**Project Title:**

# Field Test of Combined Coordinated Ramp Metering and Variable Speed Advisory for Freeway Traffic Control

## Final Report

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**Project Team**:

Dr. Xiao-Yun Lu – Principal Investigator

John Spring and David Nelson

California PATH Program
Institute of Transportation Studies
University of California Berkeley
Richmond Field Station, Building 452
1357 S. 46th Street, Richmond, CA 94804-4648


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## DISCLAIMER STATEMENT

# Project Panel

Kin Hung Yeung, Caltrans District 3, Freeway Traffic Operation,
Tel: (530) 708-7102, email: kin.hung.yeung@dot.ca.gov,
Nelson Xiao, Caltrans District 3, Freeway Traffic Operation,
Tel: (530) 682-6515, email: nelson.xiao@dot.ca.gov,
Jose Camacho, Caltrans HQ, Division of Research and Innovation,
Tel: (916) 387-5291, email: Jose.Camacho.Jr@dot.ca.gov,
Nicholas Liccardo, Caltrans District 3, Freeway Traffic Operation,
email: Nicholas.Liccardo@dot.ca.gov,
Luis Munoz, Caltrans District 3, Freeway Traffic Operation,
email: Luis.Munoz@dot.ca.gov,
Stephen Bandirola, Caltrans District 3, Freeway Traffic Operation,
Tel: (916) 859-7956, email: stephen_p_bandirola@dot.ca.gov
Leo Anselmo, Caltrans District 3, Freeway Traffic Operation,
Tel: (916) 859-7954, email: leo_anselmo@dot.ca.gov (retired)
Larry Hall, Caltrans District 3, Freeway Traffic Operation,
Tel: (916) 859-7955, email: larry_hall@dot.ca.gov
Bojana Gutierrez, Caltrans District 3 Freeway Operations,
Tel: (916) 859-7940, email: bojana.gutierrez@dot.ca.gov
Greg Larson, Caltrans HQ, Division of Research and Innovation,
Tel: (916) 657-4369, email: greg_larson@dot.ca.gov, (retired)
Zhongren Wang, Caltrans HQ, Traffic Operation, Tel: (916) 653-4575,
zhongren.wang@dot.ca.gov, (retired),
Gurprit Hansra, Caltrans HQ, Division of Research and Innovation,
Tel: (916) 654-7252, email: gurprit_hansra@dot.ca.gov, (retired)
Hassan Aboukhadijeh, *Project Manager,* Caltrans Division of Research and Innovation,
Tel: (916) 654-8630, email: hassan_aboukhadijeh@dot.ca.gov, (retired)
James Anderson, Caltrans HQ Division of Traffic Ops
Tel: (916) , email: james.r.anderson@dot.ca.gov
Terry Thompson, Caltrans HQ Division of Traffic Ops
Tel: (916), email: terry.thompson@dot.ca.gov;
Xiao-Yun Lu, PATH, University of California, Berkeley,
Tel: (510) 665-3644, email: xylu@path.berkeley.edu
John Spring, PATH, University of California, Berkeley,
Tel: (510) 665-3575, email: jspring@path.berkeley.edu

# Abstract

This report documents the field test of combined Coordinated Ramp Metering (CRM) and Variable Speed Advisory (VSA) funded by Caltrans DRISI during June 10th 2019 ~ May 31 2023. CRM and VSA are complementary in function for freeway Active Traffic Management (ATM) in the sense that ramp meter controls the demand into the freeway, while VSA mainly affects the driver behavior in the mainline. Before the field test, the project conducted several preparations including: selection of required VSA signs which are compliant with the Manual on Uniform Traffic Control Devices (MUTCD), permission applications from several organization which have the authority for field test of VSA signs including Federal Highway Administration (FHWA), and the California Traffic Control Devices Committee (CTCDC), developing a feasible Concept of Operation (ConOps), implementation of the combined algorithm in real-time code, developing a website for traffic state parameters and the system monitoring and observation, and developing a detailed progressive test plan to minimize potential negative impact on traffic operation. The team then conducted a progressive test before the formal tests. The field test has lasted about one and half years. The project team then conducted an objective and quantitative performance analysis based on the independent PeMS data by comparing the "before" scenario during 2015~2016 (no CRM nor VSA in operation), and the "after" scenario (both CRM and VSA in operation) during 2022~2023. The mobility and safety performance improvement can be summarized as follows: (a) VMT (Vehicle Miles Travelled) increased by 4.5%; (b) the efficiency Q=VMT/VHT (VHT: Vehicle Hours Travelled) increased by 8.4%; and (c) the daily average number of accidents decreased by 14.56% (safety improvement). Both Q and VMT increasing indicates the significance of the system performance improvement. However, the project team could not get conclusive results on driver compliance simply based on the analysis of some engineering data.

**Key Words:** Coordinated Ramp Metering (CRM), Variable Speed Advisory (VSA), radar speed, loop detector station, VMT, VHT, traffic mobility, traffic safety, driver compliance to VSA

# Disclaimer Statement

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- Kustom Signals Inc
- Zamp Solar Company
- Royal Battery
- Access Wireless

# Executive Summary

*Background*

As the core part of freeway Active Traffic Management (ACM), Ramp Metering (RM) and Variable Speed Limit/Advisory (VSL/VSA) play important roles. Those strategies have been adopted worldwide in recent years. Although, RM has been popularly operated in California, VSL/VSA has not been adopted yet. Besides, there were still some research questions about their application and deployment. Also, the popular RM strategy in operation in California is the Local Responsive Ramp Metering (LRRM) which determines the onramp metering rate of the subject onramp only based on its immediate upstream loop detector station occupancy measurement. This is obviously not system optimal since the freeway traffic of each section along a corridor usually affects each other for all the sections divided by the onramps. Therefore, this project implemented Coordinated Ramp Metering (CRM) which determines the metering rate at each onramp to optimize the whole corridor traffic instead of the local onramp.

RM and VSL/VSA play complementary roles in freeway traffic management. RM essentially controls the onramp demand into the freeway. However, once the vehicles get into the freeway, they are out of control. Therefore, the mainline traffic of the freeway with RM only is still dominated by the driver behavior. VSL/VSA on the other hand, directly affects the driver behavior through dynamic speed limit/advisory. Obviously, VSL should be more effective as practiced in Europe than VSA since the latter can be significantly affected by the driver behavior. However, VSL implementation would involve many challenging legal issues which could make the project impractical for field test in a short period of time. Therefore, the project adopted VSA for the field operational test.

*Project Objectives*

The main objective of this project was to conduct field test of combined CRM and VSA along the State Route99 (SR99) North Bound corridor from Stockton Blvd to 12$^{th}$ Ave. near the crossing with US-50. CRM had been operated in that corridor on 12 onramps (from Elk Grove to 12$^{th}$ Ave.) for over two years before this project starts. This project further extended the CRM to 17 onramps starting from Stockton Blvd. Based on that, the project team would need to add VSA and tightly combine those two in algorithm and real-time code/software, to implement it and to conduct field test. Besides, the project is expected to conduct objective and quantitative performance analysis for mobility and safety of the combined traffic management strategy. Later on, the project panel also requested to investigate the driver compliance rate with respect to the VSA displayed on roadside signs.

*What We Have Done*

To make sure to achieve the objective, the PATH team formed a project panel to include Caltrans HQ Traffic Operation and DRISI, Caltrans District 3 Freeway Operation Group etc. With this panel, the PATH project team regularly asked their advice on any field operation related requirement and issues. It turned out that this project panel has provided much critical assistance to guarantee the project to be successfully conducted.

To combine the CRM and VSA algorithms, the PATH team investigated in detail the two algorithms, their modeling, input parameters and output parameters, and their implementation in real-time code. The project team then designed a feasible Concept of Operation which has been used as the blueprint of the project.

For a field operational test with sustainable power supply, it is critical to find appropriate VSA signs which should meet the traffic operations requirements including: power supply, built-in radar, MUCTD and CTCDC compliance, adequate size for driver's perception, with legal trailer for easy installation, ability to remotely control/change the messages on the sign in real-time, etc.. Although, there are many products popularly used for daily freeway traffic operation, few met our project requirements due to its advanced requirements. The main gap is the real-time remote message changing requirement. For VSA display, we will need to change the displayed messaged on the VSA signs in the field remotely and in real-time. Most of the product signs in operation do not have such a capability. We searched over ten companies for sale or rental;, we eventually found only one company, American Signal Company (Amsig), that could revise their product to meet our requirements.

While searching for VSA signs, the project team started the permission application process for the field test. This process also took much longer time than what we previously expected. Those permissions include: Caltrans HQ, MUTCD, CA CTCDC, and FHWA. All permit applications were granted quickly except the one from FHWA for which we applied twice in 2020 and 2021 before being granted.

After all the permissions were granted, we started to determine the locations of the ten signs in the field. Several factors were used in the location considerations: downstream of onramp to be effective to more traffic, the shoulder to be wide enough to accommodate the trailer, at least 100 ~ 200 m straight lane available upstream for driver's good perception, not shaded by trees for better solar power, nor walls blocking wireless communication, and no other roadside signs nearby. There were 17 onramps for SR-99 corridor, but only 10 VSA signs. The team first selected tentative GPS locations based on traffic volumes and section lengths from the Google traffic map, and then made several field visits to finally determine the feasible locations of the ten signs. As an example, long sections may need two VSA signs as in Mack Rd. ; and several short sections may only need one VSA sign.

Another important task accomplished in this project is a website which describes the objectives of the project, plots all the traffic state parameters, displays the traffic data of the sections, and inlays the VSA sign location and traffic state parameters with the real-time Google traffic map. Based on the observations of this website, the project team could monitor the corridor traffic and most of the health conditions of the combined CRM and VSA, except the actual display on the sign in the field.

Before the field test, the project team had developed a detailed test plan which included: (i) the concept of operation (ConOps); (ii) VSA sign technical specifications; (iii) how the VSA signs would be installed in the field and used; (iv) how to progressively switch on the VSA display to minimize any possible negative impact on traffic operation; (v) how to conduct the public outreach; and (vi) how to regularly update the information to the project panel. During the initial progressive test period, the project team kept updating the project panel every day in the first week, and once a week afterwards. All those efforts were intended to make the project as transparent as possible and, at the same time, to minimize the negative impact.

After the first month progressive test period, the system behaved reasonably stably. The roles of the project team became system refinement and regular maintenance of the system including the repair and replacement of damaged VSA trailers and signs.

In early 2023, the project team conducted objective quantitative analysis of mobility and safety impact of the field tests. The PeMS hourly performance data were used for the analysis, which was independent from the data the project team had collected. The data used for comparison of the "before" and "after" scenarios were: (i) VMT (Vehicle Miles Travelled) which reflected the combination of demand and performance; and (ii) Q=VMT/VHT (which could be understood as the efficiency or average speed), where VHT is the total Vehicle Hours Travelled. The time periods for comparison were 2015~2016 (before COVID-19; and no CRM nor VSA) and 2022~2023 (after COVID-19; with both CRM and VSA). The performance improvements in mobility and safety can be summarized as: (a) VMT increased by 4.5%; (b) the efficiency increased by 8.4%; and (c) the daily average number of accidents decreased by 14.56%. It is noted that both Q and VMT increasing indicates the significance of the system performance improvement.

The project has conducted the driver compliance analysis based on the engineering data the project saved. We have compared the VSA speed displayed on the sign and the radar speed from the VSA sign, and with the fused speed from the radar speed and loop detector speed. We also considered the comparisons for traffic acceleration and deceleration phases. Such comparisons were conducted at all the ten VSA sign locations. It appeared that the situations are different from location to location. It seemed difficult to obtain conclusive results. However, all the comparisons have been included in this report in both data plots and table with percentage changes.

# Table of Contents

# List of Figures

# List of Tables

# List of Acronyms and Abbreviations

| | |
|---|---|
| ALINEA | (Asservissement LINéaire d'Entrée Autorouti?re) A local occupancy based traffic responsive ramp metering algorithm |
| ASC | American Signal Company |
| ATM | Active Traffic Management |
| BN | Bottleneck |
| Caltrans | California Department of Transportation |
| CMS | Changeable Message Sign |
| CRM | Coordinated Ramp Metering |
| CTM | Cell Transmission Model |
| EAR | Exploratory Advanced Research |
| FD | Fundamental Diagram |
| FHWA | Federal Highway Administration |
| FLOW | A coordinated ramp metering algorithm |
| GEH | after the name of Geoffrey E. Havers, who created a statistics test similar to a chi-squared test |
| GPL | General Purpose Lane |
| HERO | HEuristic Ramp metering coOrdination |
| HOV | High Occupancy Vehicle |
| LARM | Local Adaptive Ramp Metering |
| LP | Linear Programming |
| LQI | Linear Quadratic Control with Integral Action |
| LRRM | Local Responsive Ramp Metering |
| LWR | Lighthill-Witham-Richards |
| METANET | A second order traffic model including speed and density as state variables |
| MPC | Model Predictive Control |
| NGSIM | Next Generation Simulation |
| OFR | Exit ramp |
| ONR | Entrance ramp |
| OpenStreetMap | A map of the world, an open source |

| | |
|---|---|
| PATH | California Partners for Advanced Transportation Technology |
| PeMS | Performance Measurement System |
| PM | Postmile |
| RM | Ramp Metering |
| RMSE | Root Mean Square Error |
| RMSP | Root Mean Square Percentage |
| RTMC | Regional Traffic Management Center |
| SR | State Route |
| SVO | Speed, Volume, Occupancy |
| SWARM | System-wide Adaptive Ramp Metering |
| TD | Total Delay |
| TMC | Traffic Management Center |
| TOD | Time-of-Day |
| TOPL | Tools for Operations Planning |
| TNOS | Total Number of Stops |
| VMT | Total Travel Distance |
| TTS | Total Time Spent |
| TTT | Total Travel Time |
| VDS | Vehicle Detector System |
| VHT | Vehicle Hours Travelled |
| VII | Vehicle Infrastructure Integration |
| VMS | Variable Message Signs |
| VMT | Vehicle Miles Travelled |
| VSA | Variable Speed Advisory |
| VSL | Variable Speed Limit |

# 1 Introduction

This report documents the work conducted under the California Department of Transportation (Caltrans) Project 65A0743 entitled "*Field Test of Combined Coordinated Ramp Metering and Variable Speed Advisory for Freeway Traffic Control*".

