to merge or change lane soon. It allows compliant drivers to begin adjusting their speed and positioning accordingly, especially in high-speed zones. The second merge sign, placed 1,000 ft from the taper, further reinforces the warning and informs drivers that the lane merge or lane closure is approaching soon. It gives drivers additional time to make the necessary lane adjustments.

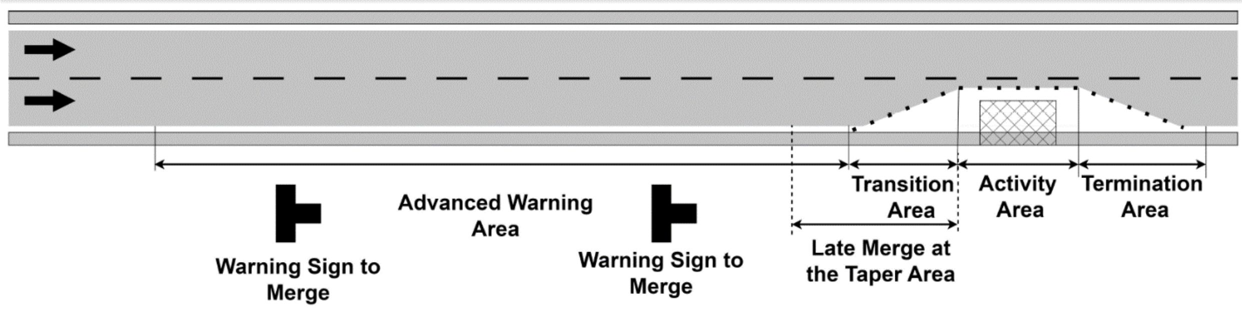


Figure 4.1: Diagram of the work zone.

Car following model:

Regarding the car following model, we use a model that allows advanced planning for temporal and spatial variations. We use the Wiedemann 99 model [7] as our car-following model, which incorporates psycho-physical factors. Findings in [8], [9], [10], [11], [12] indicated that standstill distance (CC0), desired time headway (CC1), the maximum additional following distance beyond the calculated safety distance (CC2) are the most important parameters in a work zone microsimulations. We calibrate the microsimulation model using the guidance in [8]. Specifically, we utilize distinct headway distributions for conventional passenger cars and trucks, as illustrated in Figure 4.2. The standstill and headway distance in the Wiedemann model for AVs is set based on the mixed autonomy traffic condition [13]. In particular, AVs keep smaller standstill distance and headway. Further, AVs do not apply stochastic distributions for the desired speed, speed limit, and standstill accelerations and keep these driving parameters rather strictly.

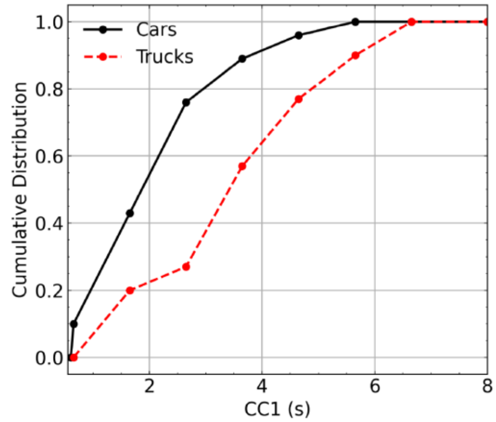


Figure 4.2: Distribution of headway (CC1) for conventional vehicles in the Wiedemann 99 model for passenger cars and trucks.

Empirical compliance distributions:

We studied eight empirical distributions for driver compliance to the two warning signs as shown in Figure. 4.3. More specifically, we considered compliance distributions as a categorical variable with 8 levels. Herein, compliance is reflective of the distribution of the drivers that intend to take a lane-changing maneuver from the closed lane to the open lane as soon as adequate space and time from the trailing vehicle in the new lane is available. We measure compliance based on distance-to-work zone (rather than time), due to vehicle speed variation caused by lane merging maneuvers. Compliant vehicles remain in the closed lane until they spot the first safe gap in the open lane for merging. Therefore, those vehicles involved in LMT (see Figure 4.1) are either those compliant vehicles that could not find adequate space and time to merge or non-compliant vehicles that deliberately delayed merging. The non-compliant conventional vehicles travel in the closed lane regardless of the warning signs until they reach the queue or the taper in the closed lane. We assume 100% compliance with the warning sign for AVs.

The distributions in Figure 4.3 show the percentage of drivers that intend to change lane from the closed lane to the open lane upon receiving the merge warning notification. Each distribution depicted in Figure 4.3 represents the cumulative percentage of compliance versus distance to taper. In all the empirical distributions, we assume full compliance when the drivers reach 600 ft upstream of the work zone bottleneck. In distributions 1 to 4, compliance is considered starting at 1,200 ft of the work zone, while in distributions 5 to 8, this distance is increased to 2,500 ft ahead of the work zone. To elaborate, in distribution 1, we assume that drivers intend to use the closed lane for as long as possible, and all drivers comply at the same time when they are 600 ft ahead of the work zone.

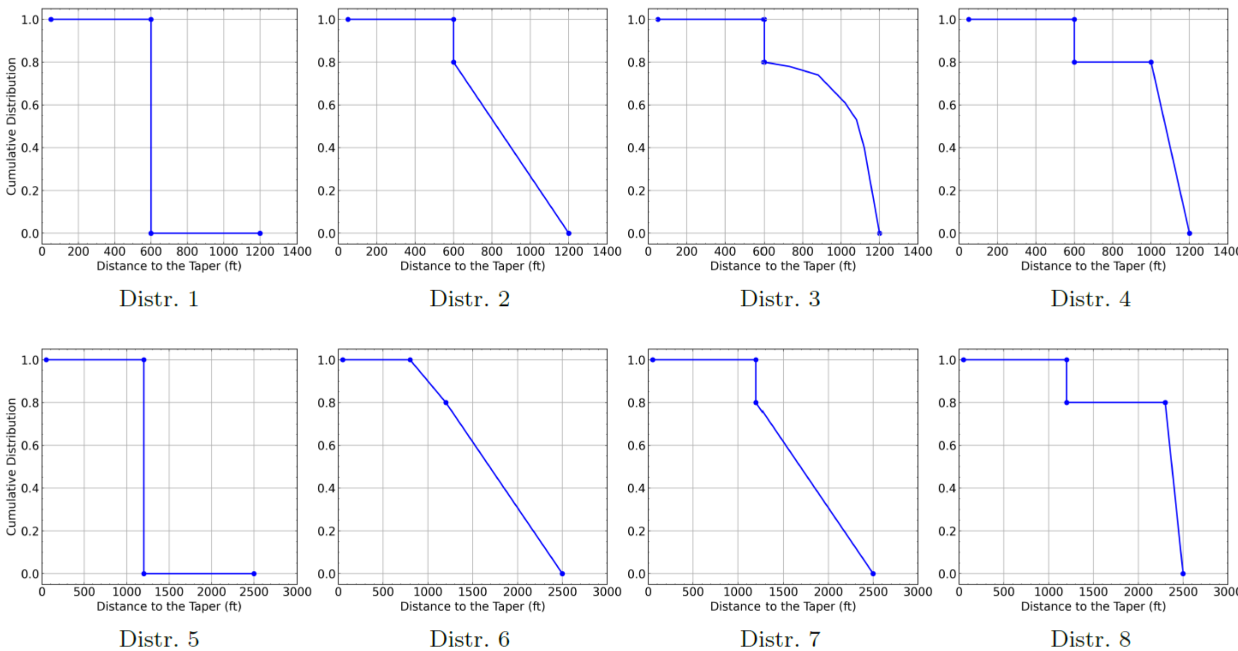


Figure 4.3: Varieties of compliance rate distributions along the closed lane, upstream of the work zone tapper.

This distribution simulates a scenario in which drivers only adhere to merging into the open lane after visually identifying the physical barrier. In Distribution 2, we assume the rate of compliance increases linearly from 1,200 ft upstream of the work zone in response to the second warning sign, still leaving 20% of the drivers as non-compliant until 600 ft ahead of the work zone. This 20% of the drivers represents the real-world fraction that would opt to use the closed lane for as far as possible to leapfrog through the traffic using the higher average speed relative to the open lanes and only start to comply when they are close to the work zone construction. In distribution 3, in contrast to the linearly increasing compliance rate seen in distribution 2, we assume a nonlinear and steep increase in compliance. In distribution 4, we assume that 80% of the drivers comply with the warning sign starting from 1,200 ft of the work zone tapper, with no additional compliance (for the remaining 20%) occurring until 600 ft upstream of the work zone. Distribution 4 aims to capture the non-merging area in the vicinity of the work zone, explored in [14], where merging is not permitted. From distribution 5 to distribution 8, the distances for the warning sign upstream of the work zone increase. In distribution 5, we assume all the drivers comply close to the warning sign starting from 1,200 ft of the work zone. In distribution 6, we assume the compliance by the drivers increases linearly starting from the proximity of the first warning sign. Distribution 7 is similar to distribution 6 except that 20% of the remaining vehicles comply abruptly in close proximity to the second warning sign. Distribution 8 is similar to distribution 4 in that a no merging area is imposed between the first and the second sign.

Ablation parameters:

This work investigates the correlation between drivers' compliance distribution and various traffic flow performance metrics in the work zone under various placement distances of the warning signs and different levels of mixed autonomy operation. We comprehensively evaluate our simulation framework by considering different work zone configurations, compliance distributions, the market penetration rate for autonomous vehicles (MPR), and Safety Reduction Factor (SRF), a measure of aggressiveness in lane changing maneuvers in the car following model. For this purpose, we consider variations of work zone configuration, such as the input volume of the vehicle per hour per two lanes (vph/2 lanes), MPR, and SRF across all compliance distributions of the conventional vehicles shown in Figure 4.3. The studied configuration parameters and values for the simulation framework are displayed in Table 4.1. The volumes for the traffic demand are selected such that traffic performance can be examined across under-saturated to saturated corridors. In summary, we conduct a simulation on a typical work zone (Figure 4.1) on eight compliance distributions, six levels of traffic volumes, four levels of MPR, three levels of truck proportions, and two different settings for safety distance reduction factor in the car following model, which is in total 1,152 microsimulation modeling scenarios. We run each case for various random seeds to achieve the 95% confidence level and compare the averaged results across all the scenarios.

Table 4.1: The parameters used in the VISSIM traffic simulations.

Variables	Categories
Traffic Volume (vph / 2 lanes)	600
	800
	1000
	15000
	1800
	2000
AV-MPR	0%
	20%
	50%
	80%
Truck Percentage	2%
	10%
	20%
Safety Reduction Factor (SRF)	0.6
	0.75
Compliance Distribution	According to Fig. 4.3

Traffic performance measurements:

As mentioned earlier, we show the number of vehicles attempting to merge at the proximity of taper by LMTs. The vehicle drivers may opt to take aggressive actions to merge, or they can stop at the taper while waiting for the right time to merge. Therefore, the LMTs can reflect the frequency of occurrence of forced merges. In this study, we consider LMTs as vehicles within 100 ft of the vicinity of the construction zone. Since for all distributions in Figure 4.3 we assume 100% compliance at 600 ft ahead of the work zone, the LMTs are composed of vehicles that had the intention to merge at least from 600 ft upstream of the work zone, but they could not find adequate time and space for a successful merge due to limited cooperation of the trailing vehicles or traffic congestion in the target lane. These vehicles, categorized as LMT, either come to a complete stop as they reach the taper and then force their way into the desired lane or perform aggressive maneuvers to merge at the taper. Variables, such as LMTs, speed (measured in mph) at the bottleneck and the traffic efficiency surrogate measurements like traffic throughput (measured in vehicles per hour per lane [vphpl]) and the mean net delay (measured in seconds per vehicle [spv]), are the studied response variables. The traffic demand, truck proportion, MPR, and SRF are the control variables. In the following sections, we seek to understand how the drivers' compliance can influence efficiency and safety performance as represented by the response parameters. Our observations show that LMTs can be used as a surrogate indicator for not only traffic mobility but also traffic safety.

We use the time to collision (TTC) as a surrogate measurement of safety. TTC is defined as

$$TTC = \begin{cases} \dfrac{L}{V_t - V_l} & \text{if } V_t > V_l \\ \infty & \text{Otherwise} \end{cases}$$

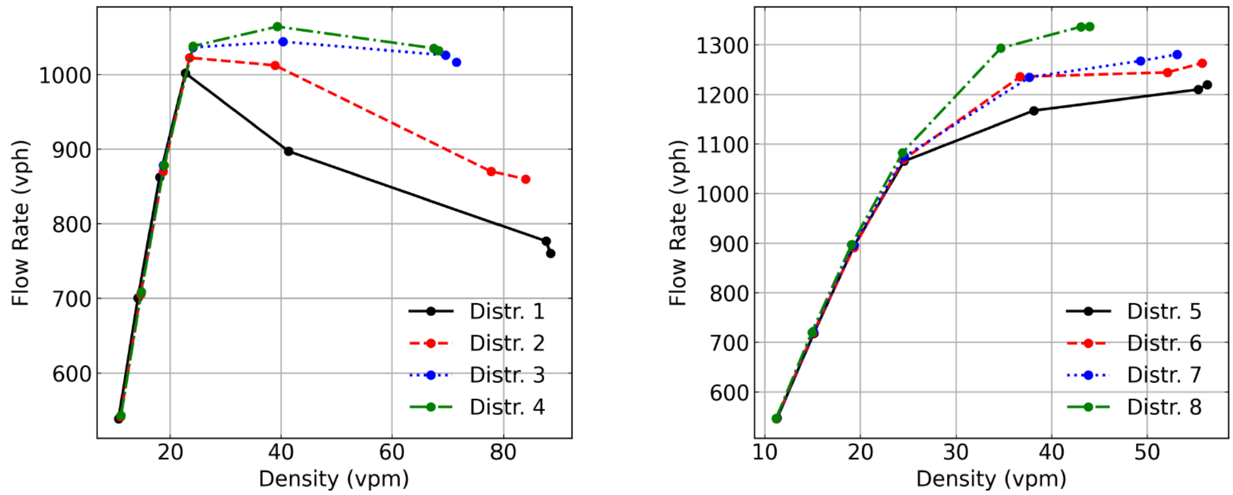
where *L* is the distance between the leading and the trailing vehicle and V_l and V_t are the speeds of the leading and following vehicles, respectively. TTC is chosen because it is a widely used measure due to its ability to reflect crash potential and is the most suitable proxy for rear-end collisions [15], [16], [17]. We use the Surrogate Safety Assessment Model (SSAM) analysis [18] to count the number of critical time to collision less than the given threshold t_c. Critical time to collisions (TTCs) is defined as the number of vehicles with TTC less than the threshold t_c for both lane-change and rear-end conflicts. The TTC threshold value, i.e., t_c, was set to 1.5 s and 2.5 s in this study [19], [20]. We study the correlation between LMTs and TTCs for the safety of roadways and find a positive correlation between these measures.

Results

In this section, the microsimulation results are presented. Regarding the simulation configuration, the vehicles still on the closed lane and within a 100 ft vicinity of the construction area are counted as LMTs. We assume that AVs fully comply with the warning signs. Therefore, the compliance distribution only applies to conventional vehicles. In the following, the default truck ratio is 2%, and the default SRF value is 0.6 unless otherwise stated. We discuss the performance of late merge traffic from the perspective of various performance measures, including throughput, density, net delay, LMTs, and speed at the bottleneck.