The project was sponsored by Caltrans and undertaken by the California Partners for Advanced Transportation Technology (PATH), of the University of California, Berkeley. The project duration was from 6/10/2019 to 5/31/2023.

## 1.1 Background

Coordinated Ramp Metering (CRM) and Variable Speed Advisory (VSA) are Active Traffic Management (ATM) measures for freeway operations. CRM is to balance the ramp metering rate (flow) from onramps into the freeway mainline considering the mainline traffic flows and the differences of demands and lengths (storage capacity) of all onramps along the corridor to maximize the throughput. However, CRM cannot completely control the traffic since, after the vehicles getting into the freeway, they are out of control in the sense that freeway mainline traffic will still be dominated by driver behavior. Therefore, CRM can only improve traffic from the demand aspect. On the other hand, VSA is to affect the driver behavior on freeway mainline. It would function in a macroscopic level for traffic harmonization in free-flow and to reduce/eliminate shockwaves at the upstream of the bottleneck when the congestion starts and to maximize the bottleneck flow, if the algorithm is designed appropriately and if the driver compliance rate is reasonably high. Those two freeway traffic control methods are obviously complementary to each other in function, with the overall intension of affecting the traffic from different aspects.

In two previous Caltrans DRISI sponsored projects, CRM and VSA have been tested respectively on SR-99 Northbound (NB) in Sacramento in District 3 [1] and SR-78 Eastbound (EB) near Escondido in District 11 in San Diego [2]. More specifically, those two projects are summarized as follows:

SR99 North Bound (NB) stretch between Calvine Road and the interchange with US 50 was used as the test site. An Optimal CRM algorithm developed by the project team was implemented for 11 onramp meters and tested between October 3rd and November 4th 2016. The CRM determined the RM rate by looking at the mainline occupancy/flow of the whole corridor and the demands of all onramps. For an objective evaluation of the performance for the field test, the independent PeMS 1-hour Vehicle Hours Traveled (VHT) and Vehicle-Miles-Traveled (VMT) data and the ratio VMT/VHT (defined as the efficiency in PeMS or understood as the average speed) were used as the performance parameters. The results showed that, compared to the same period of the previous year, for AM peak (6:00am-9:00am) traffic, VMT is increased by 5.39%, VHT is decreased by 1.64%, and VMT/VHT is increased by 7.25%. However, it did not produce noticeable improvement for the PM peak hour traffic since the traffic volume was low to moderate.

The test site of the Variable Speed Advisory (VSA) was on SR-78 EB from Vista Village Drive in the City of Vista to the freeway interchange of SR-78 EB and U.S. Route 15 in the city of Escondido. This test segment was a three-lane freeway with a posted speed limit of 65 mph and it had ten (10) on-ramps and ten (10) off-ramps. Caltrans District 11 TMC traffic data (for occupancy, speed and flow) and roadside radar data from the VSA signs were used to calculate the VSA for each section every 30 [s]. The calculated VSA was then passed to the signs on the roadside for displaying to the public driver. After system development, integration, installation on the roadside and fine tuning, the formal test was conducted for four (4) weeks in April and May 2018. Similar to the CRM project, PeMS one-hour level VHT and VMT data and the ratio VMT/VHT were used as the performance parameter for evaluation. Due to road construction of the previous year at the test site which could significantly change the traffic pattern, the project team compared with the PeMS traffic data with the week before the VSA system installation and the week after the formal test was accomplished for performance evaluation. The results showed that, on average, in the AM peak hours for workdays (6:00 - 9:00am), VMT increased by 2.72%, VHT decreased by 6.28%, and VMT/VHT increased by 8.71%. In PM peak hours (2:00 -7:00pm), VMT did not have noticeable improvement, while VHT decreased by 1.47% on average, and VMT/VHT increased by 2.80% on average.

Based on the outcomes of the two previous projects, since CRM and VSA affect the freeway traffic from different aspects, it makes sense to test those two freeway traffic management measures jointly on a freeway corridor and to evaluate the performance for traffic improvement.

## 1.2 Extension of The CRM Control Range from 11 Onramps to 17 Onramp

Jointly with a sister project funded by Caltrans DRISI and supported by District 3, PATH project team has extended the CRM control range from 11 onramps (Calvine to 12$^{th}$ Ave) to 17 onramps with 6 upstream onramps from E. Stockton to Sheldon WB. The following Table 1 includes the extended range of SR 99 North Bound direction with additional six onramps:

Table 1. Extension of CRM operation range by adding 6 upstream onramps

| Entrance ramp ID | Street Names | RM strategy | Entrance ramp ID | Street Name | RM strategy |
|---|---|---|---|---|---|
| 1 | **E. Stockton Blvd** | CRM | 10 | Mack Road WB | CRM |
| 2 | **Elk Grove** | CRM | 11 | Florin EB | CRM |
| 3 | **Laguna Blvd EB** | CRM | 12 | Florin WB | CRM |
| 4 | **Laguna Blvd WB** | CRM | 13 | 47$^{th}$ Ave EB | CRM |
| 5 | **Sheldon EB** | CRM | 14 | 47$^{th}$ Ave WB | CRM |
| 6 | **Sheldon WB** | CRM | 15 | Fruitridge EB | CRM |
| 7 | Calvine EB | CRM | 16 | Fruitridge WB | CRM |
| 8 | Calvine WB | CRM | 17 | 12$^{th}$ Ave | CRM |
| 9 | Mack Road EB | CRM | | | |

After the extension, the CRM system has been thus operating on 17 onramps on SR-99 corridor from E. Stockton to SR-50 interchange for Caltrans District 3 daily operation. The VSA implementation was based on this system from the beginning of the project.

### 1.3 Project Objectives

The objective of this proposed project is to field implement, test and evaluate the performance of Combined CRM and VSA on SR99 NB corridor in Caltrans District 3 in Sacramento. Tasks that must be completed to prove the usefulness of the system include the following:

- Combine/integrate the previous independently field-tested CRM and VSA algorithms and software into one algorithm
- Combine/integrate the previous independently field-tested CRM and VSA hardware systems into one system
  Improve the systems based on the lessons learned in previous projects where CRM and VSA were tested independently
- Investigate the dynamic interactions of the functionalities of CRM and VSA for real-world freeway corridor traffic
- Quantitatively evaluate the performance improvement for joint function of CRM and VSA
- Investigate the driver compliance to VSA and its influence on the traffic

# 2 Algorithms for Combined CRM and VSA

In this chapter, we describe the algorithm for the combined CRM and VSA which are practically implemented. The CRM algorithm is exactly the same as we implemented in the previous Caltrans project [1, 3, 4, 5]. The VSA control strategy and algorithm have been changed on those included in [3, 4, 5]. It has also been revised further on the algorithm previously implemented in the Caltrans project in San Diego SR-78 [2].

The CRM algorithm uses a simplified version of *optimal control*, called Model Predictive Control (MPC) with an objective function which is a tradeoff of the total travel time (TTT) and total travel Distance (TTD) of the whole corridor, which is linear with respect to traffic flow. The traffic state space model used is the Cell Transmission Model by Daganzo [6, 7] which is linear with respect to traffic flow. Therefore, the eventual mathematical problem of the MPC approach is linear optimization/programming over a finite time horizon which is easily to resolve at each time step in real-time. Since the CRM algorithm is exactly the same as that as reported in [1, 4, 5], the reader is referred to those reports and archived papers without repeating here.

## 2.1 VSA Algorithms for Bottleneck Flow Maximization

In our previous work [2], we determined the VSA at all the bottlenecks and then determined the VSA at other locations by distance-based interpolation. The advantage of this approach is its simplicity for implementation. Besides, the distance-based approach naturally harmonizes the traffic since the vehicles would approach the bottleneck gradually, which would reduce/avoid shockwaves.

In the algorithm implemented on SR-99 NB corridor, we revised the algorithm by adaptively determining the VSA from the bottleneck to its upstream, by successively using proportional control (P-control) or regulation. The P-control is based on several downstream sections, usually three sections, its *flow*, measured *occupancy* (or estimated *density*), and estimated *distance mean speed*, etc. This is similar to the *backstepping* design approach in the systems and control community. With this approach, the whole corridor traffic has been interconnected and integrated. The philosophy here is that, for the traffic of the subject section, its main effects came from its immediate downstream and upstream sections. Those effects will be attenuated going further downstream and upstream Therefore, it is completely justifiable to design the feedback speed control of the subject section by considering mainly the immediate downstream and upstream sections and a few sections further. This is the principle of the VSA algorithm here. To implemented it, the state parameters (flow, occupancy, density, and speed) used will be fused from the data measured in the field by the loop detector station of the immediate downstream sections.

The following four regulators are some simple feedback control algorithms for the regulation of the most downstream bottleneck flow close to its capacity.

### 2.2 Flow based Regulator

To regulate the bottleneck feeding flow to the capacity flow:

$$u_M(k) = u_M(k-1) + \gamma \cdot \min\left\{ \left(Q_b - \bar{q}_M(k)\right), \bar{v}_{M+1}(k) \cdot \left(\rho_c - \bar{\rho}_{M+1}(k)\right) \right\} \quad \text{(Eq. 2.1)}$$

Where:

$u_m(k)$ – speed control variable immediate upstream of the bottleneck, to be determined.

$\gamma$ – control gain

$Q_b$ – capacity flow of the bottleneck

$\bar{q}_M(k)$ – measured/estimated average flow at the immediate upstream of the bottleneck

$\bar{v}_{M+1}(k)$ – measured/estimated speed in the bottleneck

$\rho_c$ – critical density

$\bar{\rho}_{M+1}(k)$ – measured/estimated density in the bottleneck

To implement this algorithm, the choice of the bottleneck capacity $Q_b -$ is very critical. Usually, it should be chosen as slightly lower than the actually observed maximum flow in the field for sustainable operation.

### 2.3 Density Based Regulator

$$u_M(k) = u_M(k-1) + \begin{cases} \varsigma_1 \cdot \left(\rho_c - \bar{\rho}_{M+1}\right), & \text{if} \quad \bar{\rho}_{M+1} < \rho_c \\ \varsigma_2 \cdot \left(\rho_c - \bar{\rho}_{M+1}\right), & \text{if} \quad \bar{\rho}_{M+1} > \rho_c \end{cases} \quad \text{(Eq. 2.2)}$$

where $\varsigma_1, \varsigma_2 > 0$ are control gains. The two control gains may be different to adapt to differences in the traffic situation. Such flexibility can also be used in an anti-windup strategy to avoid control oscillations. This algorithm is intended for the situation when the traffic density can be estimated reasonably well, which is the case if the road section is covered by a series of video cameras. To implement this algorithm, the choice of the bottleneck critical density $\rho_c$ is very critical, which is suggested to be 100 ~ 110, depending on vehicle types and the estimation accuracy.

### 2.4 Occupancy Based Regulator

In practice, the density can be replaced with occupancy, and the critical density replaced with critical occupancy:

$$u_M(k) = u_M(k-1) + \begin{cases} \varsigma_{o1} \cdot (O_c - o_{M+1}), & \text{if} \quad o_{M+1} < O_c \\ \varsigma_{o2} \cdot (O_c - o_{M+1}), & \text{if} \quad o_{M+1} > O_c \end{cases} \qquad \text{(Eq. 2.3)}$$

Where:

$\varsigma_{o1}, \varsigma_{o2} > 0$ are control gains

$O_c$ – critical occupancy

$o_{M+1}$ – measure/estimated occupancy in the bottleneck

The two control gains may be different to adapt to differences in the traffic situation. Such flexibility can also be used in an anti-windup strategy to avoid control oscillations. This algorithm is intended for the situation when the occupancy is the principal detection for the bottleneck traffic, which is the case if the road sensor is an inductive loop detector, particularly true in California. To implement this algorithm, the choice of the bottleneck critical density $O_c$ is very critical. Usually, it should be chosen around 12%. Of course, the density measurement also depends on the health of the loop detector data.

## 2.5 Speed Based Speed Regulator

Instead of using occupancy-based feedback control, we propose a speed-based feedback. It can be stated as:

- The speed in the bottleneck $\bar{v}_m(k)$ (assuming section *m* is a bottleneck, indexed from most downstream to the most upstream as we did before in [1]) is measured with fixed sensors and filtered with a low-pass filter to be suggested later (for smoothing the traffic; the objective is to reduce speed variations);
- Then the VSL/VSA at the bottleneck section, $u_m(k)$, is determined by

$$u_m(k) = \alpha_m \cdot \bar{v}_m(k)$$
$$\alpha_m \in [1.1, 1.5]; \text{ default value: } \alpha_m = 1.3 \qquad \text{(Eq. 2.4)}$$

- Then the VSL/VSA at the immediate upstream section relative to the bottleneck is determined by

$$u_{m+1}(k) = \begin{cases} V_{free}, & \text{if} \quad \underline{o}_m(k) < O_{sw} \\ \beta_m \cdot \underline{v}_m(k), & \text{if} \quad \underline{o}_m(k) \geq O_{sw} \end{cases} \qquad \text{(Eq. 2.5)}$$

$$\beta_m \in [0.7, 0.9]; \text{ default value: } \beta_m = 0.8$$

$V_{free}$ - free-flow speed

$\bar{o}_m(k)$ - measured occupancy in bottleneck section

$O_{sw}$ - the switching threshold of occupancy close to the capacity flow (suggested value for $O_{sw}$: 10.0~12.5%)

$\beta_m$ - the control gain parameter .

This algorithm is intended to delay traffic breakdown and for throughput improvement for heavy traffic. The threshold for occupancy for field implementation will need to be tuned based on sensor characteristics.

This algorithm can be implemented if both traffic speed and occupancy can be measured or estimated. This is the case if the road sensor detection station has dual inductive loop detectors, which is the case for most California freeways. The dual loop detector station by itself is good for vehicle length and speed estimation.

Now we need to determine the desired speed for all the cells upstream of the bottleneck.