Exploring the Impact of Compliance Distributions

Figure 4.4 shows variations of traffic flow rate in vehicle per hour (vph) against traffic densities in vehicle per mile (vpm) across all compliance distributions for MPR of 0%. In the low-density regimes, the traffic flow rate for all the distributions is similar. However, for higher traffic demand and thereby higher density, the flow-density diagram varies significantly over different compliance distributions. For example, in Figure. 4.4.a for distribution 1, the traffic flow changes state from stable flow to breakdown congested flow sharply upon increasing the traffic demand. Nevertheless, distribution 3 and 4 can maintain the traffic demand and plateau without a sharp decrease in the traffic flow rate, which is a typical characteristic of work zones [21], [22]. Figure 4.4.b shows that the rate of traffic flow is improved when transitioning from distribution 5 to distribution 8, providing the best performance in terms of maintaining the traffic demand. In Figure 4.4.b, distribution 6 and distribution 7 show similar traffic curves for densities lower than 50 vpm; however, a breakdown is observed in the traffic flow rate for distribution 6 for densities over 50 vpm. These observations overall support the fact that, at low traffic densities, all the distributions yield similar traffic conditions in terms of mobility. However, for higher traffic demands, positioning a warning sign at a greater distance coupled with a high level of driver compliance leads to increased traffic efficiency.

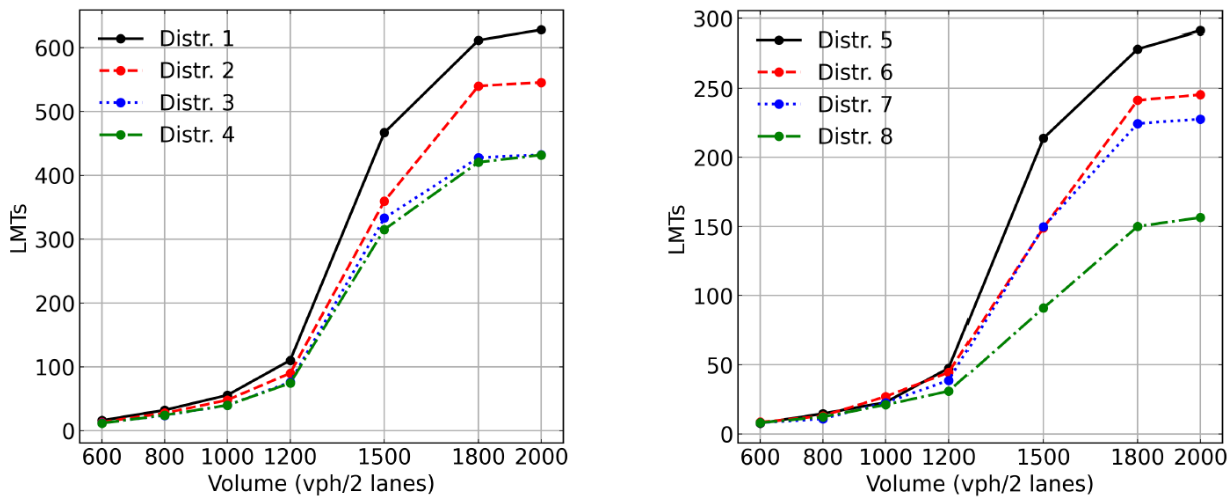


(a) Flow Rate vs. Density (b) Flow Rate vs. Density

Figure 4.4: The traffic flow rate versus density for MPR = 0% across all compliance distributions.

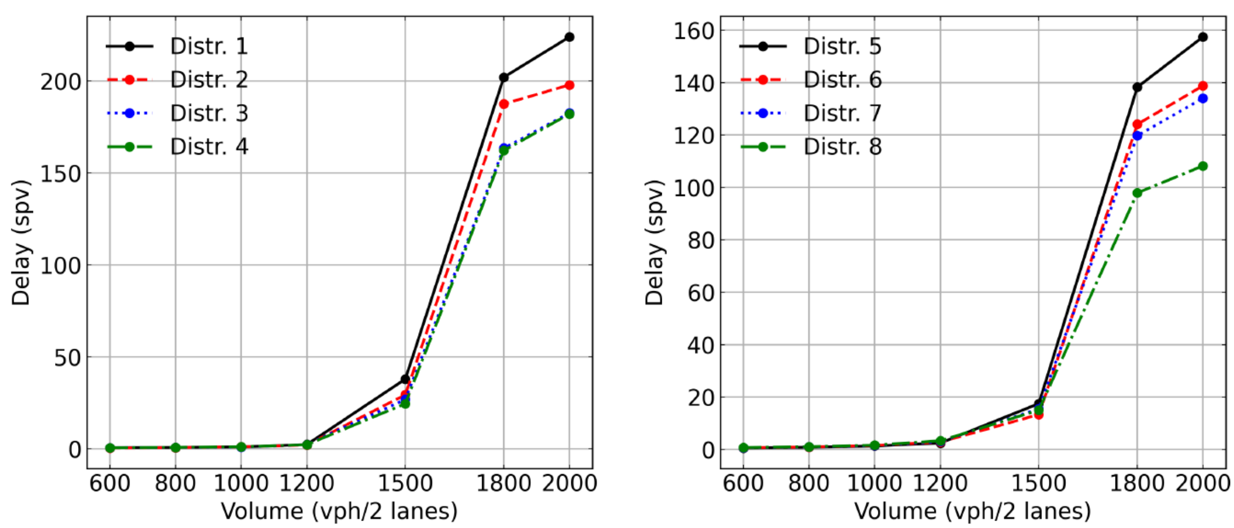
Figure 4.5 shows the LMTs versus traffic demands across all the distributions when MPR is set to 0%. The figure shows a nonlinear relationship between LMTs and volumes across all distributions, whereas different distributions show different levels of sensitivity to the increase in volumes. For example, distribution 1 is more sensitive to the increase in volume compared to distribution 4. Both figures show nonlinear increases in LMTs for volumes greater than 1,200 vph/2 lanes when the traffic flow is saturated. The effect of the compliance rate can be clearly seen when traffic demand is moderate or high, which is in line with the results in [14].

The reason behind this situation is that, when the density increases, the probability of finding a safety gap to merge decreases. As a result, drivers in the closed lane require more time and distance to merge into the open lane, leading to an increase in LMTs. The results indicate that different distributions might show different behaviors with the increase in traffic volume. The rate of LMTs increases when the rise in traffic demand is higher for distribution 1 and 5 in Figure 4.5. Comparing the results from distribution 6 and 7 shows a sharp increase in compliance reduces LMTs across all volumes. Regardless of different traffic volumes, employing distribution 8 yields the lowest LMTs across all the distributions. These results further reinforce that the warning delivery close to the work zone is not an effective option for roadways with heavy traffic demand. Further, they show that the compliance distributions for low traffic demands do not yield notable differences in LMTs. In Figure 4.5, the LMTs plateaus for almost all distributions as the volume increases from 1,800 to 2,000 vph/2 lanes , indicating a characteristic of highly saturated flow.



(a) LMTs vs. Volume (b) LMTs vs. Volume

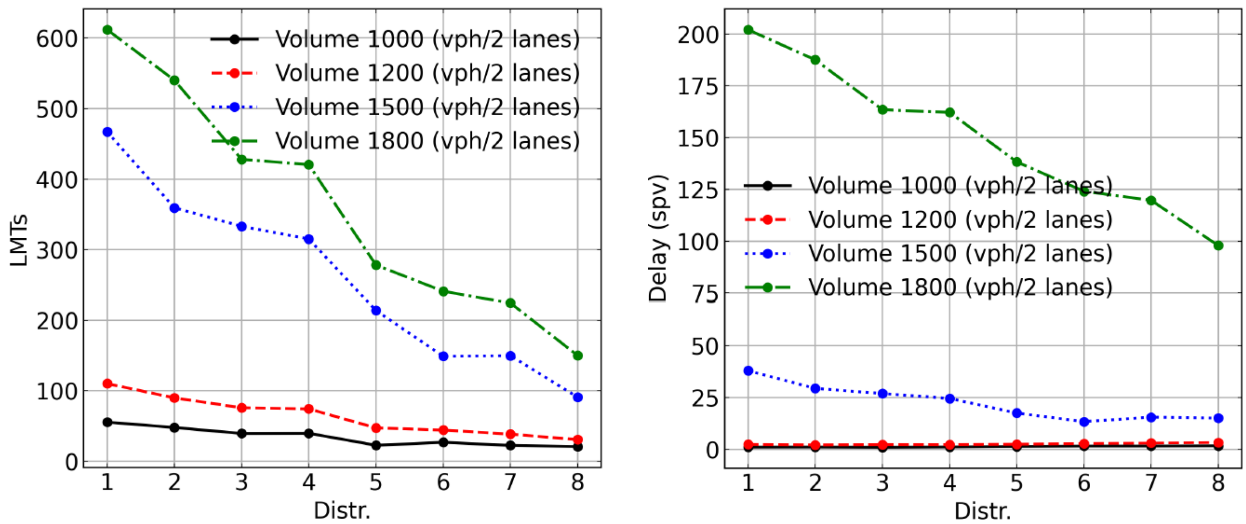
Figure 4.5: LMTs versus volume for different distributions under MPR = 0%.



(a) Delay vs. Volume (b) Delay vs. Volume

Figure 4.6: Delay versus volume for different distributions under MPR = 0%.

Figure 4.6 serves as the counterpart of Figure 4.5, illustrating the delay versus the input traffic for the spectrum of the studied compliance distributions under MPR of 0%. This figure shows that delay and LMTs are in direct correlation for all volumes with lower LMTs implying lower delay in traffic. Therefore, a lower number of LMTs results in smoother and speedier flow. The impact of different compliance rates on delay is minimal when traffic demand is low as shown in Figure 4.6, which is in line with the results in Figure 4.5. However, the placement of warning signs farther upstream of the work zone, coupled with higher compliance rates, decreases delay mainly when traffic demand is moderate or high. The results show a 28% and 34% improvement in delay, respectively, when transitioning from distribution 1 to distribution 4 and from distribution 5 to distribution 8 under saturated traffic with a volume of 2,000 vph/2 lanes.



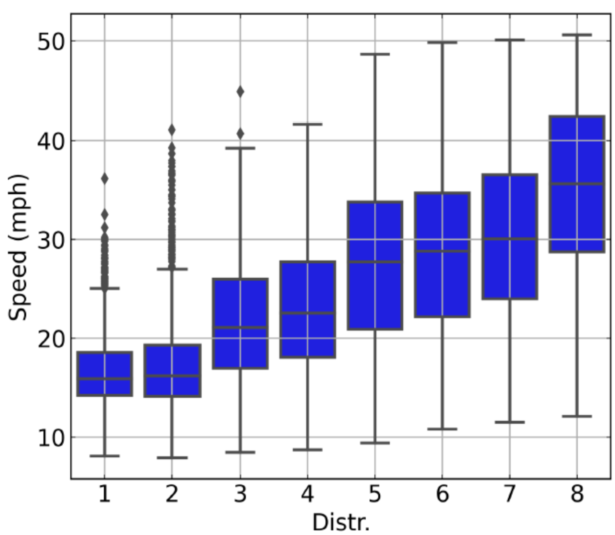
(a) LMTs vs. Distr. (b) Delay vs. Distr.

Figure 4.7: LMTs (left) and delay (right) for different distributions and traffic volumes under MPR = 0%.

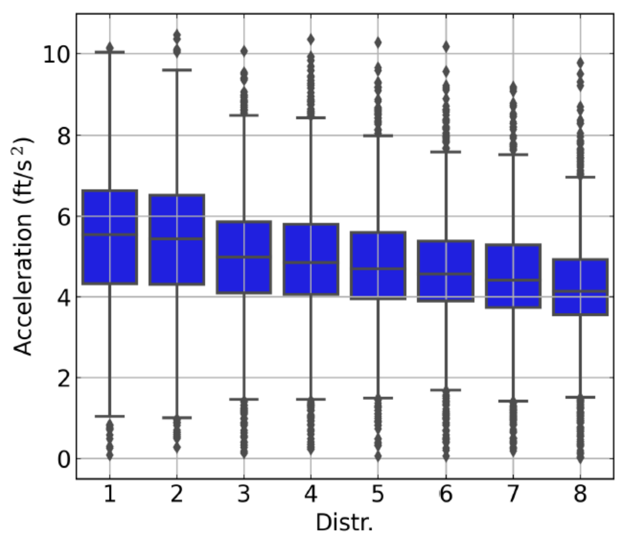
For a better illustration of early observations regarding the interconnection of compliance distributions and traffic congestion, Figure 4.7 shows the LMTs and delay versus the compliance distributions for a number of different volumes and MPR of 0%. Figure 4.7a shows that when the traffic is saturated and the density of traffic is high, LMTs increase in a nonlinear trend. Comparing LMTs across all distributions, we see a marginal increase when moving from a volume of 1,000 vph/2 lanes to 1,200 vph/2 lanes. This increase, however, is abrupt and pronounced when moving across to a volume of 1,500 vph/2 lanes and above. The results for distribution 1 show that leaving the warning sign too close to the work zone can result in high LMTs and congested traffic even for full driver compliance. The result for distribution 3 shows improvement over distribution 2, while both distributions have 20% compliance at 600 ft upstream of the work zone, which indicates that a sharp increase in compliance farther from the work zone can reduce the number of LMTs in congested traffic. Distribution 4 and distribution 8 both show a 60% reduction in LMTs compared to distribution 1 and distribution 5, respectively, when the volume is 1,800 vph/2 lanes. In these cases, the warning sign gives the drivers enough time and distance to merge to the destination lane. If the vehicles cannot find proper merging conditions, they will end up in the proximity of the work zone construction to complete merging to the open lane. Vehicles near the lane closure or the taper must either come to a full stop or take an aggressive maneuver to complete the merging process.

Distribution 8 can significantly reduce LMTs among all the traffic volumes, which reinforces that farther placement of the warning delivery when combined with a high compliance rate can improve the traffic condition. In these scenarios, the vehicles in the closed lane have enough time and distance to find a safe gap in the new lane that allows for executing the merge while maintaining a safe distance to the trailing vehicle before reaching the buffer space of activity area in the work zone.

Figure 4.7b displays a direct correlation between the delay and LMTs. A notable observation from this figure is nearly an order of magnitude increase in delay when the traffic volume rises from 1,500 vph/2 lanes to 1,800 vph/2 lanes, despite LMTs experiencing a relatively smaller increase. In addition, the trend of LMTs curves for the volumes 1,500 and 1,800 vph/2 lanes are almost the same, while it does not hold true for delay. The rate of change of delay across distribution for the volume of 1,500 vph/2 lanes is nearly flat compared to that of the volume at 1,800 vph/2 lanes. It shows that LMTs provides more detailed information in lower density regimes about the traffic situation compared to traffic indicator net delay.



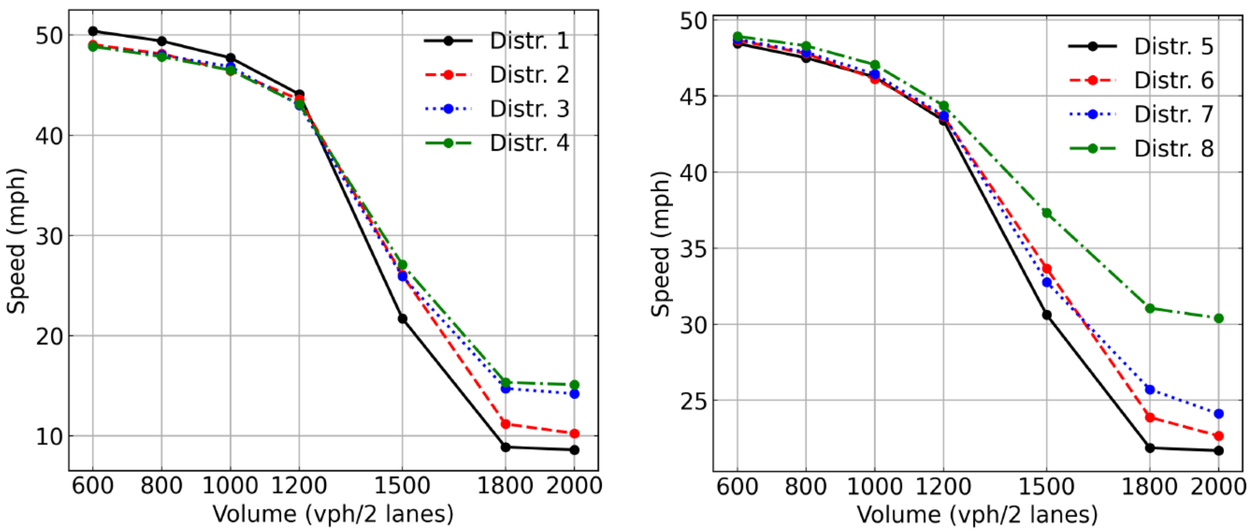
(a) Speed vs. Distr.



(b) Acceleration vs. Distr.

Figure 4.8: Traffic speed and acceleration at the bottleneck versus compliance distributions under traffic volume of 1,800 vph/2 lanes and MPR = 0%.

Figure 4.8 shows the variation of instantaneous acceleration and speed of vehicles at the bottleneck of the work zone area for the entire period of simulations. It shows how driver compliance contributes to driving regimes as indicated by the speed and acceleration. Higher speed and lower acceleration are an indication of a stable traffic flow and a smoother traffic transition from the advanced warning region near the taper to the activity area. Figure 4.8a shows that the median of the instantaneous speed of the drivers increases by 117% when compliance distribution transitions from distribution 1 to distribution 8. Likewise, it is seen from Figure 4.8b that the median of instantaneous acceleration is reduced by 28% when shifting from distribution 1 and distribution 8. The speed for distribution 1 shows a reduced range with a high number of outliers, which is an indication of congested traffic. The variation range for acceleration decreases, particularly with an increase in the number of outliers, when the compliance distribution shifts from distribution 1 to distribution 8, which indicates a shift towards more free-driving behaviors. In summary, when the drivers' compliance progresses from distribution 1 to distribution 8, the traffic flow transitions from congested and unstable to a flow regime that resembles a stable and free flow.



(a) Speed vs. Volume (b) Speed vs. Volume

Figure 4.9: Traffic speed at the bottleneck versus volume for different compliance distributions under MPR = 0%.

The result in Figure 4.9 displays the speed at the bottleneck of the work zone for MPR of 0%. This figure complements the observations from Figures 4.5 and 4.6. It shows that the speed at the bottleneck is highly affected by the compliance regime indicated by different distributions. For example, the speed increases by nearly 50% for the volume of 1,800 vph/2 lanes moving from distribution 5 to distribution 8. Placement of the warning signs near the work zone would decrease the probability of finding a safety gap to merge; hence, a queue is formed in the closed lane at the taper. Vehicles in the queue will have to perform forced merges, which significantly decreases the traffic speed at the work zone bottleneck. This phenomenon can be avoided by improving traffic speed, placing warning signs farther away from the lane closure, and adopting strategies to improve compliance rates. This observation is in line with [21], which sowed that placement of traffic lights sufficiently upstream of the merge area in work zones allows vehicles to pass through the merge area more efficiently.

Figure 4.10 shows speed-LMT relationship corresponding to Figure 4.5. This figure shows that the speed in the open lane is inversely and linearly correlated with LMTs due to the fact that a higher LMTs shows a higher number of vehicles near the lane closure that want to merge to the open lane. Therefore, it significantly reduces the speed at the bottleneck of the open lane due to either forced or cooperative merging. Similarly, Figure 4.11 shows the traffic throughput versus LMTs for all distributions, revealing the correlation between throughput and LMTs. While Figure 4.10 reveals a linear dependency between LMTs and speed, Figure 4.11 demonstrates a nonlinear correlation between LMTs and throughput. These observations show that LMTs can be used as an indicator for traffic mobility in work zone areas.

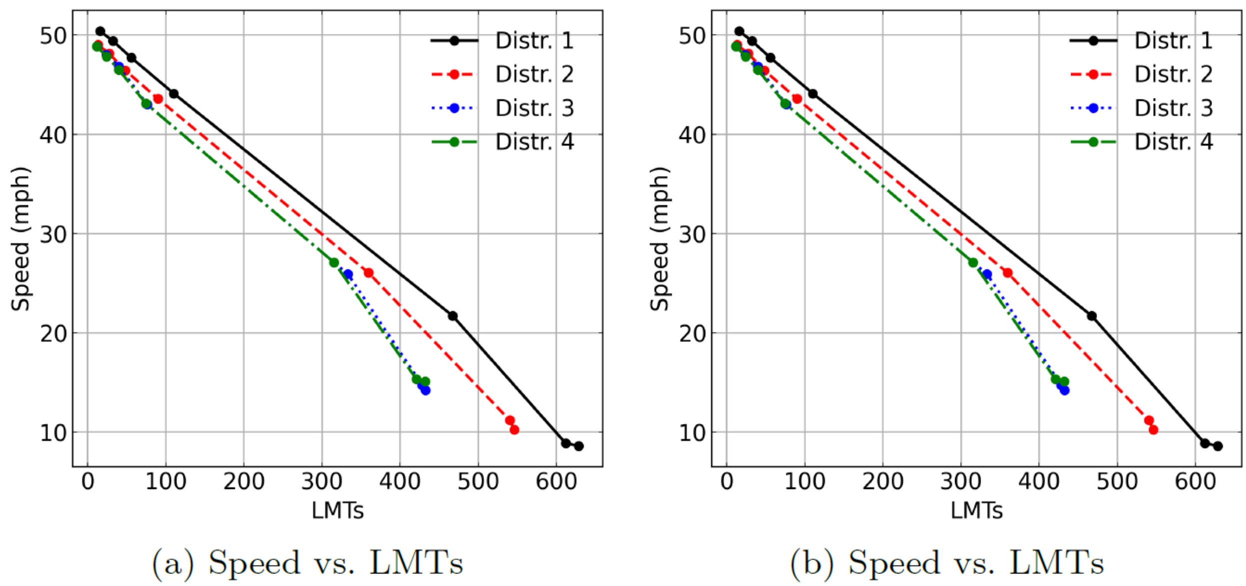
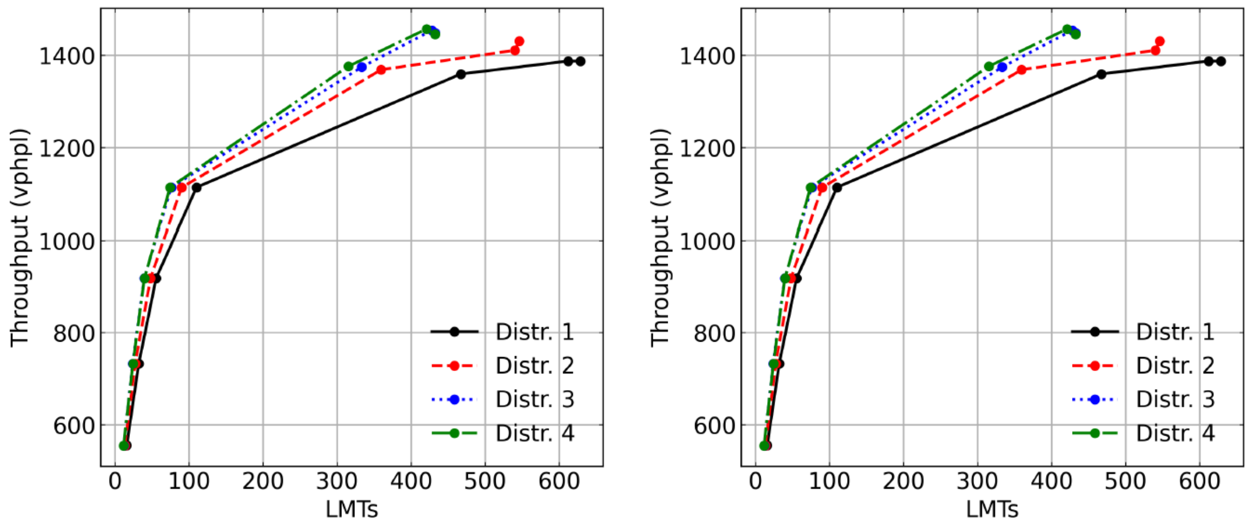


Figure 4.10: Speed at the bottleneck versus LMTs for different distributions under MPR = 0%.



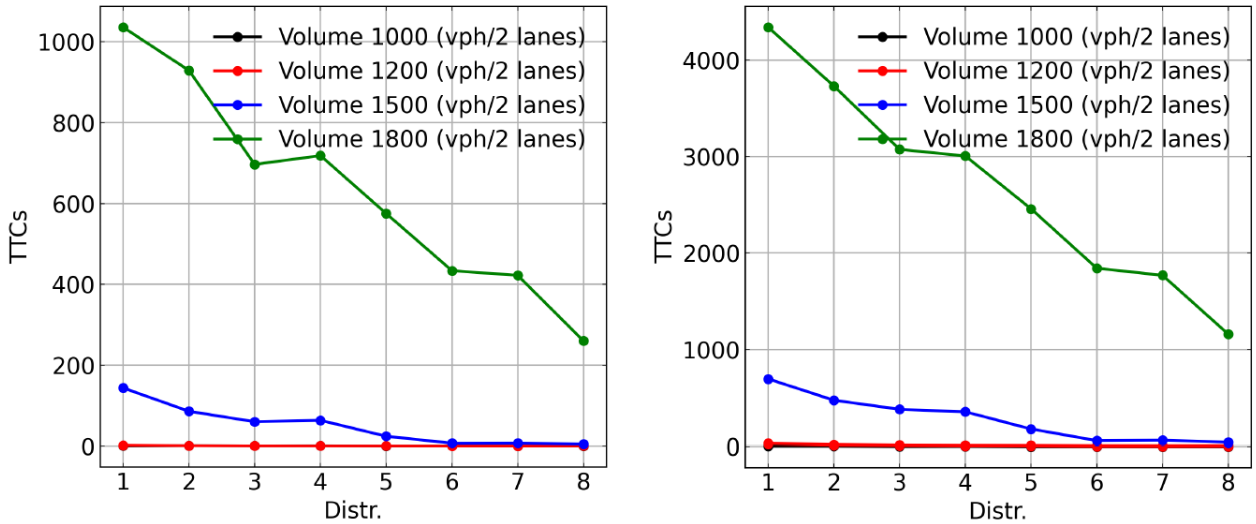
(a) Throughput vs. LMTs (b) Throughput vs. LMTs

Figure 4.11: Throughput versus LMTs for different compliance distributions under MPR = 0%.

Here, for brevity, we limited our discussion to 0% MPR and a 2% truck ratio. We have done additional analysis to include the effect of other MPR values to consider future scenarios when AVs materialize. We have further considered other truck ratios (10%, 20%) for the sake of completeness of our analysis. These analysis results are not included in this report but are available upon request.

Correlation between TTCs and LMTs

In this section we explore the safety of the work zone across different compliance distributions using surrogate safety index TTCs. In this context, TTCs shows the number of vehicles with time to collision less than the thresholds t_c across all the work zone from the advanced warning area to the termination area. Figure 4.12 shows TTCs versus compliance distributions of the drivers for selected traffic volumes for t_c = 1.5s and t_c = 2.5s under an MPR level of 0%.

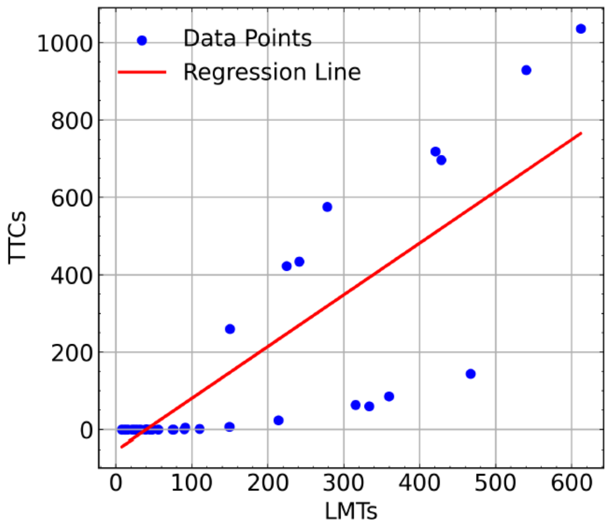


(a) TTCs vs. Distr. for $tc = 1.5s$ (b) TTCs vs. Distr. for $tc = 2.5s$

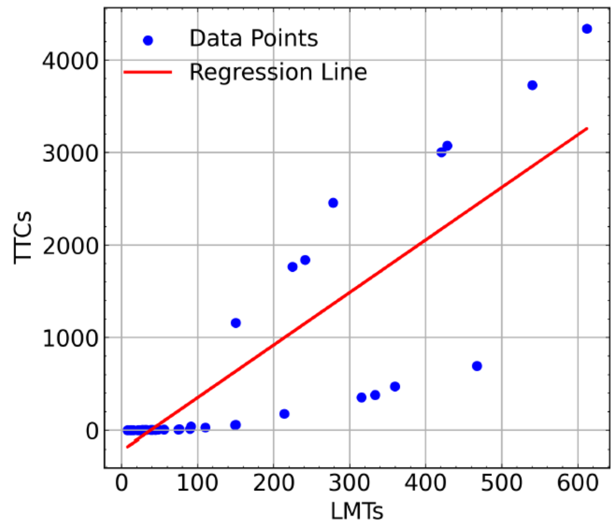
Figure 4.12. TTCs for tc = 1.5s (left) and tc = 2.5s (right) versus different distributions for selected traffic volumes under MPR = 0%.

The results show that the distribution transition from distribution 1 to distribution 8 for traffic volume of 1800 vph/2 lanes improves the TTCs by 75% and 73% for t_c = 1.5s and t_c = 2.5s, respectively. In Figure 4.12 a notable observation is the sudden increase of TTCs between traffic volumes of 1,500 vph/2 lanes and 1,800 vph/2 lanes, whereas in Figure 4.7 LMTs shows a gradual rise over these volume ranges. In particular, the LMTs from these two input traffic volumes is closer compared to TTCs in Figure 4.12.

Figure 4.13 shows the scatter plots of LMTs versus TTCs for all compliance distributions, traffic volumes and truck proportions in Table 4.1 under MPR of 0%. The blue circles in Figure 4.13 show the TTCs versus LMTs for each scenario and the red line represents the linear regression curve to forecast TTCs from LMTs. We use the thresholds of t_c = 1.5s and t_c = 2.5s for Figures 4.13a and 4.13b, respectively. The results show that LMTs is closely related to the surrogate safety measure TTCs. An increase in LMTs leads to an increase in TTCs and a reduction of LMTs results in fewer estimated TTCs in the traffic. This finding provides evidence that higher LMTs in driving regimes increases crash likelihood. These observations show LMTs can be used as a surrogate indicator for roadway safety in the work zone areas.



(a) TTCs vs. LMTs for $tc = 1.5s$



(b) TTCs vs. LMTs for $tc = 2.5s$

Figure 4.13: Scatter plot of TTCs versus LMTs. The red line shows the regression line.

Conclusions of the Traffic Simulation Study

We studied the intercorrelation of drivers' compliance with warning signs for merging and late merges at the taper in the work zone. The presence of LMTs not only increases safety risks within the work zone and impacts upstream traffic but also poses a direct threat to the safety of workers in the work zone. We developed a microsimulation framework to investigate the relationship between drivers' compliance and traffic safety and performance measurements. We comprehensively evaluated our simulation framework by considering different work zone configurations, MPR levels, and SRF levels. The study examined the correlation between LMTs and TTCs as a surrogate indicator of roadway safety, revealing a positive correlation between these measures.

The primary observations and findings of our empirical investigation are summarized as follows:

- For low to moderate traffic conditions, traffic is less sensitive to the location of warning signs and the compliance distribution of drivers.
- In high-volume traffic conditions, increased compliance with maintaining a greater distance from the downstream work zone leads to improvements in both LMTs and traffic net delay.
- The high compliance ratio far from the work zone results in an improved density-flow relationship for the traffic flow, which results in higher traffic capacity at the work zone.