## 2.6 Freeway Corridor VSA Algorithm Based on Distance

Once the most downstream bottleneck VSA has been determined, it is necessary to determine the upstream section's VSA. Assume that the effective section of the bottleneck is known, then further upstream traffic would be in free-flow. Through traffic data analysis, one can determine the sustainable free-flow location/section upstream in principle. If we do not consider other traffic fluctuations in between the most upstream free-flow section and the most downstream bottleneck, then the following distance-based interpolation algorithm can be used for determining the VSA for upstream sections along the freeway corridor. Starting from the most downstream bottleneck, the upstream VSAs are determined as follows:

- Define the freeway network to include coupled recurrent bottlenecks, which means that traffic behaviors of those bottlenecks would affect each other significantly;
- Traffic at the most upstream and most downstream ends of the freeway network are assumed to be free flow; therefore, the VSA can be computed; it is clear that this can always be achieved if the system scope is large enough;
- VSA at the bottleneck sections and their immediate upstream can be determined by the algorithm in the previous section;
- VSA at other sections in between the bottlenecks and the most upstream and downstream sections can be determined by distance-based interpolation.

The justifications for this approach are as follows:

(1) Bottleneck flow determines overall system performance. Since the algorithm is intended to operate the bottleneck at its capacity flow, therefore, each bottleneck tries to push traffic

forward. The question is: is the downstream bottleneck able to receive it? This will be analyzed as follows:

- If $F^u$ (upstream bottleneck flow) $> F^d$ (downstream bottleneck flow): this can only last for a certain period of time since the section between the two bottlenecks will be filled up; in this case, the downstream bottleneck can still be operated such that $F^d \approx F_c^d$ (downstream bottleneck capacity flow);
- If $F^u \le F^d$: this can only last for certain period of time, and then $F^u \approx F^d < F_c^d$ which is what one can do; this situation is due to either upstream bottleneck demand flow is lower, or $F_c^u$ (upstream bottleneck capacity flow) $< F_c^d$;
- If $F^u \approx F^d$: this is the ideal case for operation;

In summary: in all situations, application of the strategy for a freeway network could potentially improve overall system performance; however, when a section between two bottlenecks being used as storage fills up, it might block an off-ramp which may become a disadvantage, further analysis will be necessary to optimize and balance traffic storage to maximize all output flows.

(2) Distance-based interpolation of the VSAs at the bottlenecks has the following advantages:

- Traffic will be smoothed in each section (speed harmonization)
- VSA can be discretized as a constant in each section for feedback to the driver using a Changeable Message Sign, or can be continuous to be used as set-speed for vehicles with I2V communication and ACC, providing I2V CACC capabilities

(3) If the freeway has non-recurrent bottleneck(s), caused by incidents that can be detected, the algorithm can also be reconfigured for such a situation

### 2.7 Semi-Globally Looking-Ahead VSA Algorithm

However, if there are multiple bottlenecks along a freeway corridor with some of them to be recurrent and some are non-recurrent due to uncertainties in demand and driver behaviors, the distance-based based interpolation algorithm may not be a good option since a bottleneck upstream may significantly reduce the throughput and therefore could not provide the desired inflow for the downstream bottleneck. We therefore propose a new VSA algorithm which may be called a semi-globally looking-ahead VSA algorithm. This algorithm may be applied to any sensor detection modes such as occupancy, flow, speed and density. Since the occupancy is the principal detection mode in this project, we will use it to describe the VSA control design as follows.

(1) Determine the most downstream section ($i=1$) VSA according to Eq. 2.3;

(2) For section $i > 1$, loop detector speed and radar speed are used to calculate the VSA value as follows in several steps:

(b-1) Using speed data, occupancy data and predetermined speed

$$V_i^{VSA}(k) = \begin{cases} V_i^{d}(k) - K_i\left(O_i(k) - O_{i+1}(k)\right), & \text{if } O_i(k) > O_i^{T} \\ V_i(k), & \text{else} \end{cases}, \quad i = 1, \cdots, N$$

where $k$ is the time step (30 seconds in this field test), $i$ is the index of the VSA sign, $N$ is the number of VSAs, $O_i$ is the measured occupancy at the $i$ th VSA and $O_{i+1}$ is the downstream measured occupancy of the $i$ th VSA, $O_i^{T}$ is a threshold value of occupancy at the $i$ th VSA and $O_i^{T}$ is suggested to be 0.12, and $V_i$ is the measured speed at the $i$ th VSA. $K_i$ is a parameter and the suggested value is 0.5-0.7. $V_i^{d}$ is the desired speed at the $i$ th VSA, which is predetermined by the VSA designer. In this field test, $V_i^{d}$ is designed as a linear trend along the freeway mainline from the most downstream (the recurrent bottleneck location) to the most upstream. $V_i^{VSA}$ is the displayed speed value on the VSA device.

(b-2) Using weighted occupancy of next two downstream occupancy

$$V_i^{VSA}(k) = \begin{cases} \dfrac{\alpha_i}{\omega_i(k)}, & \text{if } O_i(k) > O_i^{T} \\ V_i(k), & \text{else} \end{cases}, \quad i = 1, \cdots, N$$

where $\alpha_i$ is a parameter, and $\omega_i$ is weighted occupancy computed as following:

$$\omega_i(k) = p_{i0}O_i(k) + p_{i1}O_{i+1}(k) + p_{i2}O_{i+2}(k),$$
$$p_{i0} + p_{i1} + p_{i2} = 1$$

A suggested set of parameters is $(p_{i0}, p_{i1}, p_{i2}) = (0.5, 0.3, 0.2)$.

Suppose the maximum flow $q_i^{max}$ of the mainline is 1800 vehicles per hour per lane. We want to regulate flow at 80% of the maximum flow, that is $0.8 \times 1800 = 1440$. Suppose vehicle density can be estimated by a constant $k_i^{occ}$ times occupancy, that is $\rho_i = k_i^{occ} O_i$ and $k_i^{occ} = 1.6$. The operation speed can be calculated by

$$V_i^{VSA} = \frac{0.8 \times q_i^{max}}{k_i^{occ} O_i} = \frac{\alpha_i}{O_i}$$

Therefore, $\alpha_i$ can be calculated as

$$\alpha_i = \frac{0.8 \times q_i^{max}}{k_i^{occ}} = \frac{0.8 \times 1800}{1.6} = 900$$

(b-3) Calculate the weighted occupancy of the next M downstream occupancy

This is a general version of using the weighted occupancy of the next two downstream occupancies:

$$V_i^{VSA}(k) = \begin{cases} \dfrac{\alpha_i}{\omega_i(k)}, & \text{if } O_i(k) > O_i^{T} \\ V_i(k), & \text{else} \end{cases}, \quad i = 1, \cdots, N$$

where $\alpha_i$ is a parameter, and $\omega_i$ is the weighted occupancy computed as follows:

$$\omega_i(k) = p_{i0}O_i(k) + p_{i1}O_{i+1}(k) + \cdots + p_{iM}O_{i+M}(k),$$
$$p_{i0} + p_{i1} + \cdots + p_{iM} = 1$$

(b-4) Choosing weight factor as follows. There are two approaches:

- The following emphasizes the high occupancy downstream

$$p_{ij} = \frac{\omega_j}{\sum_{k=i}^{M} \omega_k}, \quad j = i, i+1, \dots, M$$

- The following put higher weight on the high occupancy downstream even more:

$$p_{ij} = \frac{\omega_j^2}{\sum_{k=i}^{M} \omega_k^2}, \quad j = i, i+1, \dots, M$$

(b-5) Using the weighted speed of the next two downstream speeds

$$V_i^{VSA}(k) = \begin{cases} \beta_i V_i^{w}(k), & \text{if } O_i(k) > O_i^T \\ V_i(k), & \text{else} \end{cases}, \; i = 1, \cdots, N$$

where $\beta_i$ is a parameter, and $V_i^{w}$ is weighed speed computed as follows:

$$V_i^{w}(k) = p_{i0} V_i(k) + p_{i1} V_{i+1}(k) + p_{i2} V_{i+2}(k),$$
$$p_{i0} + p_{i1} + p_{i2} = 1$$

A suggested set of parameters is $(p_{i0}, p_{i1}, p_{i2}) = (0.5, 0.3, 0.2)$.

(b-6) Calculate the weighted speed of the next M downstream occupancy

This is a general version of using weighted speed of next two downstream speed

$$V_i^{VSA}(k) = \begin{cases} \beta_i V_i^{w}(k), & \text{if } O_i(k) > O_i^T \\ V_i(k), & \text{else} \end{cases}, \; i = 1, \cdots, N$$

where $\beta_i$ is a parameter, and $V_i^{w}$ is weighed speed computed as follows:

$$V_i^{w}(k) = p_{i0} V_i(k) + p_{i1} V_{i+1}(k) + \cdots + p_{iM} V_{i+M}(k),$$
$$p_{i0} + p_{i1} + \cdots + p_{iM} = 1$$

(b-7) Check all downstream free flow conditions

The VSA algorithm has a rule to determine if all downstream is in free flow speed or near free flow speed, such that the driver in the upstream can drive at a proper speed. The following rule is placed after $V_i^{VSA}(k)$ calculation. If occupancy of VSA i and all downstream occupancies of VSA i are less than a certain value, the calculated $V_i^{VSA}(k)$ will be overwritten by a proper speed value.

if (occupancy of VSA i <0.2 and all downstream occupancies of VSA i < 0.2){

$$V_i^{VSA}(k) = 45$$

} else if (occupancy of VSA i <0.15 and all downstream occupancies of VSA i < 0.15){

$$V_i^{VSA}(k) = 55$$

}else if (occupancy of VSA i <0.12 and all downstream occupancies of VSA i < 0.12){

$$V_i^{VSA}(k) = 65$$

}else{

// do nothing, use calculated $V_i^{VSA}(k)$
}

(3) Bound Limit: after the determination of the VSA for each upstream section as above, it is necessary to add some bound limit for the change of VSA between two consecutive locations at each time step, and at consecutive time steps at the same location. This can be achieved as follows:

- For each location, compared to the previous time step:

if $V_i(k) > V_i(k-1) + 20$
{
$V_i(k) = V_i(k-1) + 20$
}
if $V_i(k) < V_i(k-1) - 20$
{
$V_i(k) = V_i(k-1) - 20$
}
$i = 1, 2, \ldots, M$

- For each location, compared to its upstream location at the same time:

if $V_i(k) > V_{i-1}(k) + 20$
{
$V_i(k) = V_{i-1}(k) + 20$
}
if $V_i(k) < V_{i-1}(k) - 20$
{
$V_i(k) = V_{i-1}(k) - 20$
}
$i = 2, \ldots, M$

- For each location, compared to its upstream location at the previous time step:

if $V_i(k) > V_{i-1}(k-1) + 20$
{
$V_i(k) = V_{i-1}(k-1) + 20$
}
if $V_i(k) < V_{i-1}(k-1) - 20$
{
$V_i(k) = V_{i-1}(k-1) - 20$

}

$i = 2, \ldots, M$

- For each location, compared to its upstream location 2time steps before

if $\quad V_i(k) > V_{i-1}(k-2) + 30$

{

$V_i(k) = V_{i-1}(k-2) + 30$

}

if $\quad V_i(k) < V_{i-1}(k-2) - 30$

{

$V_i(k) = V_{i-1}(k-2) - 30$

}

$i = 2, \ldots, M$

### 2.8 Conclusion

The above algorithm, although simple in concept, is pretty general in the sense that:

- It always looks ahead 2~3 sections of traffic downstream in the determination of the current section's VSA. This is looking ahead in distance and therefore a prediction in time since the traffic is flowing from the upstream to the downstream, which could effectively reduce shockwave with such a feedback approach;
- The process of looking ahead at each time step may be extrapolated to cover the whole freeway corridor, with each section inter-linking directly to its immediate neighbors. Although this process is not global, it could be considered as semi-global;
- Each section could provide a reasonable in-flow to its immediate downstream section, which is what we need; however, we could claim optimality from a system point of view;
- The algorithm is robust with respect to the traffic detection;
- Its tested algorithm can be widely applied to freeway corridors with multiple bottlenecks.

# 3 Preparation for Field Implementation

Since the CRM we developed and implemented before was in operation along the SR-99 NB corridor, this project only needs to add the combined CRM and VSA algorithm in the implementation.

Before field implementation of VSA, we made several necessary preparations which include:

- VSA sign requirement design and selection
- Application for field test permission
- Determining the messages to be displayed on the VSA signs
- Location considerations of the VSA signs in the field
- Developing a detailed feasible Test Plan

## 3.1 VSA Sign Considerations

The following was the VSA sign technical specifications which we used in the search for qualified equipment:

- Large size: 4 ft (height) x 5 ft (width), or larger
- With solar panel and battery for sustainable power supply; solar panel will charge the battery; the number of batteries is flexible
- Able to change the displayed message in real-time: updatable at least 2/minute (every 30 s)
- Mounted on trailer already, which meets Caltrans (California Department of Transportation) traffic safety requirement
- Modem connection for remote control; we can add the modem
- With built-in radar for traffic speed detection
- Must be MUTCD compliant

The project team investigated over 10 vendors, sale or rental, across the US and finally selected the product of American Signal Company (Amsig) as the VSA signs to be used for the test: CMS-GP232T 3’x6′ Full Matrix Display. The following are the details of the technical specifications of this product:

- Dimensions: 60” (W)x (48)” H
- Full Matrix 28 Rows x 72 Columns
- Cellular (CDMA / IXRTT , GSM / GPRS)
- Landline or Ethernet (TCP / IP) Options
- Radar Speed Detection and Data Logging
- AIMSTAR™ Adjustable Solar Assembly
- NTCIP Compliant
- 26 MUTCD symbol signs are available

The following Figure 1  shows the real picture of the VSA signs in the manufacture's shop.