- The results show 50%, 75%, 97%, and 80%, reduction in delay with the MPR levels of 0%, 20%, 50%, and 80%, respectively, when the drivers' compliance transitions from distribution 1 to distribution 8 under traffic demand of 1,800 vph/2 lanes and truck ratio of 2%.
- The experiments demonstrate a 6%, 12%, 6%, and 0.6% improvement in throughput and a 500%, 700%, 300%, and 21% increase in speed at the bottleneck of the work zone correspondingly for MPR levels of 0%, 20%, 50%, and 80% when the distribution of drivers' compliance shifts from distribution 1 to distribution 8 under traffic demand of 1,800 vph/2 lanes and truck ratio of 2%.
- The warning distance has a more significant impact on high-autonomy traffic compared to achieving full compliance with a short-distance warning sign upstream of the work zone.
- LMTs are positively correlated with traffic delay and density and are inversely correlated with the speed at the bottleneck.
- The rate of increase for LMTs with respect to traffic demand is higher for saturated traffic compared to unsaturated traffic conditions.
- An increase in LMTs might lead to maintaining the traffic throughput due to cooperative merging; however, it decreases the speed of traffic at the bottleneck of the open lane due to vehicles merging into the open lane.
- An MPR of 50% and above will cause a significant reduction in LMTs and a reduced delay and improved throughput.
- The role of compliance distribution is more pronounced in low truck ratio regimes, serving to offset the impact of the MPR level, especially when compared to high truck ratio scenarios.
- A distanced warning, coupled with high compliance, is more effective in reducing LMTs in traffic with a high truck ratio compared to achieving full compliance with warnings in closer proximity to the taper.
- The TTC reduction is 75% when the compliance distribution of vehicles transitions from distribution 1 to distribution 8 under the MPR level of 0%.
- A positive correlation exists between TTCs and LMTs, and LMTs can be used as a proxy indicator for work zone safety.
- The feature importance analysis of the highly-performing predictive models, developed using simulation results, shows that traffic characteristics like traffic volume and drivers' compliance distribution are the most significant variables that impact the prediction of LMTs.

Recommendations for Camera and Message Board Placement

The optimization of the camera and message board placement is an important aspect of our system design, aiming at maximizing safety by accounting for the latency inherent in vehicle detection and message transmission as well as ease of implementation. Through our simulations, we have found that an early presentation of the message to the driver correlates with enhanced safety for road users. This insight has led us to propose two placement schemes illustrated in Figures 4.14 and 4.15.

We begin by explaining the existing signage placement guidelines in work zones involving a lane closure. The current guideline forms the basis for our proposed schemes. Referencing Figures 4.14 and 4.15, the taper length stretches 900 feet from the beginning of work zone to Point 1 which accommodates a merge arrow sign which constitutes the fourth sign presented to the drivers. Following this, the third sign, a lane closure warning, is located 1,050 feet away from Point 1. This sign is followed (upstream) by two more signs: the second sign to the drivers is a warning about right lane closure, positioned 1,500 feet before the merge lane sign (third sign), and the first sign to the drivers, alerting about the upcoming road work, is situated 2,640 feet further upstream from the second sign (lane closure warning).

The first proposed arrangement of targeted message board and camera system aims to integrate seamlessly with existing guidelines, leveraging current locations of passive signages without necessitating new placements. This positioning may be more desirable given the minimal modifications it introduces to the existing practices. In this approach, only the number of items placed at two locations will be different from conventional practice.

The second scheme adopts a more proactive approach by placing the message board farther upstream, requiring an additional placement for the camera. This approach is grounded purely in our simulation results indicating that increased lead time for targeted message display improves road safety.

The following sections detail the proposed placement methodologies.

Message board and Camera Placement Considerations

The proposed placement schemes take into account factors related to vehicle speed, driver reaction time, and the system's processing and transmission delays. With the assumption of highway conditions and that the target vehicle is traveling at 60 mph (88 ft/sec), we have:

Trigger Distance: A span of 100 feet is set for the camera and radar activation upon which the system captures vehicle image and speed. The raw data are later used for detection and message composition, which corresponds to roughly 1.1 s.

Processing and Transmission Time: The system then processes the captured image to extract the license plate information and vehicle make and model. The extracted data form the basis for message composition, which is then relayed to the message board. Even though our tests indicate that virtual message boards present messages within the trigger distance on highway, the addition of a detection and transmission buffer is prudent to ensure the reliability of message transmission to physical boards. We allocate 1.1 more seconds (approximately 100 feet) for processing and transmission. Given our preliminary test results, this is a very conservative assumption.

Driver PIEV Time: Upon message display, drivers require adequate time for perception, identification, emotion, and volition (PIEV). For example, when a dynamic stop sign message appears, drivers must first perceive the sign visually, identify it as a stop command, emotionally process the urgency or need to stop, and finally decide to initiate the braking action. Referring to the warning sign placement guidelines published by Federal Highway Administration [23], the positioning should ensure a PIEV duration of 14.0 to 14.5 seconds for vehicles traveling at 60 mph, minus the legibility distance of 175 feet. Hence, the placement of the message board must be a minimum of 1,050 feet from the construction zone (beginning of taper) given 60 mph travelling speeds and 14.0 seconds PIEV. This minimum distance requirement mandates the positioning of the message board at or before the third warning sign. Consequently, we evaluate two schemes for message board placement: at the third and alternatively, at the location of the seconds warning sign.

Legibility & Visibility: Legibility is defined as the maximum distance at which drivers can accurately read message boards. California Manual on Uniform Traffic Control Devices (MUTCD) guidelines and Caltrans specifications mandate a minimum legibility distance of 750 feet and a visibility distance of 1,500 feet [24]. When the message can potentially be displayed earlier than its visibility range, we apply a legibility timing adjustment delay (LTAD) to ensure that messages are presented after vehicles enter the legibility distance.

Placement Scheme 1

Scheme 1, depicted in Figure 4.14, positions the message board at Point 2, adjacent to the third sign (merge warning sign), and situates the camera at Point 4, near the second sign (right lane closure warning). Vehicles approaching Point 4 trigger the camera from 100 feet. The first 100 feet beyond the camera, leading up to Point 2, are dedicated to message transmission, resulting in 1,400 feet from Point 2 to Point 3 for message display. Since 1,400 feet exceeds the legibility distance of 750 feet, the LTAD distance is set at 650 feet to adjust the message timing, ensuring it appears when vehicles enter the legible range. This arrangement meets the minimum PIEV time requirements without necessitating additional placements. It should be noted, however, that in practice the system may detect vehicles consecutively with a few second gaps in between. Therefore, it may not be practical to display a single message targeting a specific driver continuously for a long period of time. The optimal duration of targeted message display will be investigated as part of the implementation phase of this research (not within the scope of this work).

Placement Scheme 2

Scheme 2, shown in Figure 4.15, adopts a more proactive positioning for the camera at an earlier point, corresponding with the "Right Lane Closed" warning sign at Point 2. This targeted message sign placement allows for more reaction time and better complies with our simulation-based findings and recommendations.

We introduce an extra placement location for the camera, marked as Point 4. The 750 feet between Points 2 and 3 is in accordance with the legibility requirement. In other words, the message is displayed on the message board when the vehicle enters the legibility distance of 750 feet. The message display can be displayed to the driver for up to a maximum of 8.5 s (assuming 60 mph vehicle speed). Whether to use the maximum available display time to maintain the same targeted message or switch to the next message after $t < 8.5$ s is a topic of investigation and will be addressed in the next phase of this research (outside the scope of this project). The distance between Points 3 and 4 serves as a transmission buffer, mirroring the first scheme, with the stretch from Point 4 to 5 acting as the trigger distance.

Scheme 2 focuses on earlier detection and message display, maximizing the reaction period for drivers to respond to impending road conditions, thus improving road safety. Additionally, the 750-feet message display segment equal to the 750-feet legibility distance supports more immediate message updates than Scheme 1 and avoids the need for artificially delaying the message display. It is noted that in the previous scheme we are inherently assuming that the detected vehicle continues to remain on the closed lane for an additional 7.3 seconds (following detection) within LTAD before being presented with the targeted warning message.

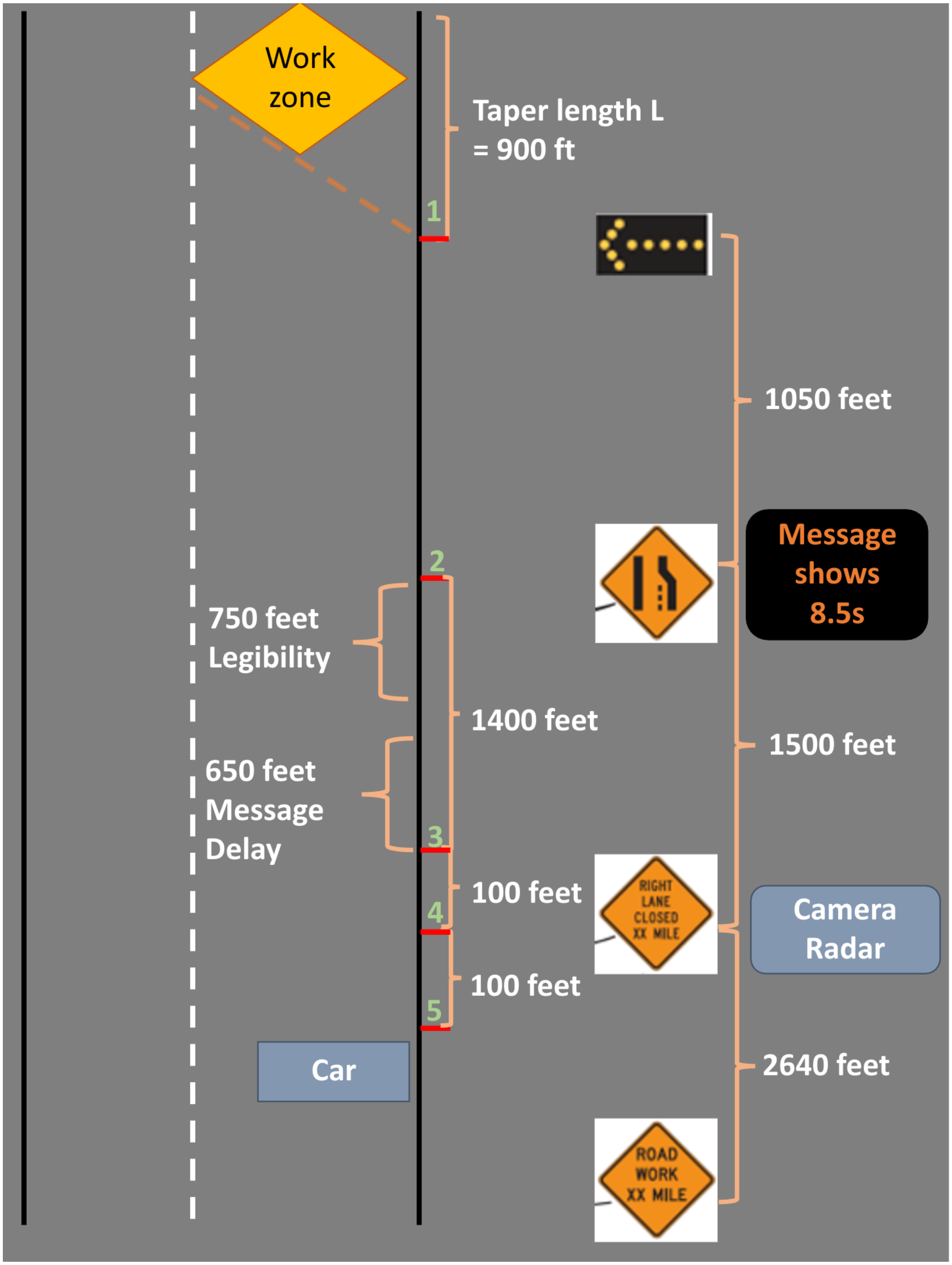


Figure 4.14: Placement Scheme 1

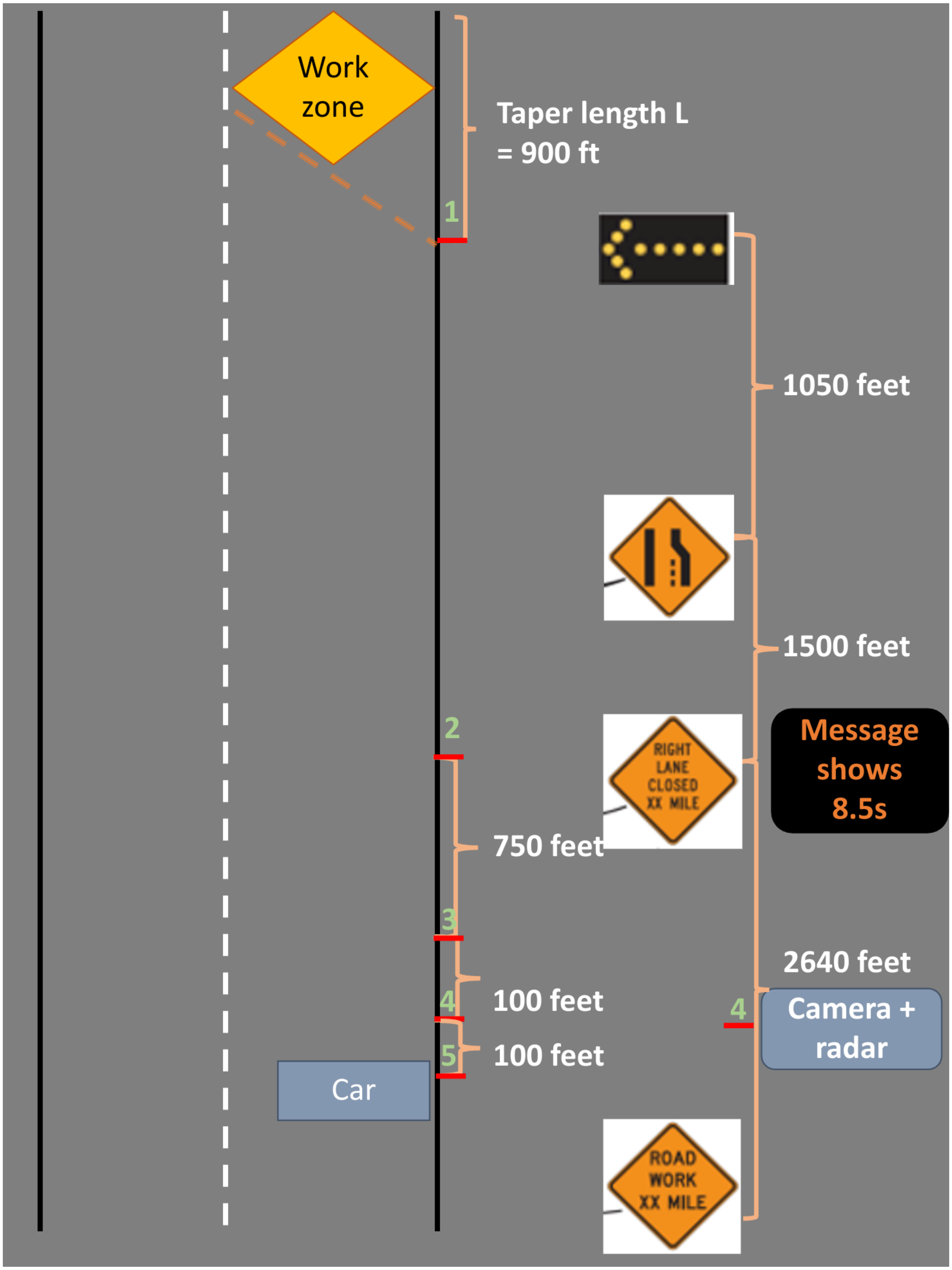


Figure 4.15: Placement Scheme 2

Chapter 5 Field Tests and Results

We carried out nearly 30 comprehensive field tests in total for Milesight and VIDAR cameras across diverse roadway conditions and during both day and night. The main goals were to assess and enhance (via proper calibration) the LPR and VMMR capabilities and to evaluate the message generation system. This section details the deployment approach for both camera systems, the test methodologies and procedures we employed, the software developments to facilitate field tests, message generation, and data analysis, as well as the results obtained from these field tests.

Milesight Field Tests

We performed 16 comprehensive field tests for the Milesight camera with the primary aim of assessing and maximizing its performance across various environmental conditions and camera configurations. Throughout the experiments, we aimed to identify optimal settings that maximize performance, e.g., accuracy, in detection outcomes. The findings of this evaluation are documented in Table 5.1, which details deployment methodologies and provides an analysis on performance-influencing factors.

Deployment

The tests were conducted in freeway and highway environments, focusing on both single-direction and dual-direction two-lane roads. Priority was given to the lane nearest to the deployment site for detection purposes. The Milesight camera was mounted on a 3.6-m pole affixed to a pickup truck (Figure 5.1) positioned approximately 2 m from the target lane on the road shoulder. The camera was mounted on a remote-controlled pan/tilt stage that allowed for controlling the camera perspective from within the vehicle.


Figure 5.1: Milesight field test deployment on a pickup truck

Software Development

Real-Time Access to Detection Results

There is a need for immediate access to camera detection results, including LPR, VMMR, vehicle colors, and types. These data points are essential for generating accurate and timely warning messages for vehicles. A significant challenge arose from the lack of direct access to the product's internal API, which is necessary for fetching these detection results efficiently.

To overcome this limitation, our development team devised a two-stage strategy focusing on the creation of a bespoke software system. This system is designed to interface with the Milesight camera, facilitating the real-time retrieval of detection data. The software architecture encompasses a front-end UI and a back-end data collector, ensuring seamless operation and user experience. The code for real-time camera data access is available at https://github.com/Soltanilara/Targeted-Warning-Message

Approach 1: Using Selenium WebDriver

The initial phase of backend development leveraged the Selenium WebDriver to simulate user interactions with the Milesight UI. These interactions included adjusting camera settings, navigating through the UI, and extracting data directly from the displayed information. Figure 5.2-left schematically demonstrates this approach. While it enabled us to access the needed detection results, it suffered from some drawbacks. The reliance on UI simulation introduced delays and presented reliability issues as the process was inherently slower and less stable than direct data access methods.

Approach 2: Direct Data Access without Internal APIs

Acknowledging the limitations of the first approach, our team adopted a more efficient method to circumvent the absence of internal API access. By analyzing and capturing the web requests sent by the Milesight UI to alter camera settings, we identified a viable pathway for data access. This method involved the packaging of these requests, encrypted with Digest authentication, to authenticate our backend system. This method, as illustrated in Figure 5.2-right, effectively mimics the original UI requests, thereby enabling direct and real-time access to the camera's detection results without the need for Selenium WebDriver.

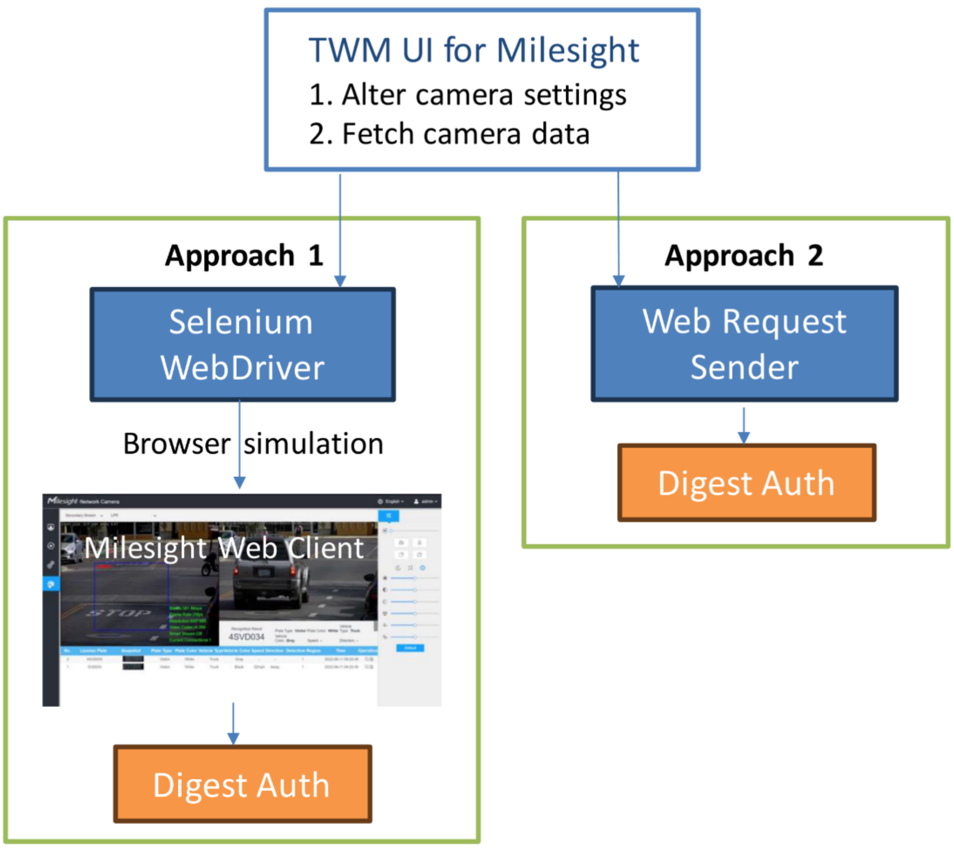


Figure 5.2: Real-time access to camera detection results: Approach 1 (left) based on Selenium WebDriver and approach 2 (right) directly accessing camera data.

Observations & Analysis

Field of View and Region of Interest

Initial observations highlighted a significant decrease in detection rates and an increase in detection lag when the camera's field of view encompassed vehicles in both lanes. An adjustment to the camera's zoom to 12x effectively narrowed the field of view to exclude the adjacent lane traffic, which significantly improved detection rates and reduced processing delay.

Bounding Box

Further testing revealed that a smaller bounding box size correlates with improved detection accuracy. Maintaining a confidence level of 1 and ensuring the bounding box does not touch the frame edges of the camera view minimized double detections. Adjusting the bounding box dimensions to cover the lane area of interest eliminated double detections as illustrated in Figure 5.3, which demonstrates an example bounding box (blue box on top left).

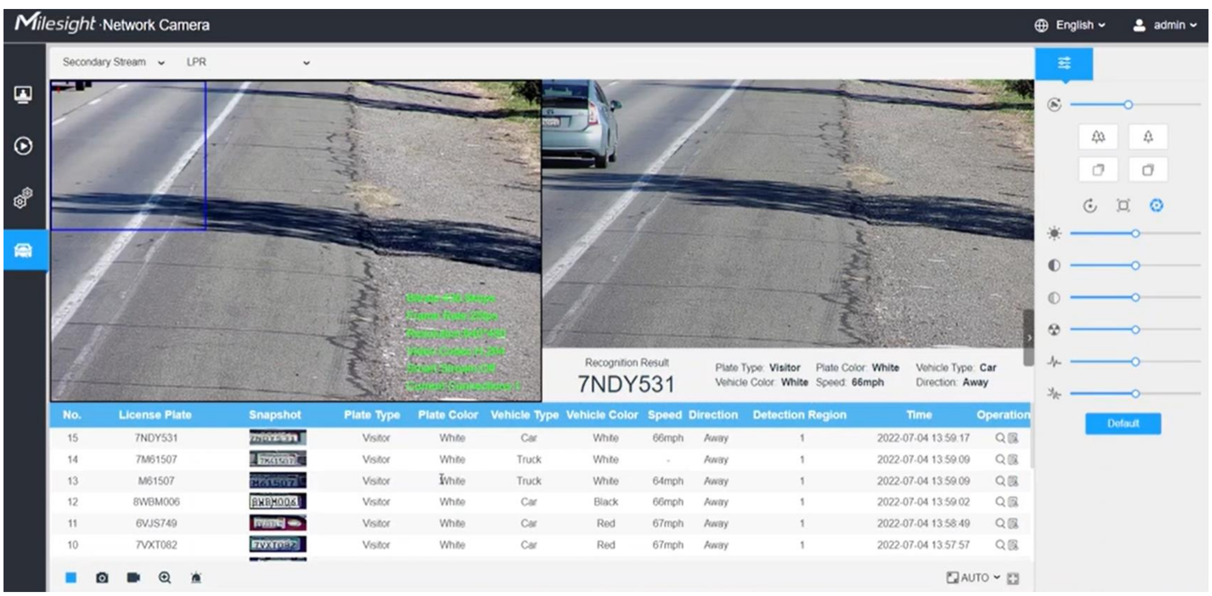


Figure 5.3: An example of using bounding boxes in Milesight.

Camera Focus

The clarity of camera focus was identified as a critical factor for successful detection. Tests indicated that a well-focused camera significantly enhances detection rates, underscoring the importance of proper camera calibration as it relates to clear focus.

License Plate Detection

Tests also indicated that a higher detection rate is obtained for front license plates compared to rear plates. This observation suggested that orienting the Milesight camera towards incoming vehicles may lead to better results.

Nighttime Detection

"Image Mode" is one adjustable parameter related to the lighting condition (daytime vs nighttime). Tests indicated that detection rates during nighttime improved with higher image mode levels, with a 0% detection rate at the lowest setting. This finding highlights the necessity for properly adjusting the image mode to accommodate the lighting condition for optimal detection performance.

Results & Conclusion

The Milesight system detects all the vehicles that pass by. Tests show acceptable LPR accuracy, performing well both during day and night times, with a notable increase in accuracy when vehicle speeds are also detected. During daytime, the LPR accuracy is 92.59%. It is noted that for some recognized license plates the camera fails to measure speed. We observed for those detected vehicles where a speed is properly measured by the camera, the LPR accuracy rises to 96.15%. At night, the system starts with an LPR accuracy of 72.46%, but when accompanied with successful speed detection, the LPR accuracy increases to 86.21%. The camera also reported the color of the detected vehicles, but it was often inaccurate, making it unusable for targeted message generation.

Table 5.1: Overall performance of Milesight

LPR Accuracies	With/Without Detected Speeds	With Detected Speeds	Settings
Day	92.59%	96.15%	1011*840 bounding box + LPR mode level off
Night	72.46%	86.21%	1015*840 bounding box + LPR mode level 5

VIDAR Field Tests

Deployment

For the purposes of the VIDAR evaluation, the deployment strategy mirrored that of the Milesight setup. The camera system was mounted atop a 3.6-meter pole, which was securely attached to a pickup truck. During field tests, the truck was positioned approximately 2 meters from the designated target lane, situated on the road shoulder to optimize detection capabilities (see Figures 5.4 and 5.5). Furthermore, the camera was placed on a remote-controlled pan/tilt stage to allow for fine adjustments of the camera. As shown in Figure 5.6, the pan-tilt stage is linked to a remote control, enabling adjustments to the camera's position and orientation from inside the truck. A Type-C data cable is provided with the camera, which was connected to a laptop. For data retrieval, it's necessary to configure the laptop's IP address to match the camera's local area network (LAN). Access to the camera's web interface is then available through a standard web browser.

Figure 5.4: Deployment illustration during daytime and nighttime.

Figure 5.5: The camera orientation and vehicle placement on the shoulder.

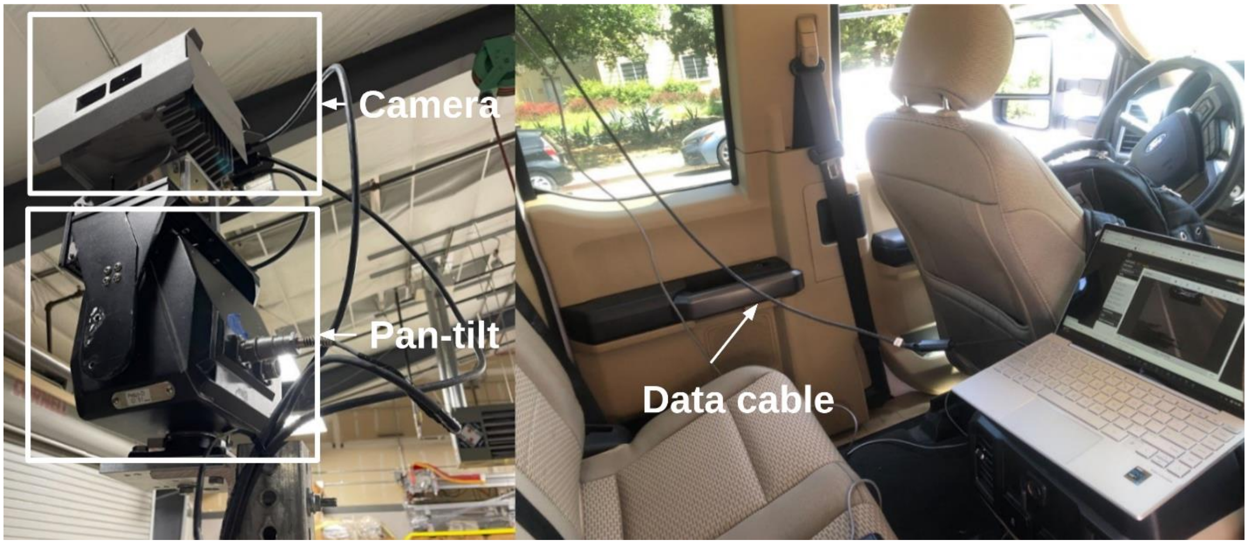


Figure 5.6: The camera is mounted on a pan-tilt, and connected to a laptop.

As illustrated in Figure 5.5, the camera is oriented to face incoming traffic. In this form, the camera can be placed closer to the message board, which may simplify the tasks of the work zone crew in setting up the system in the field. The camera trigger distance was set to approximately 100 feet, which ensured the camera's detection model activates prior to the vehicle passing by the camera, allowing sufficient time for message generation and transmission to the message board and a more compact placement of the camera and the message board.

Although nighttime performance fell outside the scope of this research, in several field trials we evaluated the nighttime performance of the camera. The results were not promising, especially when it comes to vehicle make, model, and color recognition. In very dark settings, often only the vehicle license plate is visible, making it impossible to extract any other vehicle-specific information. As shown in Figure 5.7, we further attempted to improve visibility using infrared projectors. However, this modification did not improve visibility of vehicle features. As discussed earlier, upon the availability of the license plate information, it is still possible to extract vehicle specific information via database servers, such as those managed by the DMV. As noted before, this approach can be explored when nighttime adoption is a requirement and upon collaboration between Caltrans and DMV for server access while in the field.

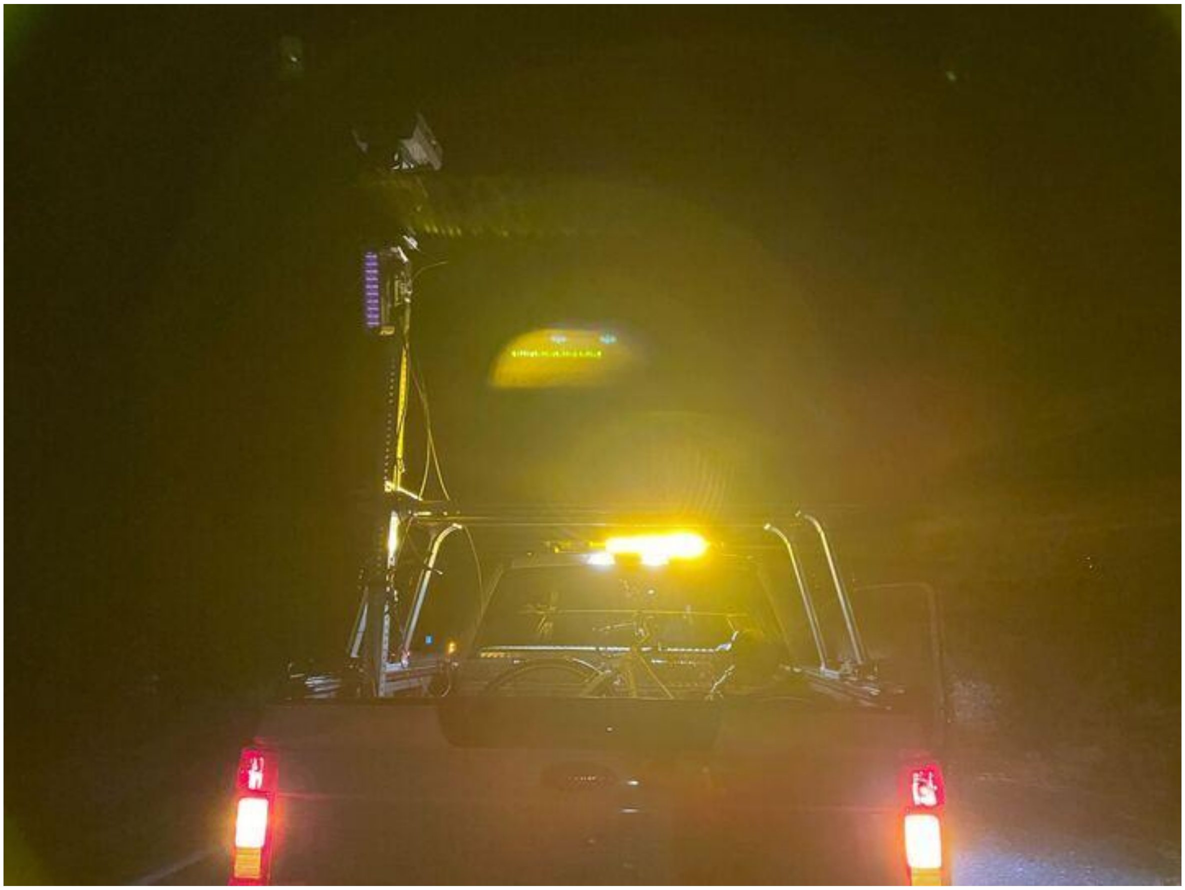


Figure 5.7: IR projector placement illustration.