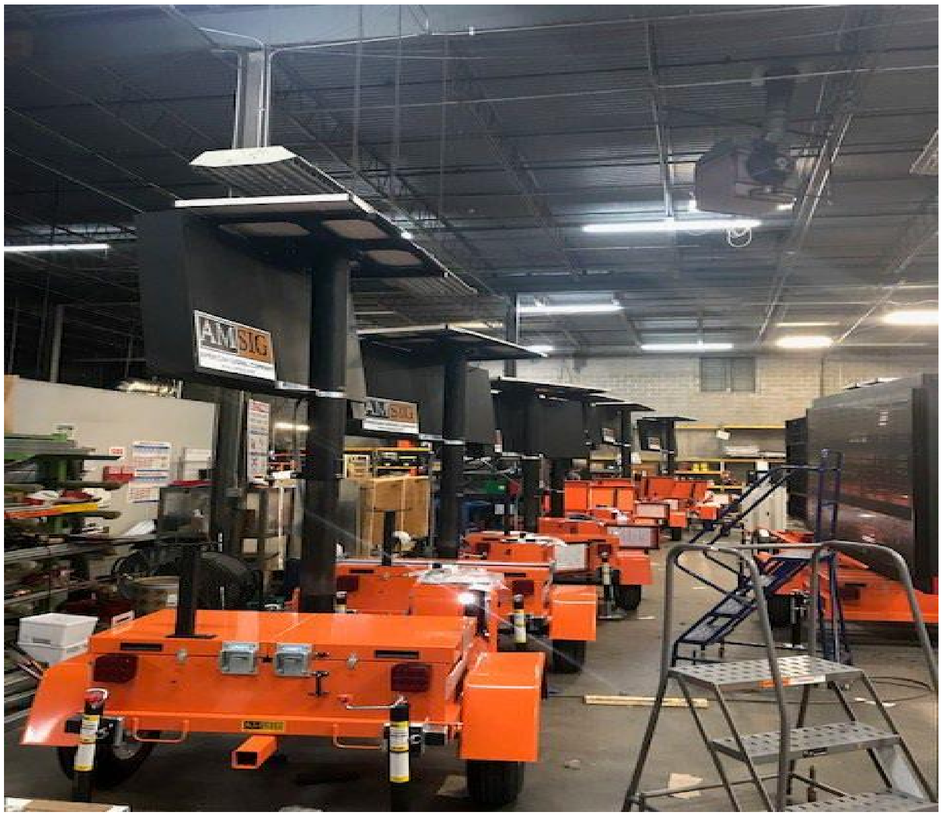



Figure 1 VSA signs in the Workshop of American Signal Company (ASC)

The electronic variable speed display portion are orange LED numbers on black background following Manual on Uniform Traffic Control Devices (MUTCD) W13-1P. The MUTCD Section 2C addresses advisory speed signs including the W13-1p, but it is fixed sign instead of a variable speed sign to be used in this test.  According to FHWA, any changeable message sign should be able to display up to three pages alternatively with each page present for a minimum of 3 seconds. We suggest using two pages as follows: page 1 displays "CONGESTION AHEAD"; page 2 displays the VSA number, e.g. 35 [mph].

All VSA units will be equipped with solar panels and batteries and operated and monitored remotely during the operational hours. The power is adequate for the operation as confirmed with the manufacturer.

The LED display with the suggested size and color scheme is commercially available.

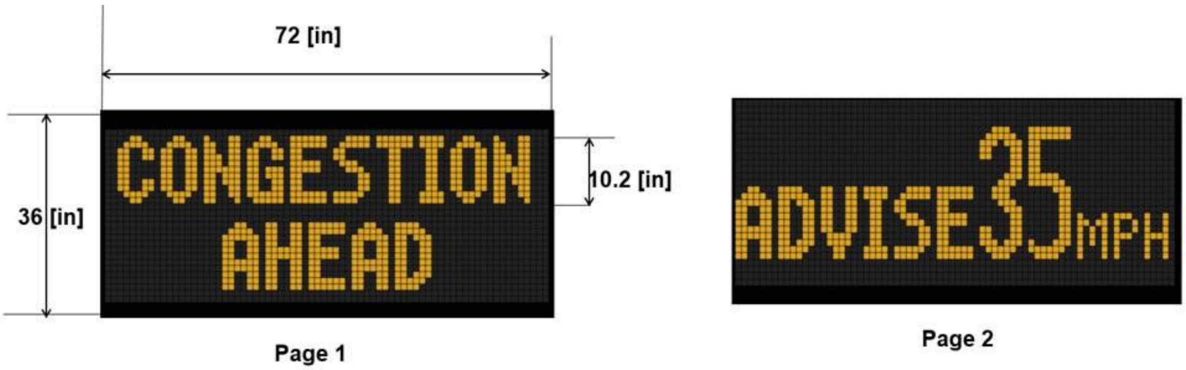



Figure 2. VSA Signa Message design and 2 display pages


Figure 3. Real VSA Display Style, Dimensions, Color Schemes, and Messages

**Other Components**:

The radar unit on each VSA sign collected aggregated traffic speed data every 30 [s] and sent it back through the modem to a central application for analysis.

Modem and internet connection between PATH computer, the Cloud and the VSA signs in the field – update every 30 [s]. Solar panel and batteries to provide sustainable power for operation on each unit for the proposed test period on weekdays.

### 3.2 Field Test Permission Application

The permission application of the field test took a much longer period of time than what we previously expected.

We first got the permission from Caltrans HQ and MUTCD approval rather quickly in 2020 since the VSA sign we selected were MUTCD compliant. After that, CA Traffic Control Devices

Committee (CTCDC) unanimously granted permit for using the proposed VSA sign for field test for similar reasons in 2020. The application is in Appendix 2.
However, the permission application from FHWA was not that smooth. We first applied the permission with Caltrans DRISI in 2020 but it was rejected. We then applied again with Caltrans DRISI with more justifications. This was approved in 2021 with recommendations on display character size etc.

### 3.3 Displayed Message Determination

The project team then discussed with the project panel regarding the message to be displayed. We initially suggested the following messages for the two pages to be alternately displayed on the VSA sign:

- Page 1: **Congestion downstream**
- Page 2: **VSA: 35 mph**

After several roundtable discussions, the panel agreed to use the following messages on the two alternative pages:

- Page 1: **CONGESTION AHEAD**
- Page 2: **ADVISE 35 MPH**

with all letters capitalized.
It is noted that the actually calculated VSA numbers could be non-integers which are all rounded to the nearest multiple of 5 for displaying.

### 3.4 Locations of VSA Sign Location Considerations

In principle, the VSA signs should be put immediately downstream of the onramps where there is a location on the roadside. If a section has two onramps from different directions, then the VSA sign should be put immediately downstream of both onramps, not in between.

The project team made several trips to the field to determine the location of the VSA signs. The following factors have been used in the consideration: (a) an adequately wide shoulder available; (b) the upstream of the VSA sign is a straight road so that drivers have a good visibility above 150~200 m; (c) maximum exposure to the sun for adequate power from the solar panel; (d) if not on the shoulder, the location should be level with the freeway; (e) not on a bridge nor in a tunnel; (f) no other road side signs to avoid distraction. The following Table 3. Selected GPS locations of the 10 VSA signs along the SR-99 NB Corridor shows the GPS coordinates of the selected 10 VSA sign location on SR-99 NB corridor.

Table 2. Selected GPS locations of the 10 VSA signs along the SR-99 NB Corridor

| VSA Sign ID | Upstream Onramp Name, SR99 NB | Field Selected Locations GPS Coordinates (N, W) | Revised GPS Locations (N, W) |
|---|---|---|---|
| 1 | Elk Grove | (38 24' 38"N, 121 23' 21" W) | (38 24' 38"N, 121 23' 21" W) |
| 2 | ond St. (Laguna Blvd | (38 25' 53"N, 121 23' 55" W) | (38 25' 53"N, 121 23' 55" W) |
| 3 | Sheldon | (38 27' 04"N, 121 24' 27" W) | (38 27' 04"N, 121 24' 27" W) |
| 4 | Calvine Road | (38 27' 37"N, 121 24' 42" W) | (38 27' 37"N, 121 24' 42" W) |
| 5 | Mark Road 1 | (38 28' 42.9"N, 121 25' 37.7" W) | (38 28' 42.9"N, 121 25' 37.7" W) |
| 6 | Mark Road 2 | (38 29' 23"N, 121 26' 20" W) | (38 29' 23"N, 121 26' 20" W) |
| 7 | Florin Road | (38 30' 29.1"N, 121 27' 29.7" W) | (38 30' 29.1"N, 121 27' 29.7" W) |
| 8 | 47th Ave | (38 31' 21.3"N, 121 27' 58.2" W) | (38 31' 21.3"N, 121 27' 58.2" W) |
| 9 | Fruitridge Road | (38 32' 05"N, 121 28' 21" W) | (38 32' 05"N, 121 28' 21" W) |
| 10 | 12th Ave 1 | (38 32' 39"N, 121 28' 25" W) | (38 32' 39"N, 121 28' 25" W) |

The following Table 4 shows the VSA sign locations versus ramp metering locations at the onramps along SR-99 NB corridor. It can be observed that some sections have a VSA sign but others do not. This is mainly based on the length of a section. Those that do not have a VSA sign are usually short sections.

Table 3. VSA Sign locations vs. onramp CRM meter locations along the SR-99 NB corridor

| Onramp ID | Street Names | RM strategy | VSA Sign # | Filtered ML data Sec ID | * | Onramp ID | Street Name | RM strategy | VSA Sign # | Filtered ML data Sec ID |
|---|---|---|---|---|---|---|---|---|---|---|
| 1 | Stockton Blvd | CRM | | | * | 10 | Mack Road WB | CRM | VSA 5 | |
| 2 | Elk Grove | CRM | VSA 1 | | * | | 2nd VSA | **No** | VSA 6 | |
| 3 | Laguna Blvd EB | CRM | | | * * | 11 | Florin EB | CRM | | |
| 4 | Laguna Blvd WB | CRM | VSA 2 | | * * | 12 | Florin WB | CRM | VSA 7 | |
| 5 | Sheldon EB | CRM | | | * | 13 | 47th Ave EB | CRM | | |
| 6 | Sheldon WB | CRM | VSA 3 | | * | 14 | 47th Ave WB | CRM | VSA 8 | |
| 7 | Calvine EB | CRM | | | * | 15 | Fruitridge EB | CRM | | |
| 8 | Calvine WB | CRM | VSA 4 | | * | 16 | Fruitridge WB | CRM | VSA 9 | |
| 9 | Mack Road EB | CRM+VSA | | | * * | 17 | 12th Ave | CRM | VSA 10 | |
| | | | | | * * | 18 | Downstream of 12th Ave | | | |

N. B. The sequential order is the same as the traffic moving direction.

Since the VSA signs will be located after the EB-WB onramps, the data to be used should be further downstream data.

CRM uses upstream data but VSA uses downstream Occupancy data.

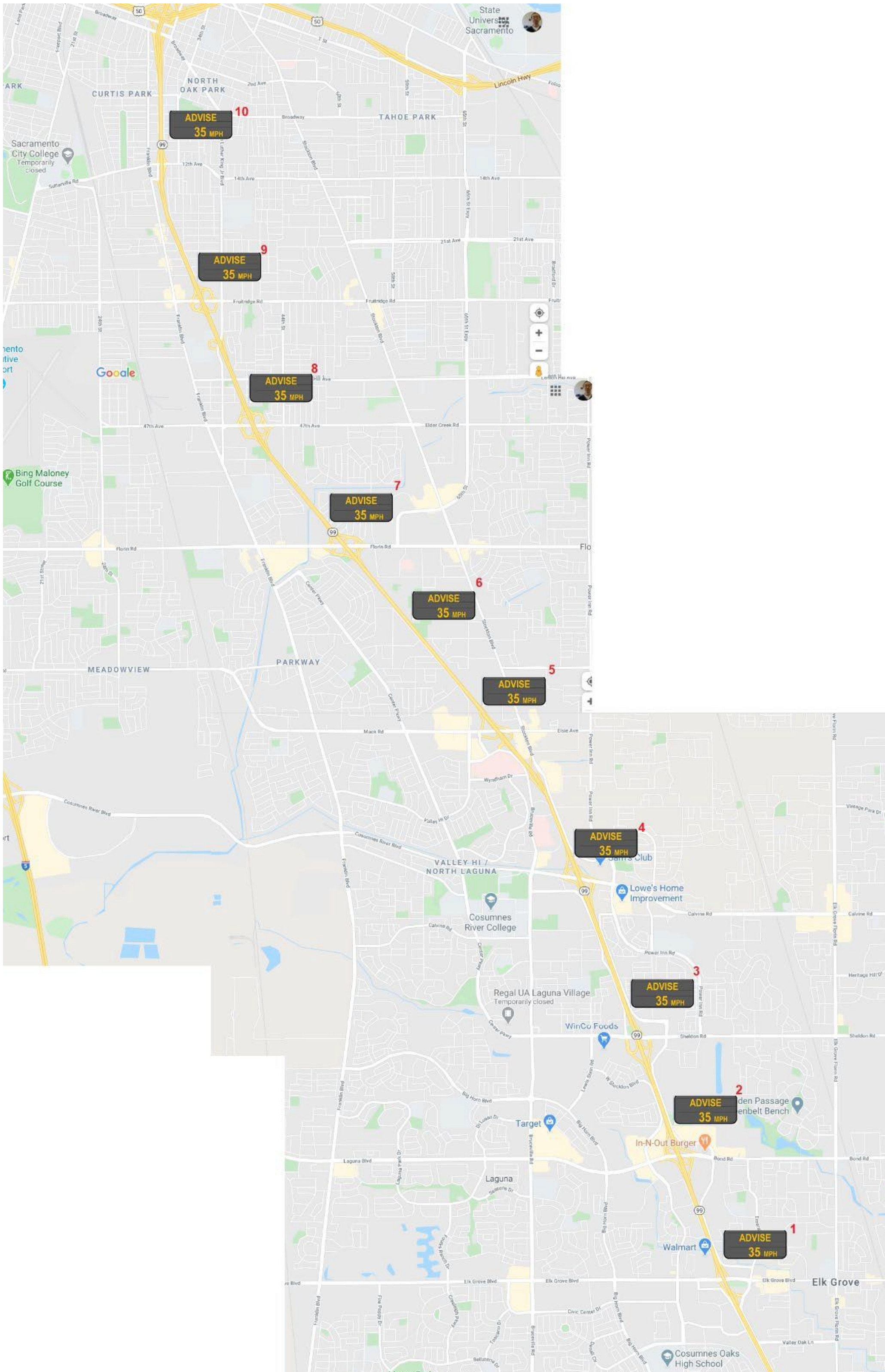
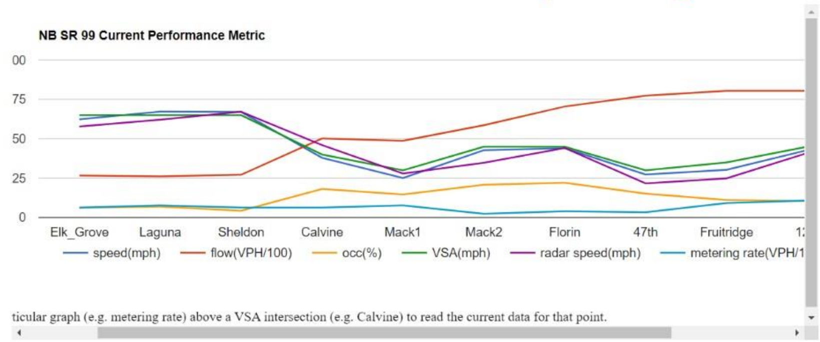


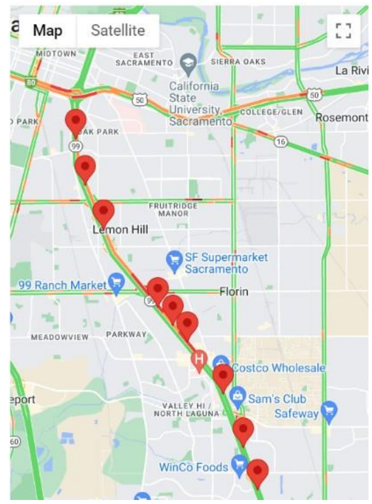

Figure 4. Schematic locations of 10 VSA signs inlay over the Google Map on SR-99 NB Corridor

### 3.5 System, Monitoring and Traffic Observation

For the convenience of traffic observation and system monitoring for the combined CRM and VSA field test, the PATH team has developed a website which can be accessed by the whole project panel and the public. The website address is: [http://128.32.234.154/VSA_CRM/](http://128.32.234.154/VSA_CRM/) . The following is an example of the website. This website is updated every 30 s.

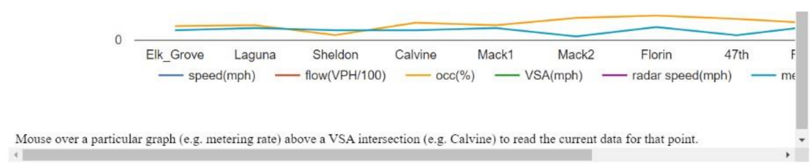
**Combined Coordinated Ramp Metering and Variable Speed Advisory**

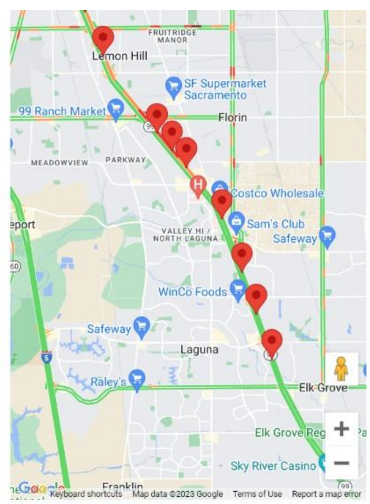



| Traffic Monitoring Table (red=invalid data) | | | | |
|---|---|---|---|---|
| Controller Name | Flow (VPH) | Speed | Occupancy | Density |
| E_Stockton | 3480.0 | 64.2 | 9.0 | 31.2 |
| Elk_Grove | 3480.0 | 64.2 | 9.0 | 31.2 |
| Laguna_EB | 3240.0 | 66.0 | 7.6 | 30.3 |
| Laguna_WB | 4080.0 | 64.9 | 9.0 | 30.8 |
| Sheldon_EB | 3960.0 | 69.0 | 7.9 | 29.0 |
| Sheldon_WB | 3960.0 | 69.0 | 7.9 | 29.0 |

Figure 5. CRM & VSA website for real-time traffic monitoring




| Traffic Monitoring Table (red=invalid data) | | | | |
|---|---|---|---|---|
| Controller Name | Flow (VPH) | Speed | Occupancy | Density |
| E_Stockton | 1920.0 | 57.4 | 5.1 | 33.4 |
| Elk_Grove | 1920.0 | 57.4 | 5.1 | 33.4 |
| Laguna_EB | 2280.0 | 73.6 | 4.3 | 27.2 |
| Laguna_WB | 3540.0 | 67.0 | 7.2 | 30.2 |
| Sheldon_EB | 3480.0 | 56.1 | 12.2 | 35.7 |
| Sheldon_WB | 3480.0 | 56.1 | 12.2 | 35.7 |
| Calvine_EB | 3240.0 | 73.1 | 6.8 | 27.4 |
| Calvine_WB | 2040.5 | 32.1 | 4.3 | 25.8 |
| Mack_Rd_EB | 1380.5 | 34.4 | 2.9 | 24.7 |
| Mack_Rd_WB | 5520.0 | 75.0 | 4.9 | 20.2 |
| Florin_EB | 6360.0 | 44.1 | 16.2 | 82.5 |
| Florin_WB | 5100.0 | 56.5 | 10.3 | 36.8 |
| 47th_EB | 4980.0 | 48.6 | 14.4 | 48.7 |
| 47th_WB | 6420.0 | 33.5 | 21.9 | 60.6 |
| Fruitridge_EB | 6300.0 | 52.1 | 14.2 | 41.6 |
| Fruitridge_WB | 6300.0 | 52.1 | 14.2 | 41.6 |
| 12th_St | 5520.0 | 66.7 | 7.2 | 30.0 |

Figure 6. CRM & VSA website for real-time traffic monitoring, with full data table

The above Figure 5 and Figure 6 are the appearance of the website the PATH team has developed for observation and monitoring of the real-time traffic, the data system and the traffic state parameters. Figure 5 is focused on traffic state parameters' plot for each section of the corridor. Those parameters include: fused speed, flow, occupancy, VSA (advisory speed), radar speed, and ramp metering rate of CRM. Those plots can be used to observe if the VSA advisory speed and CRM rate calculated are reasonable.

Figure 6 is focused on the lower part of the loop detector station health condition, which also includes the traffic state parameters from the detector stations. Observe those parameters will be able to tell if those field detector station data is healthy.

The right side is the Google real-time traffic map of the SR99 NB test section. The color code over the map tells the current traffic situations. The bubbles' locations are the VSA sign locations. Each bubble contains the traffic state parameters including VSA advisory speed and CRM rate at the location, which can be viewed by putting the mouse over it.

# 4 Field Implementation and Operational Test

According to the test plan we presented before, after installing the VSA signs in the field and getting them all connected with Amsig, we started the field test progressively. In this chapter, we present the details of the field test initially started from December 2021. During the first few months, the VSA control could not be activated fully because many detector stations in the field were off due to several construction projects in the SR-99 corridor overlapping with our test sections. Therefore, the project team progressively working with Caltrans District 3 to get most of the loop detector stations in the field back to normal working condition. This is also required by the CRM algorithm running previously on that corridor.

## 4.1 Concept of Operation

The overall control systems structure and the preliminary Concept of Operation (ConOps) are shown in Figure 1 below.

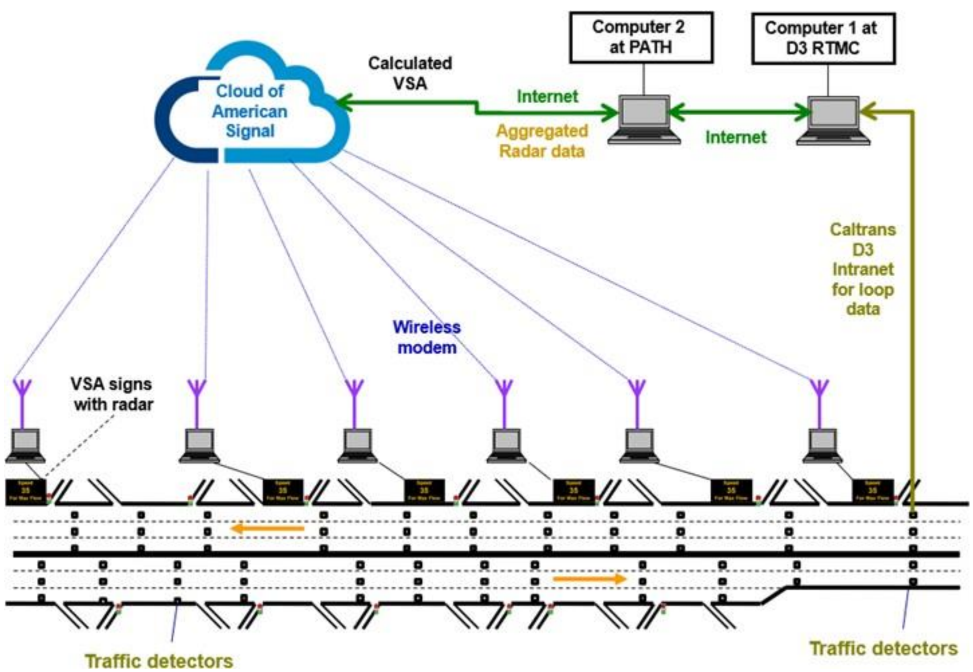



Figure 7. ConOps System Structure for Combined CRM and VSA

Main functions and data flow of each component for the ConOps in Figure 7 are briefly described as follows:

- PATH Central Control Computer located in Caltrans District 3 TMC has the following functionalities:

- Direct link with 2070 RM controllers in the field and obtaining Real-Time (RT) traffic data (**red line**) through Caltrans District 3 intranet.
- Data mapping based on the IP address of the data with the location of the detector in the freeway corridor modeling.
- Estimate traffic state parameters of the corridor; fusing traffic detector data and radar traffic speed data.
- Calculate RM rate for each onramp with the CRM algorithm using the CRM module.
- Calculate VSA for each section based on the traffic state parameter with the VSA module.
- Sending RM rate to 2070 controller for execution through the intranet (**blue line**) through D3 Intranet.
- Sending the corresponding advisory speed to each VSA sign for display (update time interval: 30s) through 4G wireless modem connection (**dotted green line**).

## 4.2 Field Test Plan

The following is a tentative Test Schedule for system preparation and progressive tests:

Table 4 Test Plan Schedules

| Actions/Activities | Start Date | End Date | Comments |
|---|---|---|---|
| Interface and system integration of 10 Trailers Responsible: PATH, John and David | 5/20/21 | 8/25/21 | |
| Preparing trailer 10 Trailers for ready to ship to D3 Responsible: PATH, David | 8/28/21 | 9/10/21 | 10 trailers ready to leave |
| Transport 10 trailers to D3 Maintenance Yard/install signs Responsible: PATH-David | 9/30/21 | 10/1/21 | Ready to go to the field |
| Install trailers and VSA signs in the field Responsible: PATH-David (Need D3 engineers to help) | 10/4/21 | 10/6/21 | VSA signs ready in the field |
| Integrate VSA signs and the real-time Website Responsible: PATH, John | 6/20/21 | 10/8/21 | VSA signs and website are integrated |
| System checking/integration/Dry run and verification in the field Responsible: PATH-John, Dave, Xiao-Yun | 10/6/21 | 10/8/21 | VSA signs and Website working for field test |
| Message display test period starting Responsible: Caltrans-D3 Engr; PATH: John and Dave | 10/11/21 | 10/15/21 | Display VSA test in progress messages |
| Week 1 preliminary test Responsible: Caltrans-D3, PATH-Xiao-Yun, John, Dave | 11/15/21 | 11/19/21 | Make necessary adjustments and system tuning/improvement |

| | | | |
|---|---|---|---|
| From Week 2: Extensive tests<br>Responsible: Caltrans-D3, PATH-Xiao-Yun, John, Dave | 11/22/21 | 11/23/22 | Including extensive data collection and progressive monitoring and tuning; if further funding is available; otherwise, end date will be 4/29/22 |
| Remove trailers from field to D3 Maintenance Yards or leave there for operation (TBD)<br>Responsible: D3-PATH | 11/24/22 | 11/25/22 | D3 maintenance Division would like to keep the 10 VSA signs |

### *1.1.1 Progressive Test Procedure*

The PATH project team will adopt the following progressive test procedure to reduce/avoid any negative impacts on daily traffic operation on the SR99 NB test section in Caltrans District 3. The progressive test procedure consists of three steps: practice-run, initial test, and extensive test. The test will continue as planned even in the event that any one VSA sign does not work or has been damaged or stolen. This should not affect the test greatly since the immediate upstream and downstream signs will provide the relevant speed information to the motoring public.

It is noted that the CRM will keep running for all the progressive stages listed below.