Targeted Message System Development

System Design

The system is engineered to leverage VIDAR's capabilities for generating LPR/MMR events and speed data upon activation. A centralized server is tasked with receiving these events and formulating warning messages tailored to the specifics of each event. Although a physical message board has not yet been acquired, the system is designed to accommodate a virtual message board, which can later (during implementation phase) be extended to a physical board.

The system architecture is depicted in Figure 5.8, highlighting the workflow from event generation to message dissemination.

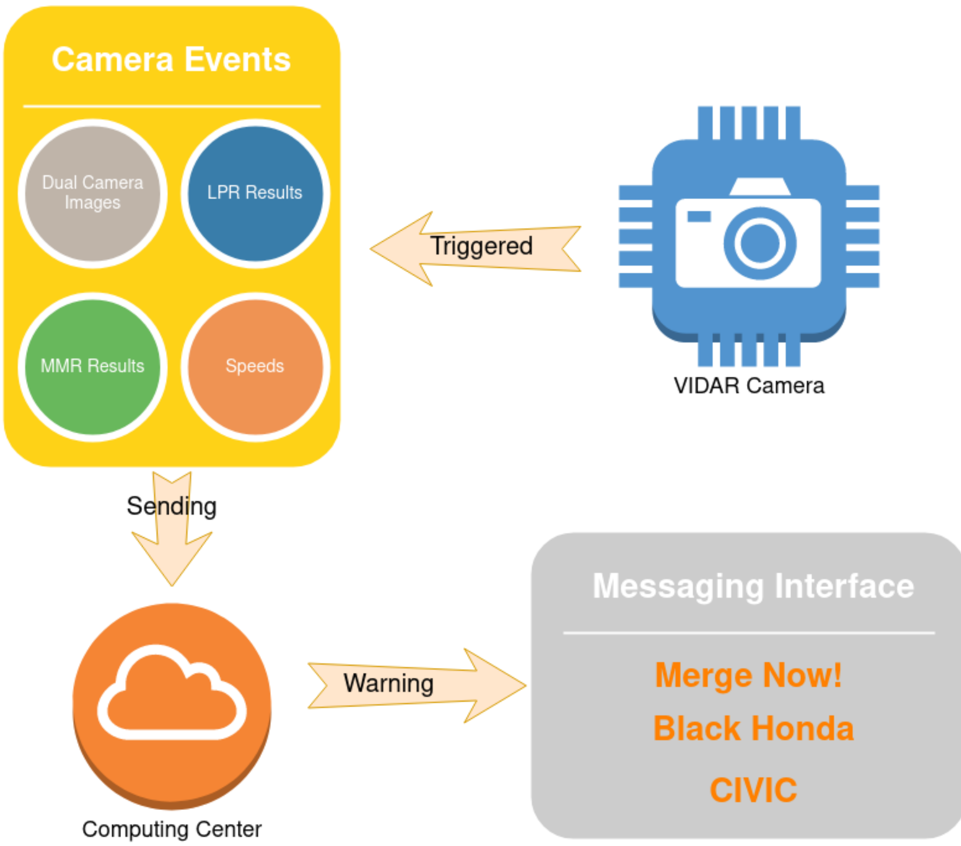


Figure 5.8: A centralized server is developed and deployed to fetch real-time detection results from VIDAR and subsequently generate targeted messages.

To ensure prompt communication, the system continuously monitors for new events, employing a mechanism to regularly check for events by incrementing the last known event ID. This process, occurring within milliseconds (ranging from 0.01 s to 0.05 s), allows for rapid processing of incoming data. An event queue is utilized to calculate average vehicle speeds over a set interval in case a targeted message aims to use speed information in message generation either directly (speed display) or indirectly (Black Honda reduce speed!). The message composer then formats this information for delivery to the message board via its API (see Figure 5.9).

Virtual Message Board Design Specifications

In the development of our virtual traffic message board, we aimed to emulate the specifications of a real-world traffic message board closely. This process involved not only the replication of visual aesthetics and functionalities but also ensuring that our virtual model could simulate operational characteristics pertinent to field applications, including panel display ratio, character number per line, and font size. Our implementation enables users to customize the virtual board's settings to match various product specifications seamlessly.

For instance, the virtual board utilized in our field tests is modeled after VerMac PCMS-1500, a full-matrix portable message board. Its display ratio is approximately 1.74, accommodating 8 to 11 characters per line depending on the font size selected. We've meticulously replicated these attributes within our virtual board design, offering the flexibility to adapt to and simulate other product designs with ease.

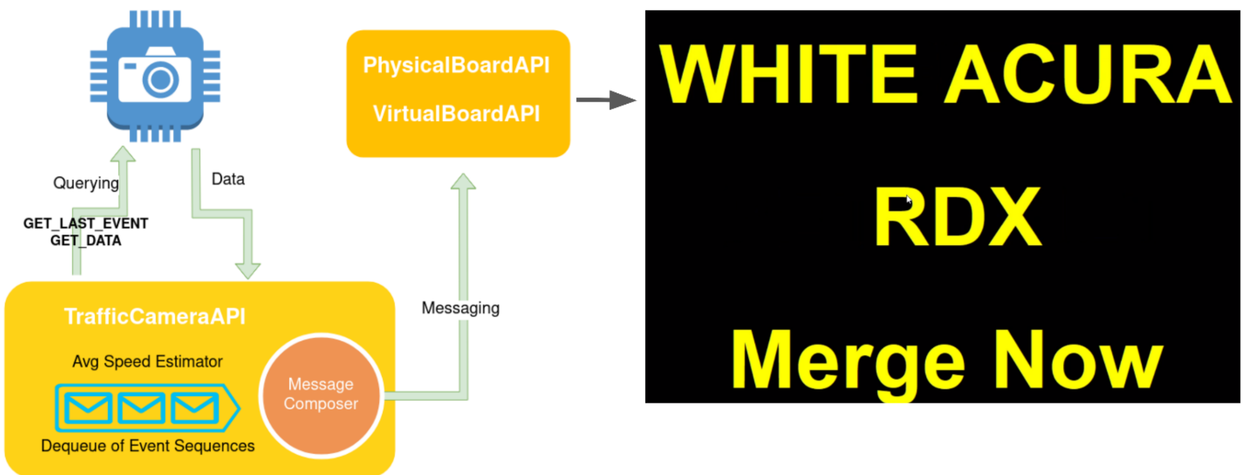


Figure 5.9: API design (left) and a virtual message example (right).

Deployment Considerations

The system's adaptability to varying traffic conditions was a key feature during our field tests. For high-speed environments, such as highways with average speeds of 70 mph, message boards are positioned father away from the detection camera to provide drivers with sufficient response time. Conversely, in lower-speed areas, like freeways with traffic moving at an average of 20 mph, message boards can be placed closer to the camera, ensuring timely visibility of the messages.

Message Composition

Recognizing the challenges drivers face in remembering and identifying their own license plates while driving, the system prioritizes vehicle color, make, and model in its messages. These elements are more easily recognized and processed by drivers at high speeds. License plate information is only included if critical identifiers are missing. This approach enhances message relevance and driver response time.

Additionally, the system's ability to incorporate speed data into messages enables the provision of "Slow Down" warnings, further enhancing road safety. The camera's lane differentiation capability ensures messages are directed to the appropriate lane, improving the precision and effectiveness of communication. In summary, the messaging system is designed with an emphasis on real-time data processing, flexible deployment, and the creation of intuitive, actionable messages for drivers.

We uploaded the implementation of the TWM message system to GitHub https://github.com/Soltanilara/MessageWarning

Observations & Analysis

Throughout the field experiments with VIDAR camera system, we engaged in numerous remote consultations with the supplier to optimize the performance of the system. The vendor engineers were available for discussions and improvements. This support, as noted earlier, is an important advantage of the VIDAR camera system. This section details the structured approach taken during the field trials, segmented into distinct stages, each with specific objectives, activities undertaken, and the outcomes achieved. Our methodology aimed to ensure that every aspect of the system's functionality was thoroughly vetted.

Stage 1: Preparation & System Setup

Objectives:

The primary aim was to acquaint ourselves with the device's configuration options, focusing on optimizing the settings for field of view, camera orientation, radar, and optics to enhance the system's effectiveness. This process included evaluating the system setup, particularly the camera's efficiency and accuracy in LPR and VMMR, under different lighting and road conditions.

Activities:

We conducted three remote sessions with the vendor, which facilitated a deeper understanding of the device's setup and was instrumental in refining the camera placement and adjusting the settings of the camera system.

We executed four preliminary tests, including two daytime tests and two nighttime tests, across freeways and highways. The tests aimed to assess the camera's capability in accurately executing LPR and VMMR on both single-direction and dual-direction roads.

Outcomes:

Daytime testing achieved a promising 100% accuracy rate in LPR and vehicle make identification among 19 vehicle samples, albeit with 12% discrepancies in model recognition. It is noted that even when the model is ambiguous, the vehicle make and color can be used in targeted message generation, which in many cases can still be as effective. The VIDAR camera was reliable and effective in extracting the vehicle information required for targeted warning message generation.

Nighttime testing, however, highlighted challenges with optical settings under low-light conditions. Captured images were overexposed or underexposed, leading to a reevaluation of the system's nighttime configuration.

Stage 2: Performance Improvement for nighttime

Objectives:

Given the suboptimal nighttime performance observed in Stage 1, our efforts pivoted towards enhancing the system's accuracy and reliability in low-light conditions. It is noted that the scope and focus of this study is limited to daytime conditions; although, our nighttime investigation can provide insight into future extension of a TWM system to nighttime settings.

Activities:

This stage included a strategic session with the vendor to explore potential improvements, adjustments in parameter settings, and the integration of an IR projector. Regular updates and feedback exchanges through the VIDAR Support Portal were important in this iterative improvement process. We conducted three additional nighttime tests on freeways and highways for data collection and diagnosis.

Outcomes:

Substantial improvements were noted with nighttime LPR accuracy exceeding 97%. However, the effectiveness of the IR projector in improving VMMR was limited, leading to its subsequent removal. As noted before, high LPR accuracy leaves the possibility of extracting vehicle-specific information by tapping into the license plate database managed by the DMV, meaning that, if needed in the future, the system can still be adopted for TWM generation in nighttime.

To highlight the pivotal factors contributing to the enhancement of nighttime performance, the adjustment of the iris parameter emerged as a critical element. After consulting with the vendor, we set this parameter to 380, resulting in significantly clearer nighttime imagery. Equally important was the adjustment of camera focus. Given the challenges of fine-tuning focus under low-light conditions, we adopted a pragmatic approach: conducting daytime tests prior to each nighttime session to adjust the camera focus accurately. These settings remained constant throughout the night, ensuring optimal performance.

Stage 3: Message Warning System

Objectives:

With the system demonstrating high accuracy in VMMR, the next phase focused on the development and testing of a message warning system, evaluating its clarity, informativeness, and response time.

Activities:

We focused on implementing and refining a warning message system capable of composing and transmitting targeted warnings to drivers via a virtual message board that we developed. This system was also designed to monitor vehicle speeds within the targeted lane, leveraging the rich metadata captured by the VIDAR camera system.

Tests were conducted on a dual-lane freeway to assess the system's ability to generate and display messages in real-time, based on LPR, VMMR, and color detection.

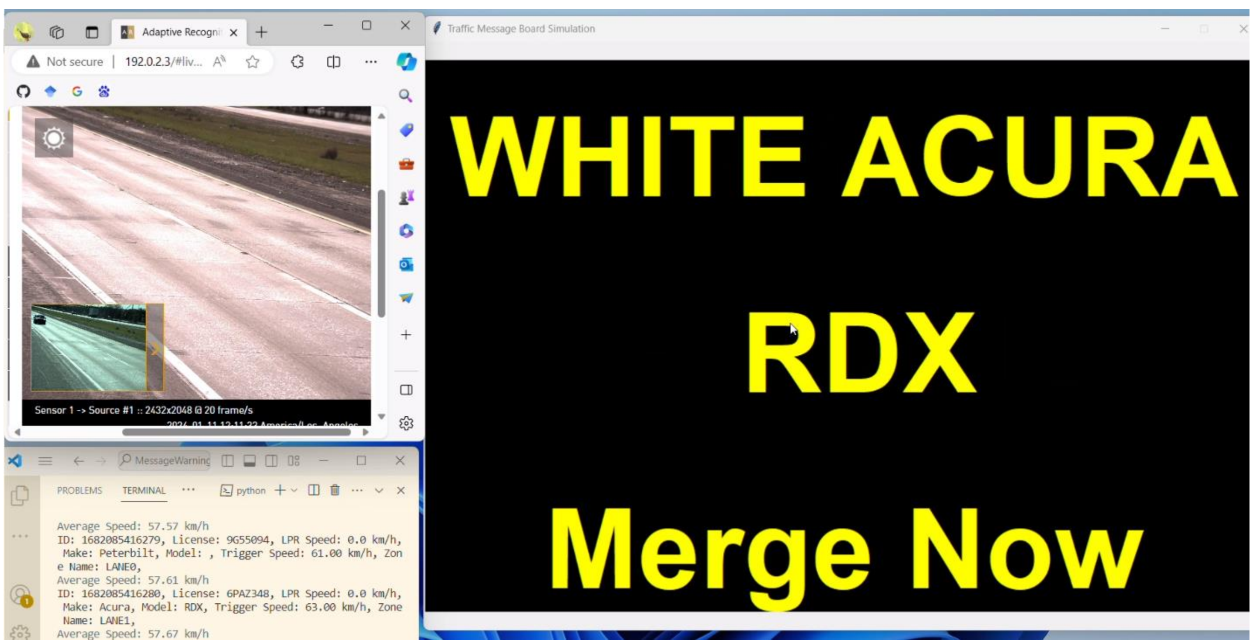


Figure 5.10: Camera streaming (top left); terminal outputs of LPR, VMMR, speeds of detected vehicles (bottom left); a virtual message board showing targeted message generated (right)

Outcomes:

In short, the system effectively displayed messages with an acceptable delay, demonstrating applicability for real-world application. However, challenges in color detection under varying lighting conditions were identified, highlighting areas for future improvement.

The effectiveness of this system was demonstrated through a series of tests, which showcased the system's capability to display messages approximately 5 to 7 m on the freeway before vehicles reached the camera, affirming that the message generation delay was within acceptable limits. We consistently monitored and recorded the individual vehicle speeds and average speeds for each lane to enrich our data, which can, in future studies, provide insights into the influence of messages to traffic flow given different deployment settings.