### *4.2.1 Traffic Data Use*

- Traffic speed data acquisition from the radar units on the 10 VSA signs (every 15~30s, independent from the traffic detector data from internet)
- Process the traffic data to generate traffic state parameters for each section by fusing both radar data and loop detector data from D3 in real-time
- It would be desirable if the Inrix real-time mobile traffic data is available since this will compensate for the missing loop detector data during construction period
- The real-time Inrix data could be saved for the performance analysis after the test together with the PeMS data

### *4.2.2 Before System Activation-Dry Run (the Week before starting)*

During the week before starting the test, PATH project team will check if the system is properly integrated using the steps outlined below. This will be verified through a practice trial (Dry Run) starting one week before the real test is to begin:

- VSA control system reads the field traffic detector data every 30s
- Calculate advisory speed for each section using PATH developed VSA algorithm
- Save all the processed data and the calculated advisory speeds to files without sending to the roadside VSA signs for display

- Analyze all the saved data to make sure that the overall system works properly
- Present the practice trial results to the project panel
- Make revisions or adjustments if necessary and address any comments by D3 freeway traffic engineers and the project panel

#### *4.2.3 Preliminary Field Test of VSA (Week 1):*

On the first day the VSA display is implemented in the field, all the project panel members will be invited to the D3 Regional Traffic Management Center. PATH team members will closely monitor the system behavior. The traffic will be displayed to the panel during the test starting period using the website developed. The following progressive switch-on process will be adopted on Day 1 of the first week:

- Activate VSA in non-peak hours for a short time to check if the system functions correctly; PATH staff will drive along the SR-99 NB Corridor test section to check that displays are functioning correctly
- Evaluate if the displayed VSA messages are appropriate and make changes or refinements if necessary
- Activate VSA in PM peak hours (which has less traffic volume)
- Evaluate again if the displayed VSA messages are appropriate, and make changes/refinement if necessary
- Activate VSA in AM peak hours with close traffic monitoring and data collection
- Data analysis for preliminary assessment of the behavior of VSA for Day 1, which will be reported to the project panel through email
- Data analysis for preliminary assessment of the performance of VSA for Week 1, which will be reported to the project panel through email
- D3 needs to have a freeway traffic engineer to watch out the system and give feedback to PATH

After Day 1, a preliminary test including system adjustment/tuning will be conducted for the rest of the first week for both AM peak periods. These tests will confirm the most downstream bottleneck location and be used to adjust the corresponding VSA sign location if necessary. The PATH team will closely monitor the traffic situation, overall control systems, displays in the field, and website real-time update, etc. The project panel will be updated daily during the testing progress for this week.

#### *4.2.4 Extensive Tests of VSA (from Week 2)*

From Week 2 to the test end, the VSA control will be primarily operated during AM peak hours, or both AM and PM peak hours if the solar panel and battery power permit. Data will be collected during the test period for analysis and algorithm refining/tuning. PATH project team members will monitor the overall system remotely, refining the system if necessary and addressing any comments or concerns from D3 freeway traffic engineers and the public. The project panel will be updated with the progress, as well as any pros and cons observed at the end of every week.

The test will continue in case of incident/accident or the test section including a Work Zone. PATH team intends to design a VSA algorithm to handle non-recurrent bottlenecks caused by incident/accidents in the test section. This requires that the bottleneck flow maximization algorithm be applied to the detected non-recurrent bottleneck, and that the VSAs in its upstream be reshaped to harmonize the traffic and to provide appropriate in-flow rate to the non-recurrent bottleneck. However, to achieve this goal, it is necessary to revise and tune the algorithm progressively during the test.

#### *4.2.5 Test Deliverable Update to the Project Panel*

During the first week of testing, the project panel will be provided with daily updates through email briefing. Beginning week 2 the panel will get weekly progress reports. The project panel can also observe the traffic, CRM rates and VSA at a public Website.

The following information will be provided to the project panel near the end of the tests:

- Actual traffic situation of the test corridor based on sensor data and Google Traffic
- The VSA message that was displayed on the signs in the field during testing period that day/week
- Driver compliance rate estimation near the VSA signs based on radar data
- System performance of the VSA control for efficiency improvement
- Any system modifications that have been made such as tuning or refining
- Any issue or feedback that has been addressed from either the project panel or the driving public

### 4.3 Operational Test Monitoring and Algorithm Refinement

After system integration and the initial tests, PATH project team conducted several rounds of algorithm refinement and tuning to make the VSA displayed more reasonable. The project team then continued monitoring the website: http://128.32.234.154/VSA_CRM/ for the traffic situation and also responded to Caltrans District 3 traffic engineers for any incidents and accidents they observed in VSA sign display problems, and any damage due to driver crash etc. The team conducted data analysis for system performance and health check.

## 4.4 Regular Maintenance of VSA signs in the Field

Besides monitoring VSA trajectories and data on the website, PATH team has made several trips to the field to observe the display on the signs in the field. In particular, we work with Caltrans District 3 maintenance Yard at Elk Grove to repair and change the damaged VSA signs due to vehicle crashing.

# 5 Traffic Performance Analysis and Results

This chapter describes the quantitative analysis of the performance for the field test of CRM and VSA. To be objective in the analysis, we have used PeMS 1-hour performance data which are independent from our test data. The performance analysis has been conducted in two aspects: mobility and safety. The mobility analysis has used the ratio (TTD/TTT) which can be explained as the average traffic speed in hourly intervals. This ratio is also celled efficiency in PeMS, which can be considered as how efficient the highway is used. Another similarly important factor is the demand. It is particularly interesting to look at the ratio when the demand increases, which measures robust performance of the traffic control approach.

Since the CRM changes the demand from the onramp and VSA changes driver behavior in the mainline, it would make sense to find out how the combination and CRM and VSA could affect safety. Similarly, we have used PeMS data for this analysis. The data were from two sources:

- California Highway Patrol (CHP)
- State Highway Safety Improvement Program (HQ)

For data quality, we only used the data for which the loop detector stations in the field had at least 70% valid observations.

## 5.1 Data Source and Time Period

Although we saved all the engineering data from the algorithm, for an objective quantitative analysis, we used PeMS historical data. Specifically, we have used PeMS historical data for the analysis in mobility and safety during the test period. We also considered the effect of COVID-19 which could possibly affect the traffic demand significantly.

The following parameters are considered:

Q = VMT/VHT which is the ratio of Total Travel Distance and Total Travel Time. In fact, it is average distance mean speed in miles-per-hour.

VMT (Vehicle Miles Traveled): to evaluate the demands, we use the VMT as an independent parameter.

Number of Lane Points: This is another indicator of data health.

Percentage of data observed: this the measure of the data health. We prefer to use traffic data which has at least 80% health observation for most loop detector stations in the period of performance analysis.

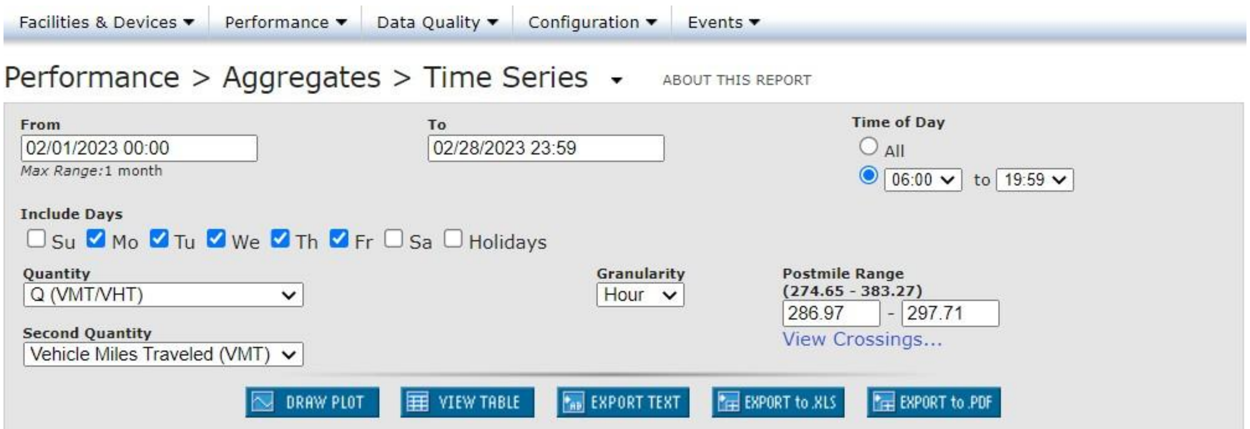



Figure 8. PeMS data selected for performance analysis

Considering the pandemic COVID-19 effect and detector stations healthy conditions due to several construction projects along the SR-99 corridor test sections, we choose the following time periods for comparison in performance analysis:

- June 1, 2015 ~ Dec 31, 2015 when the CRM and VSA were not implemented.
- Feb 2, 2016 ~ Sep 1, 2016 when the CRM and VSA were not implemented.
- June 27 2022 ~ Apr 30, 2023 when the CRM and VSA were implemented and in action.

The first two time periods are before the pandemic period which started from 2020. The third time period is after the pandemic when most traffic has recovered.

We only use data for Monday through Friday and removed weekends as shown in Figure 8.

The operation hours used for analysis is: 6:00am ~ 10:00am and 3:00pm~7:00pm.

## 5.2 Mobility Improvement

The following Table 5 shows the monthly performance parameters: Q= VMT/VHT, VMT, average percentage health observation of the loop detector station in the field.

The table after, is the average across all the months during the analysis period.

Table 5. Monthly average mobility performance parameters

| | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| | 7/1 ~ 7/31/2022 | 8/1 ~ 8/31/2022 | 9/1 ~ 9/30/2022 | 10/1 ~ 10/31/2022 | 11/1 ~ 11/30/2022 | 12/1/2022 ~ 12/31/202 | 1/1-1/31/2023 | 2/1 -2/28/2023 | 3/1 -3/31/2023 | 4/1 -4/30/2023 |
| Q | 61.75 | 57.10 | 55.86 | 56.66 | 58.49 | 59.19 | 58.54 | 57.17 | 57.46 | 57.12 |
| % Observed | 90.40 | 92.66 | 93.90 | 90.57 | 81.97 | 90.64 | 86.54 | 88.97 | 87.42 | 94.29 |
| VMT | 48648 | 50,311 | 50,380 | 50,186 | 46732.56 | 47,349 | 45,105 | 47,107 | 47,075 | 48,967 |
| | | | | | | | | | | |
| | | | | | | | | | | |
| | | 2/2 ~ 3/1/2016 | 3/2 ~ 4/1/2016 | 4/2 ~ 5/1/2016 | 5/2 ~ 6/1/2016 | 6/2 ~ 7/1/2016 | 7/2 ~ 8/1/2016 | 8/2 ~ 9/1/2016 | | |
| Q | | 52.58 | 53.76 | 51.61 | 52.74 | 54.29 | 54.17 | 53.40 | | |
| % Observed | | 90.58 | 85.61 | 85.50 | 81.26 | 78.54 | 80.19 | 84.15 | | |
| VMT | | 46,599.14 | 45,637.69 | 46,479.04 | 46,342.48 | 46,096.56 | 46,474.75 | 46,445.69 | | |
| | | | | | | | | | | |
| | 6/1 ~ 6/30/2015 | 7/1 ~ 7/31/2015 | 8/1/ ~ 8/31/201 | 9/1 ~ 9/30/2015 | 10/1 ~ 10/31/2015 | 11/1 ~ 11/30/2015 | 12/1 ~ 12/31/2015 | 1/1 -1/31/2016 | | |
| Q | 56.95 | 56.18 | 54.78 | 50.62 | 51.46 | 52.05 | 54.00 | 53.29 | | |
| % Observed | 96.95 | 83.66 | 90.28 | 90.28 | 88.26 | 89.73 | 86.69 | 83.54 | | |
| VMT | 46,096.56 | 46,933.00 | 46,469.65 | 46,836.83 | 46,090.35 | 46,034.43 | 44,225.00 | 43,648.40 | | |
| | | | | | | | | | | |

Table 6 Average of Q and VMT overall all months in the analysis periods

| | | |
|---|---|---|
| | | |
| 6/27/2022 ~ 4/30/2023 | | [%] improvement |
| Average Q=(VMT/VHT) | 57.94 | |
| [%] Observed data | 89.74 | |
| VMT | 48185.88 | |
| | | |
| 2/2/2016 ~ 9/1/2016 | | |
| Average Q=(VMT/VHT) | 53.22 | 8.86% |
| [%] Observed data | 83.69 | |
| VMT | 46296.48 | 4.08% |
| | | |
| 6/1/2015 ~ 1/31/2016 | | |
| Average Q=(VMT/VHT) | 53.67 | 7.96% |
| [%] Observed data | 88.68 | |
| VMT | 45,791.78 | 5.23% |

In Table 6, the left column lists the time periods for data analysis and parameters used. The middle column lists the corresponding value. The right column in green are the percentage of improvement for the test period 6/27/2022 ~ 3/1/2023 with CRM and VSA compared to the two time periods when the CRM and VSA were not implemented. More specifically, we have the following observations from Table 5 and Table 6:

- The efficiency (or average speed) with CRM+VSA in 2022~2023 has improvements of 8.86% and 7.96% compared to the two time periods in 2015 and 2016 without CRM and VSA before the pandemic.
- VMT is also increased by 4.08% and 5.23%, which implies the overall demand and performance increases.
- Both Q and VMT increasing indicates the significance of the system performance improvement.

### 5.3 Safety Improvement

We still have used the PeMS data of the same time periods for safety analysis as in the previous section for mobility analysis. To quantify safety, we have used the daily average number of accidents along the corridor under the field test as the measure.

For similar reasons, we have used the following periods for comparison in performance analysis:

- June 1, 2015 ~ Dec 31, 2015 when the CRM and VSA were not implemented.
- Feb 2, 2016 ~ Sep 1, 2016 when the CRM and VSA were not implemented.
- June 27 2022 ~ April 30 2023 when the CRM and VSA were implemented and in action.

The following Figure 9  shows how we selected PeMS safety data. It can be observed that we only selected ***accident data***, but not other data types such as *Breakdown, Closure* and *Congestion* etc., and that both the CHP data and the TASAS data have been selected as indicated in Figure 10.

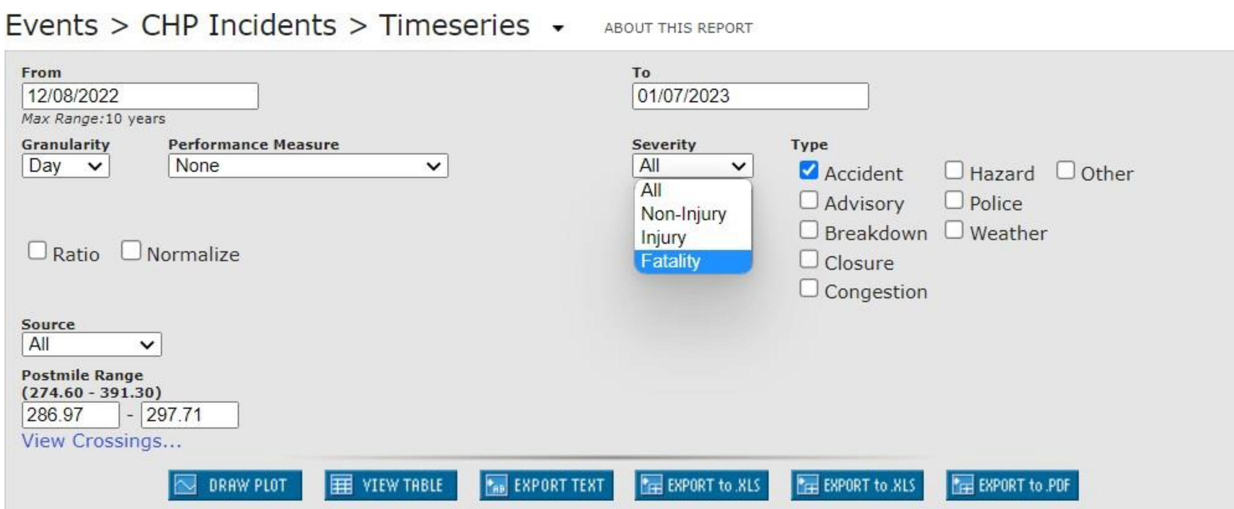



Figure 9. PeMS safety data type selection for analysis.

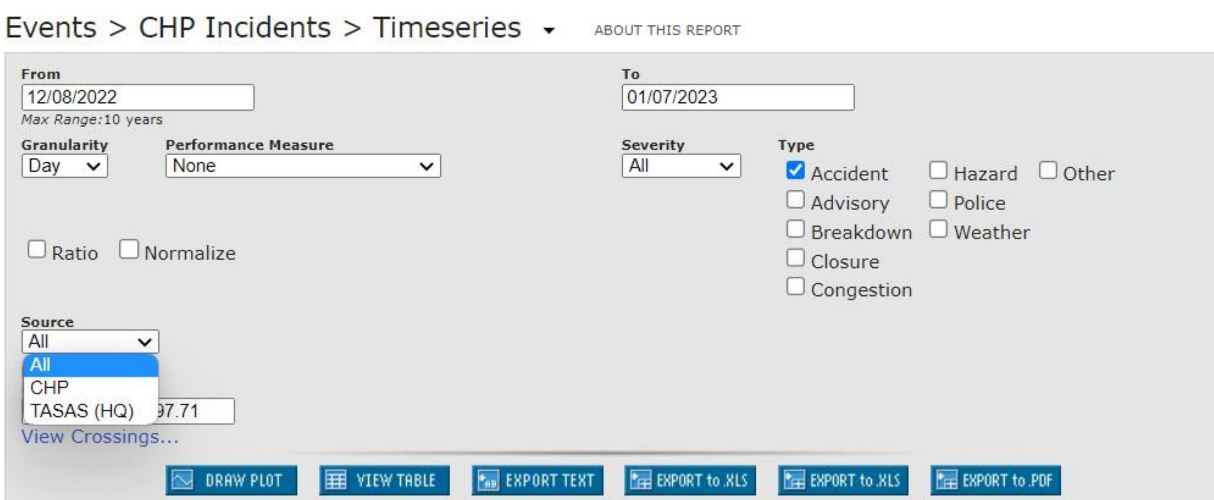



Figure 10. Safety data selection, with both CHP and TASAS data have been selected.

The following Table 7  is the daily average number of accidents for each month during the analysis periods.

Table 7. Daily average number of accidents for each month during the analysis periods

| Period | 7/1/ ~ 7/31/2022 | 8/1 ~ 8/31/2022 | 9/1 ~ 9/30/2022 | 10/1 ~ 10/31/2022 | 11/1 ~ 11/30/2022 | 12/1 ~ 12/31/2022 | 1/1 ~ 1/31/2023 | 2/1 ~ 2/28/20231 | 3/1 ~ 3/31/20231 | 4/1 ~ 4/30/20231 |
|---|---|---|---|---|---|---|---|---|---|---|
| Daily average | 1.857142857 | 2.80952381 | 3.4375 | 2.904761905 | 2.333333333 | 2.578947368 | 2.5 | 3.105263158 | 3.473684211 | 2.75 |
| Period | 1/1 ~ 1/31/2016 | 2/2 ~ 3/1/2016 | 3/1 ~ 3/31/2016 | 4/1 ~ 4/30/2016 | 5/1 ~ 5/31/2016 | 6/1 ~ 6/31/2016 | 7/1 ~ 7/31/20161 | 8/1 ~ 8/31/20161 | | |
| Daily average | 4.571428571 | 3.2 | 3.055555556 | 3.35 | 2.727272727 | 2.470588235 | 2.85 | 2.80952381 | | |
| Period | 6/1/ ~ 7/1/2015 | 7/1/ ~ 8/1/2015 | 8/1/ ~ 8/31/2015 | 9/1/ ~ 30/1/20151 | 10/1/ ~ 10/31/2015 | 11/1/ ~ 11/30/2015 | 12/1/ ~ 12/31/2015 | | | |
| Daily average | 2.952380952 | 3.428571429 | 3.266666667 | 3.157894737 | 4.565217391 | 3.260869565 | 3 | | | |
| | | | | | | | | | | |

The following Table 8 is the daily average number of accidents for each analysis periods.

Table 8. Daily average number of accidents based on CHP and TASAS data

| 7/1/2022 ~ 2/28/2023 | | [%] Reduction |
|---|---|---|
| Average daily number of accidents | 2.78 | |
| | | |
| 1/1 ~ 8/31/2016 | | |
| Average daily number accidents | 3.13 | 11% |
| 6/1/2015 ~ 12/31/2015 | | |
| Average daily number of | 3.38 | 18% |
| Total Average | | 14.56% |
| | | |

In Table 8, the left two columns show the time intervals for the analysis and the daily average number of accidents for the three analysis periods. The right column in green is percentage of reductions of the average daily number of accidents of the periods in 2015 and 2016 compared to that in 2022~2023. It can be observed from Table 8 that the reductions in 2022-2023 compared to that of 2015 and 2016 are 11% and 18% respectively. The average daily number of accident reduction is about 14.56% which is the quantitative measure on safety improvement.

### 5.4 Conclusion

PATH project team has conducted progressive initial test, system refinement and formal operational test which has lasted about one and half years. Then the team conducted an objective and quantitative performance analysis based on the independent PeMS data by comparing the "before" scenario during 2015~2016 (no CRM nor VSA in operation), and the "after" scenario (both CRM and VSA in operation) during 2022~2023. The reason for using PeMS data are of two folds:

(a) It is independent data collected and cleaned by a third party, which would be more objective than the field data the project team collected;
(b) PeMS data has performance parameters, such as VMT, VHT, Q etc., calculated; therefore the project team do not need to re-calculate them based on the raw field data.

The mobility and safety performance improvement can be summarized as follows:

(1) VMT (Vehicle Miles Travelled) increased by 4.5%;
(2) the efficiency Q=VMT/VHT (VHT: Vehicle Hours Travelled) increased by 8.4%; and
(3) the daily average number of accidents decreased by 14.56% (safety improvement).

It is emphasized that both Q and VMT increasing indicates the significance of the system mobility performance improvement.

# 6 Quantitative Analysis of Driver Compliance

This chapter presents some quantitative analysis on driver compliance rate based on saved engineering data. What we hope to find out is how close the drivers have been following the advisory speed. For this reason, we have used the engineering data (not driver monitoring data) we have saved during the test. Those data include: (i) VSA (the advisory speed) the algorithm calculated and displayed on the ten VSA signs; (ii) VSA sign built-in-radar based 30 [s] average speed; (iii) fusion of the speed estimated from the dual-loop detector stations in the field and the radar speed. In the speed fusion, we have used 3~4 detector station data downstream of the subject section. Therefore, the loop speed could be understood as a distance mean speed in a section traffic level. The fusion strategy is the following: if they both are fine, a weighted average is the output; and otherwise, use the correct one of the two. We then compared the VSA (displayed speed) with the radar speed and the fused speeds at ten VSA sign locations during the field test hours which is 6:00am-10:00am and 3:00pm – 7:00pm.

The reason for using the fused-speed instead of just radar measured speed is that, the VSA signs were mounted on the right shoulders or even off the road. It would expect that the radar would mainly catch the traffic in lane 1 (or near side lane) vehicle speed. It may reflect less the speed of vehicles in lane 2 through lane 4 (off-side lane). One more thing we would like to mention is that the loop speed is interpolated over several loop detector stations upstream and downstream of the subject onramp location. Such interpolation was for the reliability of the traffic data.

## 6.1 Data Use

We have used the engineering data we saved during the test period. The data include the following:
VSA displayed to the driver using the VSA signs at each location
Radar speed obtained from the VSA signs
Fused loop detector data and radar data used for calculation of VSA at each section

Date for analysis: Feb 1st , 2023 – Apr 30th, 2023
Time: 6 AM – 12 AM (18 hours)
VSA activation period: 6-10 AM, 3-7 PM

## 6.2 Calculation Approach

The radar data was obtained through American Signal Company Cloud. All the loop detector data was obtained directly form the traffic controllers in field through Caltrans District 3 intranet. All the engineering data were aggregated over 30 [s] by default. We then have cleaned up the data by removing invalid data and aggregated further to 5 m for plotting. We have used this aggregation level for slightly higher granularity. For the comparison of the speed in tables, we have aggregated over 15 m.
We considered three scenarios based on VSA speed changes:
Speed increases larger than 3 [mph]
Speed decreases smaller than 3 [mph]
Speed relatively constant: changes are less than 3 [mph]

### 6.3 Results

The results are presented in two ways. We first present the 5 minutes aggregation data for speed comparison for VSA (advisory speed) with radar and fused speeds respectively. We then present the percentage off of VSA speeds compared to radar and fused speeds respectively. Data Plot for Speed Comparison at Each VSA Sign Location

#### *6.3.1 Plots of 5 min Aggregated Data Comparison*

In this subsection, we present the intuitive plots for comparison of the displayed VSA speed and the radar detected speed in the field and the fused speed of the radar and the loop detector speed. In each plot, the legend indicates the color-code. The middle red-line separate AM peak and PM peak operation hours.

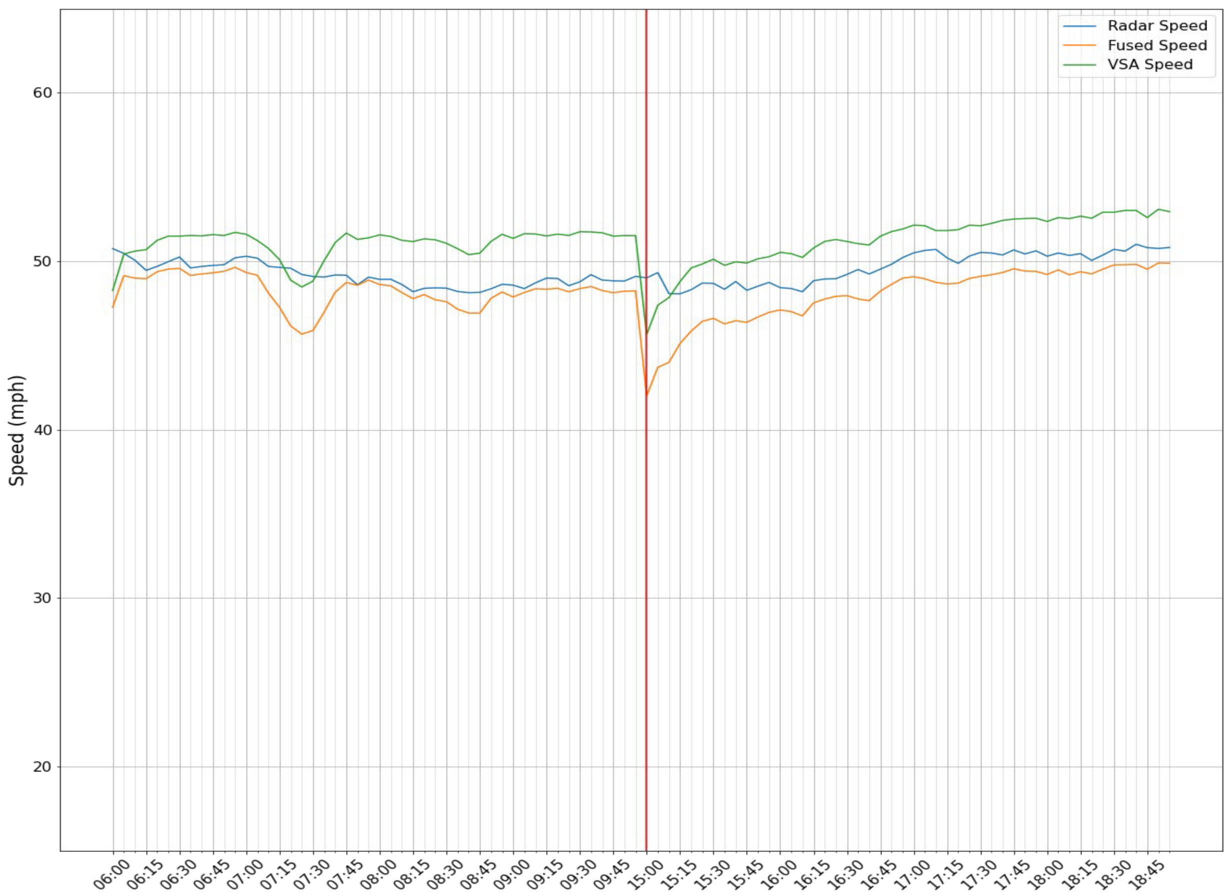



Figure 11. Speed comparison at VSA sign 1 (downstream of Elk Grove onramp)