A critical test conducted on Highway 100A, a dual-lane road, showcased the system's proficiency in handling high-speed vehicles. Vehicles traveling at speeds around 70 mph were accurately detected, and pertinent vehicle information was transmitted and fetched by the system. The messages were successfully displayed as vehicles approached the camera's location, demonstrating the system's potential to alert drivers effectively in real-time. It is noted that in these evaluations, the virtual message board is, in essence, co-located with the camera. As discussed in Chapter 4, for field implementation, the message board is positioned away from the camera. As such, we anticipate that working with physical message boards is going to be less challenging in terms of meeting our timing requirements.

Data Processing

Data Processing and Model Development

To understand the LPR and VMMR capabilities of the VIDAR camera, we executed a comprehensive data collection endeavor, leading to 40GB of high-quality traffic footage obtained during the day and at night. Our field tests yielded over 10,000 camera trigger events collected from a highway and freeway, encompassing a wealth of data, including images, LPR, VMMR outputs, and additional metadata like lane positions, coordinates, color, and speed. This dataset was then curated to retain only high-quality events, resulting in a robust dataset of 4,000 events for detailed analysis and future research initiatives.

Annotation and Analysis Tools

To facilitate the detailed examination of these camera events, we developed a specialized software tool for annotating the license plate (LP) and make and model (MM) data. In this approach, the LP information is used to extract the true MM and compare those results with the MM detected by the camera. This process included the creation of a web-based Plate Search Tool, leveraging Selenium and Flask for automated real-time MM queries from available web services that provide access to vehicle information for a given license plate number. This tool allows for automated queries to a web service capable of retrieving vehicle specifications using LP information. A Python-based GUI further streamlines the annotation process.

As shown in Figure 5.11, our annotation software displays dual camera images alongside a focused view of the LP, with VIDAR's detection results listed for comparison on top right. Users compare the detected LP with the focused LP view to annotate “LPR Result” on the bottom right. Then users obtain ground-truth vehicle makes and models with a simple click on “Get Make & Model” button given the integration with Plate Search Tool. The tool automatically requests ground-truth vehicle information given the detected LP or manually calibrated LP. Fortunately, LP detection accuracy is over 93% to 97%; therefore, calibration is usually not needed. After the ground-truth MM is displayed, users compare the detection result with retrieved MM, and annotate “MMR Result”.

Figure 5.11 is an example showcasing the tool's UI, including camera data, ground-truth make, and model along with VIDAR's recognition results for comparison and annotation.

During our annotation process, we first filtered out low-quality data under suboptimal settings that led to invisible images or wrongly triggered events out of 4,000 events collected throughout all of VIDAR field tests. Then we manually annotated 522 samples uniformly sampled from the filtered dataset. These samples are generated with several combinations of camera settings that have demonstrated reliable and robust performance during both daytime and nighttime. The annotation software significantly facilitated efficient data labeling. We were able to build a dataset comprising 308 daytime and 214 nighttime samples for data analysis. The human annotation process allowed us to deepen our understanding of the camera performance with respect to different camera settings while looking closely at each individual sample.

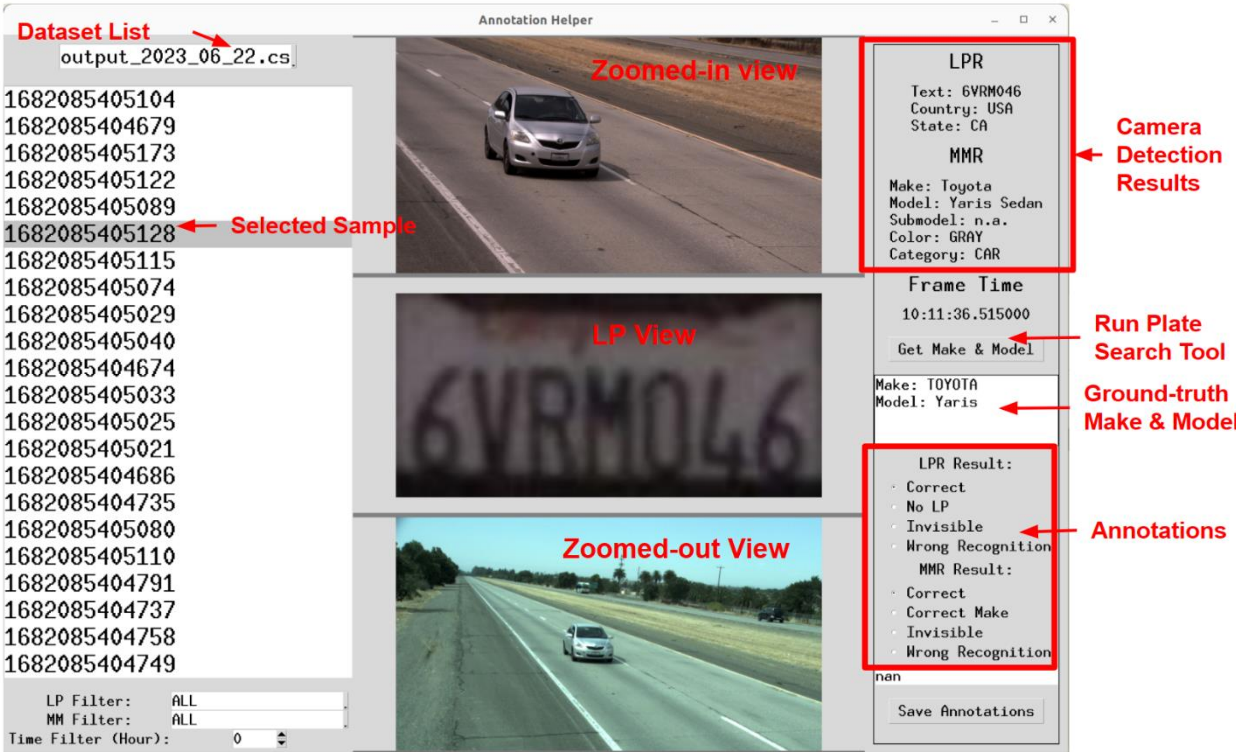


Figure 5.11: An example of our annotation software

Statistical Analysis and Insights

The annotated dataset enabled a comprehensive statistical analysis of VIDAR's performance under various conditions. Events were classified into categories such as INVISIBLE_LP (where LPs/MMs were undetectable or unclear even to humans), WRONG_RECOG (visible but incorrectly recognized LPs/MMs), NO_LP (vehicles without a visible LP to the camera), and CORRECT_MAKE (accurate make recognition but incorrect model). We showcase the percentage of each annotated category in Figure 5.13.

Beyond that, we recorded event indices alongside camera settings, which helped us identify optimal parameter settings given the statistical results. Through these analyses, as shown in Figure 5.14, we were able to chart the performance fluctuations of LPR/MMR over time, pinpointing the parameter adjustments corresponding to peak recognition accuracy.

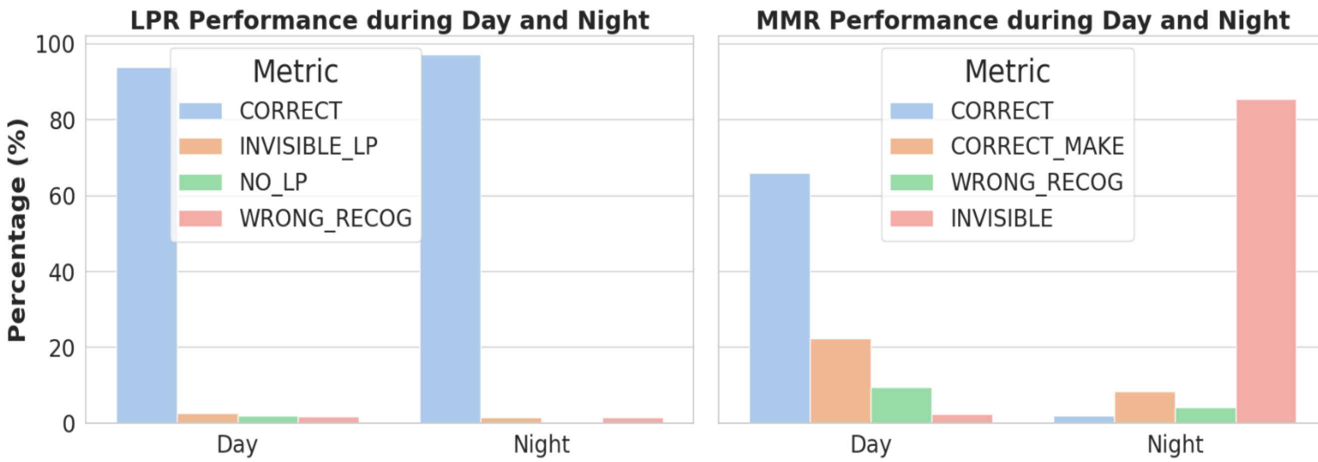


Figure 5.12: Performance statistics during daytime and nighttime.

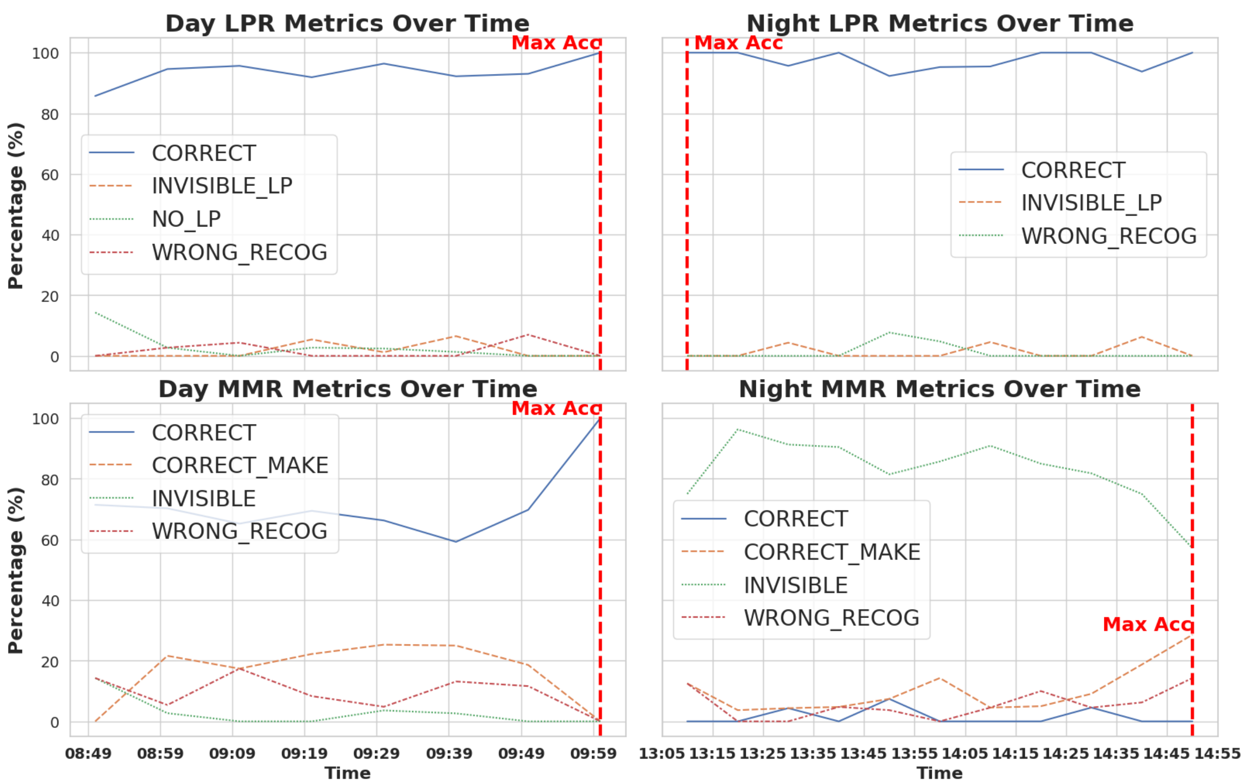


Figure 5.13: The change curve of the percentage of each annotated category over time.

The code for our plate information search tool, annotation tool, data analysis, and visualization for VIDAR are available at GitHub https://github.com/Soltanilara/TWM-Dataset

Results

The VIDAR camera demonstrates robust performance in LPR under varying lighting conditions. However, its VMMR and color detection capabilities are notably diminished in low-light scenarios, with VMMR and color detection showing a marked decrease in accuracy at night, proving unreliable in varying light intensities. This result underscores LPR's significance as a reliable and consistent metric for vehicle identification when it comes to lowlight conditions.

Table 5.2: Overall performance of VIDAR

	LPR	MMR (Correct, Correct Make Only)	Color	Settings
Day	93.83%	66.01%, 22.22% (=88.23%)	46.4%	Triger distance is 100 feet; iris is 380; automatic focus during daytime, and the same focus was used later for nighttime
Night	97.16%	1.87%, 8.41% (=10.28%)	-	Same as above

Chapter 6 Conclusions and Future Research

Key contributions and conclusions:

In our quest to enhance traffic management and safety within work zones, we embarked on evaluating two distinct solutions for vehicle detection, speed measurement and automatic extraction of vehicle specific information: a cost-effective system utilizing the Milesight camera, and a higher-end solution featuring the VIDAR camera. Each system presented its advantages and areas for improvement, which are pivotal for guiding future implementations by Caltrans.

The Milesight camera proved effective in LPR and speed measurement during both day and night, making it a reliable component of our low-cost solution. However, its capability to distinguish between vehicle types (e.g., truck vs. car) and their color, was rather coarse and did not meet our reliability criteria, underscoring a limitation in its utility. To address this gap, we developed a custom machine learning scheme for VMMR, which, through testing, demonstrated the potential to offer a budget-friendly alternative to the more expensive VIDAR system. A notable consideration for this approach is the requirement for ongoing Caltrans involvement to ensure the system's currency and functionality in recognizing new vehicle models; however, our development of an updating mechanism aims to mitigate this challenge by autonomously integrating the latest vehicle data from the web.

Conversely, the VIDAR system encompasses LPR, speed measurement, and VMMR capabilities within a single, albeit more expensive, package. This system's advantage lies in its provision of bi-annual updates and after-sales service, offering a turnkey solution that might justify the higher investment for Caltrans. Despite its robust performance in LPR and speed detection under various lighting conditions, the VIDAR camera's VMMR and color detection functionality exhibited limitations in low-light scenarios. To complement its evaluation, we developed a tool for web-based retrieval of make and model information, enhancing our analysis with a comprehensive validation of LPR and VMMR accuracy.

Our tests—validated statistically for both daytime and nighttime conditions—establish the VIDAR camera as a viable option for Caltrans, particularly for initial adoption phases. The system's performance, coupled with the support from the manufacturer, underscores its potential for facilitating scalable and effective traffic management solutions. For broader implementation, especially under budget constraints, the Milesight-based solution remains a considerable option, particularly for daytime operations.

As part of our tests, we further developed a virtual message board system, with specifications matching those of the commercially available refreshable message board, that displayed targeted messages to detected vehicles. The inclusion of this virtual board helped us test the system performance as a whole from the very first step of vehicle detection all the way to targeted message generation and message display. For implementation, the virtual message board can be replaced by a physical board.

Looking forward, we recommend daytime deployment of the targeted warning message technology, leveraging the VIDAR camera's automatic detection capabilities. Nighttime adoption, while beyond the current project scope, suggests a reliance on LPR data to web-fetch vehicle specifics—a process that necessitates collaboration with the DMV for secure and compliant data access. For nighttime adoption, either systems based on the VIDAR or the Milesight cameras are feasible.

Future work:

The initial stages of our TWM system development concentrated on vehicle detection and message generation technology. The next phase focuses on the practical field implementation of the system. This transition from theoretical development to real-world application brings to the forefront several critical questions and hypotheses that require experimental validation through field tests.

1. **Assessing the Impact of Targeted Warning Messages**: A central hypothesis driving our research is the potential of TWMs to influence driver behavior, encouraging earlier and safer merging practices. While our simulation results support the notion that improved driver compliance enhances traffic flow and safety, these outcomes remain hypotheses until proven in a field setting. Therefore, a key aspect of future work involves observing and measuring the real-world impact of targeted messaging on driver behavior, traffic flow, and safety. This empirical assessment will provide the necessary validation for our theoretical models and simulations.

2. **Tuning System Parameters:** Another area for future exploration involves refining the operational parameters of the TWM system. Currently, decisions regarding the duration of message display, the distance from the message

board at which to initiate the message, and the frequency of message updates are made based on heuristic approaches. Determining the optimal settings for these parameters is essential for maximizing the effectiveness of the TWM system. For example, finding the right balance in message update frequency is important as a higher turnover rate may target more vehicles but could also diminish the individual impact of messages due to the shorter time assigned to the display of each targeted message. These parameters, among others, will be subject to rigorous testing in real-world scenarios involving actual lane closures.

Baseline Comparisons: To objectively evaluate the efficacy of the TWM system, future field tests will incorporate baseline comparisons. By systematically toggling the targeted warning system on and off, we can directly compare traffic parameters with and without the activation of targeted warning messages while maintaining the rest of the experimental conditions intact. This methodical approach will enable us to quantify the system's benefits and identify areas for further refinement.

The path forward includes extensive field testing under various traffic conditions and operational scenarios. Through this iterative process of implementation, observation, and adjustment, future research aims to refine the TWM system into an effective tool for traffic management and at the same better understand its limitations. The next phase of research promises to bridge the gap between theoretical potential and practical utility, bringing us closer to realizing our goal of improving road safety and efficiency.

References

[1] "CHAPTER 6H. TYPICAL APPLICATIONS Section 6H.01 Typical Applications." Accessed: Mar. 30, 2024. [Online]. Available: https://mutcd.fhwa.dot.gov/pdfs/2003r1r2/ch6h.pdf

[2] K. He, X. Zhang, S. Ren, and J. Sun, "Deep Residual Learning for Image Recognition," in 2016 IEEE Conference on Computer Vision and Pattern Recognition (CVPR), Jun. 2016, pp. 770–778. doi: 10.1109/CVPR.2016.90.

[3] J. Deng, W. Dong, R. Socher, L.-J. Li, K. Li, and L. Fei-Fei, "ImageNet: A large-scale hierarchical image database," in 2009 IEEE Conference on Computer Vision and Pattern Recognition, Jun. 2009, pp. 248–255. doi: 10.1109/CVPR.2009.5206848.

[4] D. E. Rumelhart, G. E. Hinton, and R. J. Williams, "Learning representations by back-propagating errors," Nature, vol. 323, no. 6088, pp. 533–536, Oct. 1986, doi: 10.1038/323533a0.

[5] F. Tafazzoli, H. Frigui, and K. Nishiyama, "A Large and Diverse Dataset for Improved Vehicle Make and Model Recognition," in 2017 IEEE Conference on Computer Vision and Pattern Recognition Workshops (CVPRW), Jul. 2017, pp. 874–881. doi: 10.1109/CVPRW.2017.121.

[6] "Manual on Uniform Traffic Control Devices (MUTCD) 2009 Edition." Accessed: Mar. 30, 2024. [Online]. Available: https://mutcd.fhwa.dot.gov/pdfs/2009/mutcd2009edition.pdf

[7] T. Toledo, H. Koutsopoulos, M. Ben-Akiva, and M. Jha, "Microscopic Traffic Simulation: Models and Application," in Simulation Approaches in Transportation Analysis: Recent Advances and Challenges, R. Kitamura and M. Kuwahara, Eds., Boston, MA: Springer US, 2005, pp. 99–130. doi: 10.1007/0-387-24109-4_4.

[8] N. L. Jehn and R. E. Turochy, "Calibration of Vissim Models for Rural Freeway Lane Closures: Novel Approach to the Modification of Key Parameters," Transp. Res. Rec. J. Transp. Res. Board, vol. 2673, no. 5, pp. 574–583, May 2019, doi: 10.1177/0361198119842824.

[9] I. Chatterjee, P. Edara, S. Menneni, and C. Sun, "Replication of Work Zone Capacity Values in a Simulation Model," Transp. Res. Rec. J. Transp. Res. Board, vol. 2130, no. 1, pp. 138–148, Jan. 2009, doi: 10.3141/2130-17.

[10] P. Edara and I. Chatterjee, "Multivariate regression for estimating driving behavior parameters in work zone simulation to replicate field capacities," Transp. Lett., vol. 2, no. 3, pp. 175–186, Jul. 2010, doi: 10.3328/TL.2010.02.03.175-186.

[11] "Simulation Guidance for Calibration of Freeway Lane Closure Capacity | Semantic Scholar." Accessed: Mar. 30, 2024. [Online]. Available: https://www.semanticscholar.org/paper/Simulation-Guidance-for-

Calibration-of-Freeway-Lane-Yeom-Rouphail/4b9d03bf07a94917ff7764768630d747bce8adc5
[12] N. Lownes and R. Machemehl, "Sensitivity of Simulated Capacity to Modification of VISSIM Driver Behavior Parameters," Transp. Res. Rec. J. Transp. Res. Board, vol. 1988, pp. 102–110, Jan. 2006, doi: 10.1177/0361198106198800113.
[13] "Micro-simulation guide for automated vehicles - final." Accessed: Mar. 30, 2024. [Online]. Available: https://www.rupprecht-consult.eu/fileadmin/user_upload/D2.11-Guide-for-the-simulation-of-AVs-with-microscopic-modelling-tool-Final.pdf
[14] M. Algomaiah and Z. Li, "Exploring work zone late merge strategies with and without enabling connected vehicles technologies," Transp. Res. Interdiscip. Perspect., vol. 9, p. 100316, Mar. 2021, doi: 10.1016/j.trip.2021.100316.
[15] A. J. Khattak, A. J. Khattak, and F. M. Council, "Effects of work zone presence on injury and non-injury crashes," Accid. Anal. Prev., vol. 34, no. 1, pp. 19–29, Jan. 2002, doi: 10.1016/S0001-4575(00)00099-3.
[16] M. Rahman, "Assessing the Safety and Operational Benefits of Connected and Automated Vehicles: Application on Different Roadways, Weather, and Traffic Conditions," Electron. Theses Diss., Jan. 2019, [Online]. Available: https://stars.library.ucf.edu/etd/6561
[17] S. M. S. Mahmud, L. Ferreira, Md. S. Hoque, and A. Tavassoli, "Application of proximal surrogate indicators for safety evaluation: A review of recent developments and research needs," IATSS Res., vol. 41, no. 4, pp. 153–163, Dec. 2017, doi: 10.1016/j.iatssr.2017.02.001.
[18] A. Papadoulis, M. Quddus, and M. Imprialou, "Evaluating the safety impact of connected and autonomous vehicles on motorways," Accid. Anal. Prev., vol. 124, pp. 12–22, Mar. 2019, doi: 10.1016/j.aap.2018.12.019.
[19] Y. Zhang, E. K. Antonsson, and K. Grote, "A new threat assessment measure for collision avoidance systems." Accessed: Mar. 30, 2024. [Online]. Available: https://www.researchgate.net/publication/224650767_A_new_threat_assessment_measure_for_collision_avoidance_systems
[20] K.-P. Chen and P.-A. Hsiung, "Vehicle Collision Prediction under Reduced Visibility Conditions," Sensors, vol. 18, no. 9, p. 3026, Sep. 2018, doi: 10.3390/s18093026.
[21] A. Tympakianaki, A. D. Spiliopoulou, A. Kouvelas, and M. Papageorgiou, "Real-Time Merging Traffic Control for Throughput Maximization at Motorway Work Zones," Procedia - Soc. Behav. Sci., vol. 48, pp. 1545–1556, Jan. 2012, doi: 10.1016/j.sbspro.2012.06.1130.
[22] G. Hou, S. Chen, and Y. Han, "Traffic Performance Assessment Methodology of Degraded Roadway Links Following Hazards," J. Aerosp. Eng., vol. 32, no. 5, p. 04019055, Sep. 2019, doi: 10.1061/(ASCE)AS.1943-5525.0001050.
[23] "FHWA - MUTCD - 2003 Edition Chapter 2C." Accessed: Mar. 30, 2024. [Online]. Available: https://mutcd.fhwa.dot.gov/htm/2003/part2/part2c.htm

[24] “Changeable Message Sig Gudelines Changeable Message Sign Guidelines.” Accessed: Mar. 30, 2024. [Online]. Available: https://dot.ca.gov/-/media/dot-media/programs/traffic-operations/documents/mobility/f0019529-cms-guidelines-a11y-.pdf

Appendix A Advanced Data Center for TWM System

Our workflow is designed around a centralized server that communicates with cameras in real-time, generating and transmitting messages to digital message boards. The seamless operation of the centralized server, cameras, and message boards is essential for the smooth functioning of the entire system.

The TWM system demands significant data processing, model training, and inference. The reliability of our server is important to ensuring the system's efficiency, effectiveness, and ultimately, road safety.

Additionally, we aim to empower Caltrans personnel to monitor the system's health status and traffic flow in real-time whenever needed. The centralized server is configured to alert Caltrans if a server, a camera, or message board malfunctions, enabling prompt onsite maintenance. Furthermore, camera data are invaluable for analyzing traffic flow and monitoring in real-time, particularly at construction sites. These data are instrumental in assessing deployment effectiveness and refining future deployment strategies by offering insights into traffic patterns. Therefore, we plan to enhance the system's capabilities for real-time data collection, analysis, and visualization, encompassing the health status of each component, traffic flow, and the messages displayed.

In response to these requirements, we have developed an advanced data center capable of collecting data on component health (including central processing unit (CPU) and graphics processing unit (GPU) usage of the centralized server, camera and message board status), traffic flow (density, speed, etc. captured through our real-time API tool), and message generation. Should a server exhibit issues, it automatically sends a warning to Caltrans, facilitating rapid response and maintenance. Additionally, Caltrans personnel have the capability to review historical traffic data processed by our data center for future evaluation and planning purposes. This feature ensures that insights derived from past traffic patterns and system performance can inform strategic decisions and operational improvements.

The data center docker configurations and setup instructions are uploaded to GitHub: https://github.com/Soltanilara/LARA-server-monitor.

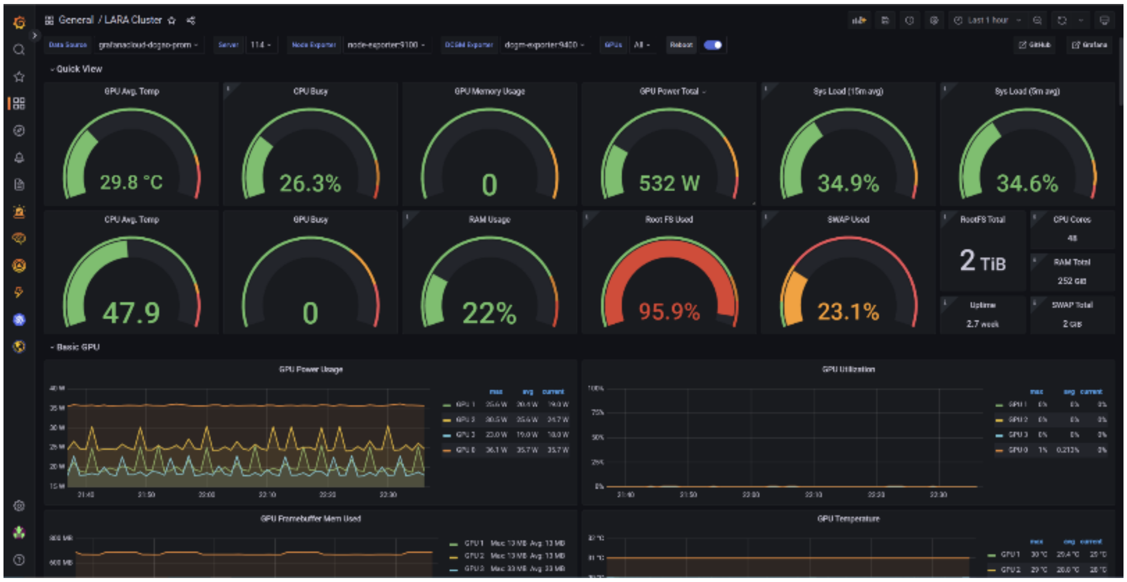


Figure A1: An example front panel of the developed data center.

The monitoring infrastructure is built on a robust combination of Docker, Prometheus, and Grafana, forming a cohesive ecosystem for real-time data collection, storage, visualization, and analysis.

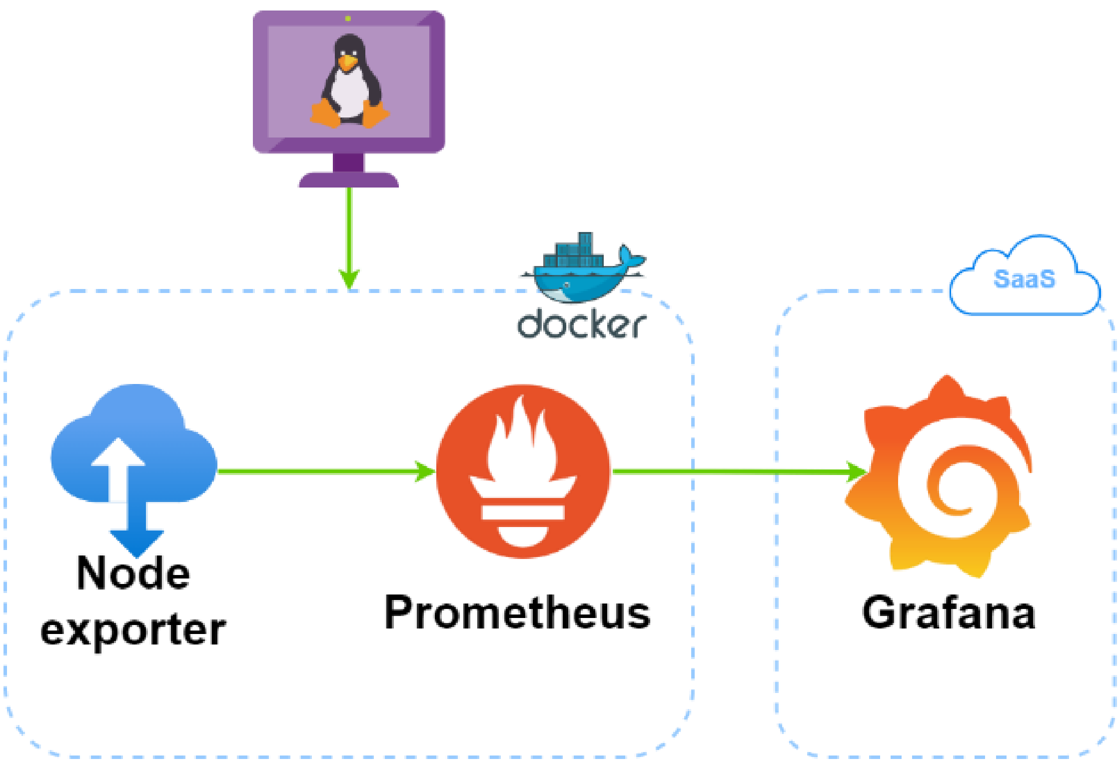


Figure A2: Data flow diagram.

Docker containers are utilized to encapsulate the monitoring components, ensuring a seamless and consistent deployment process. This containerized approach facilitates easy scalability and management of the monitoring services.

At the core of our monitoring system is **Prometheus**, a powerful time-series database optimized for collecting and processing metrics. Prometheus is configured to gather data from various sources, with a primary focus on capturing detailed system performance metrics. This setup enables us to track the server’s operational status comprehensively.

To capture the specific metrics required for our monitoring objectives, we deployed two specialized system status exporters. These exporters are designed to generate real-time data on GPU performance, and other system metrics, such as CPU utilization, disk activity, and memory consumption. The choice of exporters is tailored to our needs, focusing on the components most critical to our server's performance and reliability.

Grafana is integrated into our monitoring solution to provide a powerful and intuitive interface for data visualization. It connects to Prometheus to retrieve the collected metrics, allowing us to create customizable dashboards that display the server's operational status. Grafana's capabilities extend to long-term data storage, ensuring that historical performance data are preserved for trend analysis and retrospective troubleshooting.