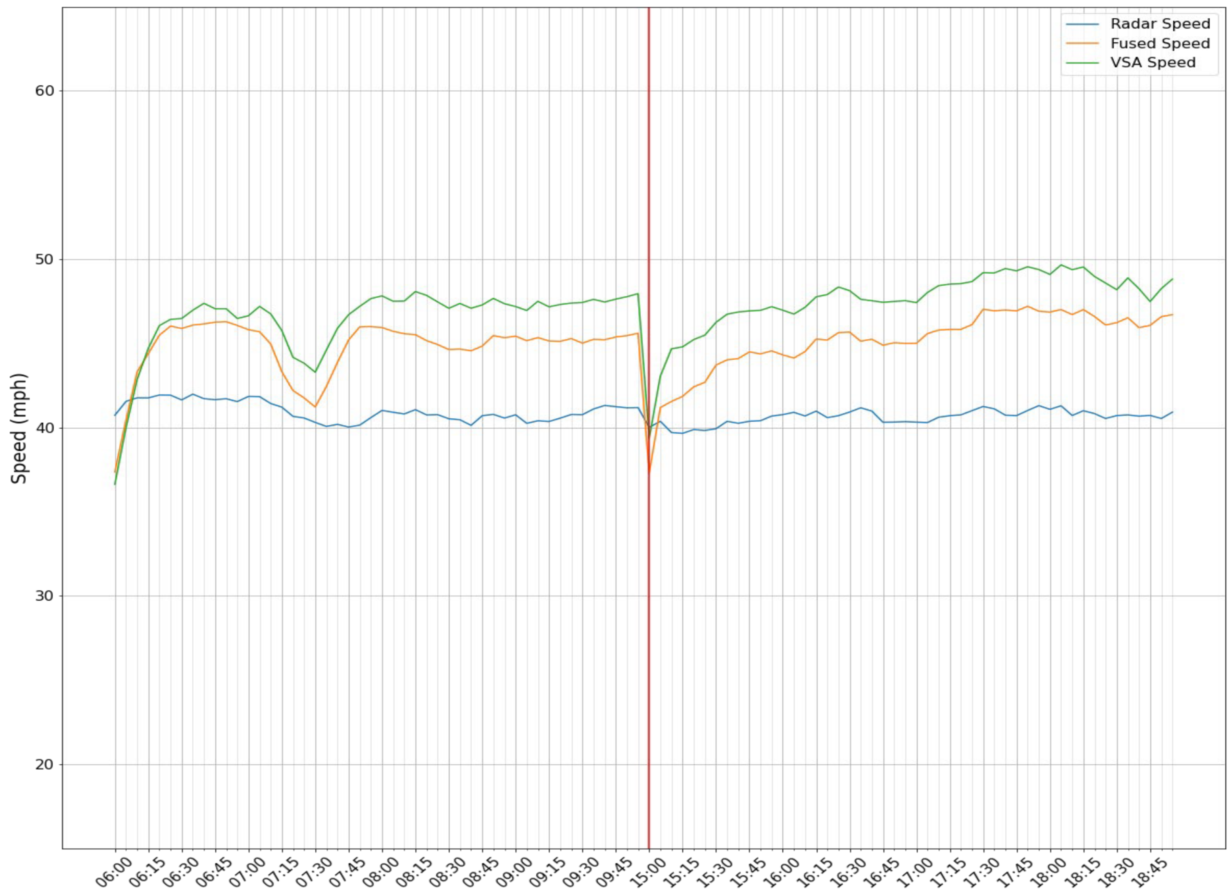


Figure 12. Speed comparison at VSA sign 2 (downstream of Laguna Blvd WB onramp)

Comparing Figure 11 and Figure 13, it can be observed that, at those two locations, the VSA speed is slightly higher than the other two speeds. For Figure 11, the radar speed is higher than the fused speed, but for Figure 12, it is the other way around.

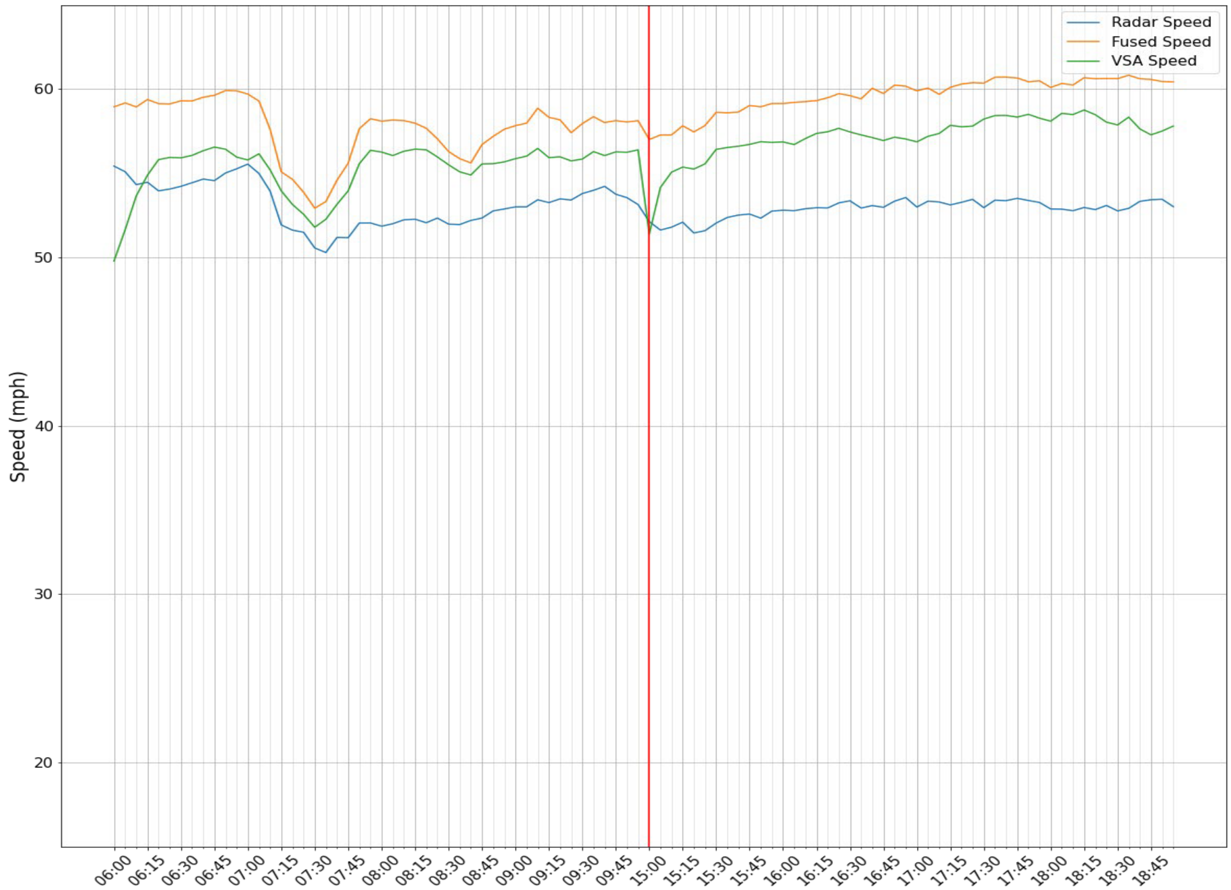



Figure 14. Speed comparison at VSA sign 3 (downstream of Sheldon WB onramp)

It can be observed from Figure 13 that, at this location (near the Sheldon WB onramp), the fused speed is the highest, and the radar speed is the lowest, and the VSA speed is in the middle.

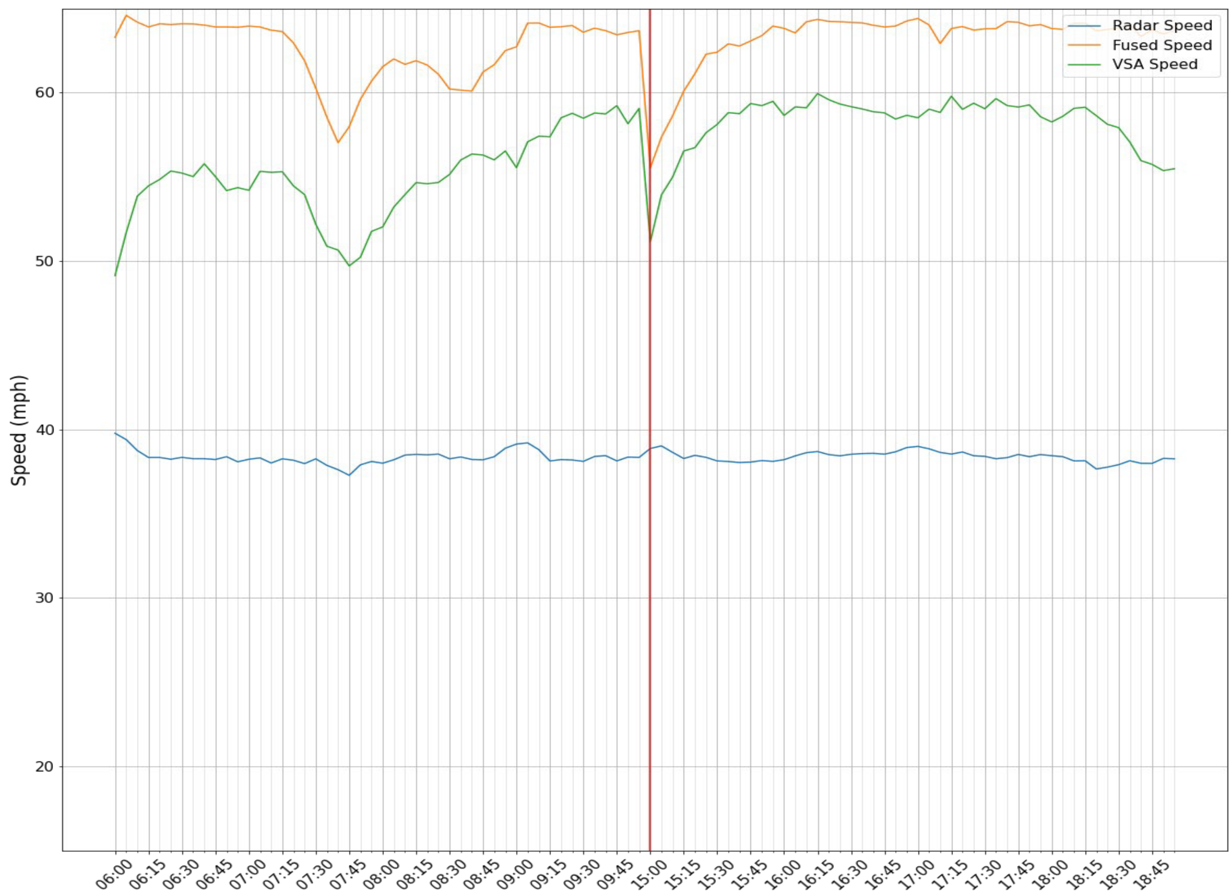


Figure 15. Speed comparison at VSA sign 4 (downstream of Calvine WB onramp)

The plot in Figure 14 indicates that the radar speed reading had persistent error. This may be due to a driver crash that damaged the VSA sign at this location.

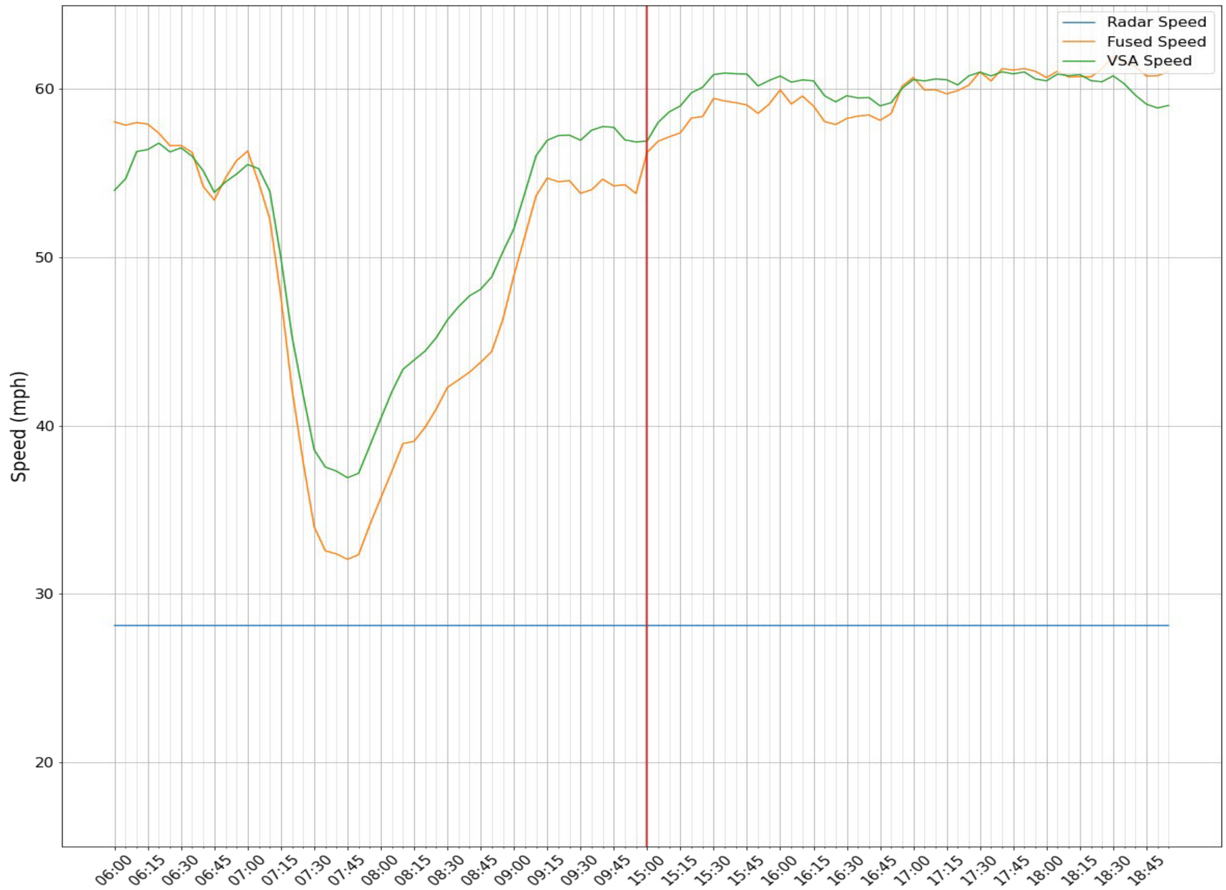



Figure 16. Speed comparison at VSA sign 5 (downstream of Mack Road WB onramp, 1st sign)

The plot in Figure 15 also indicates that the radar speed reading had persistent error. This may be due to a driver crash that damaged the VSA sign at this location.

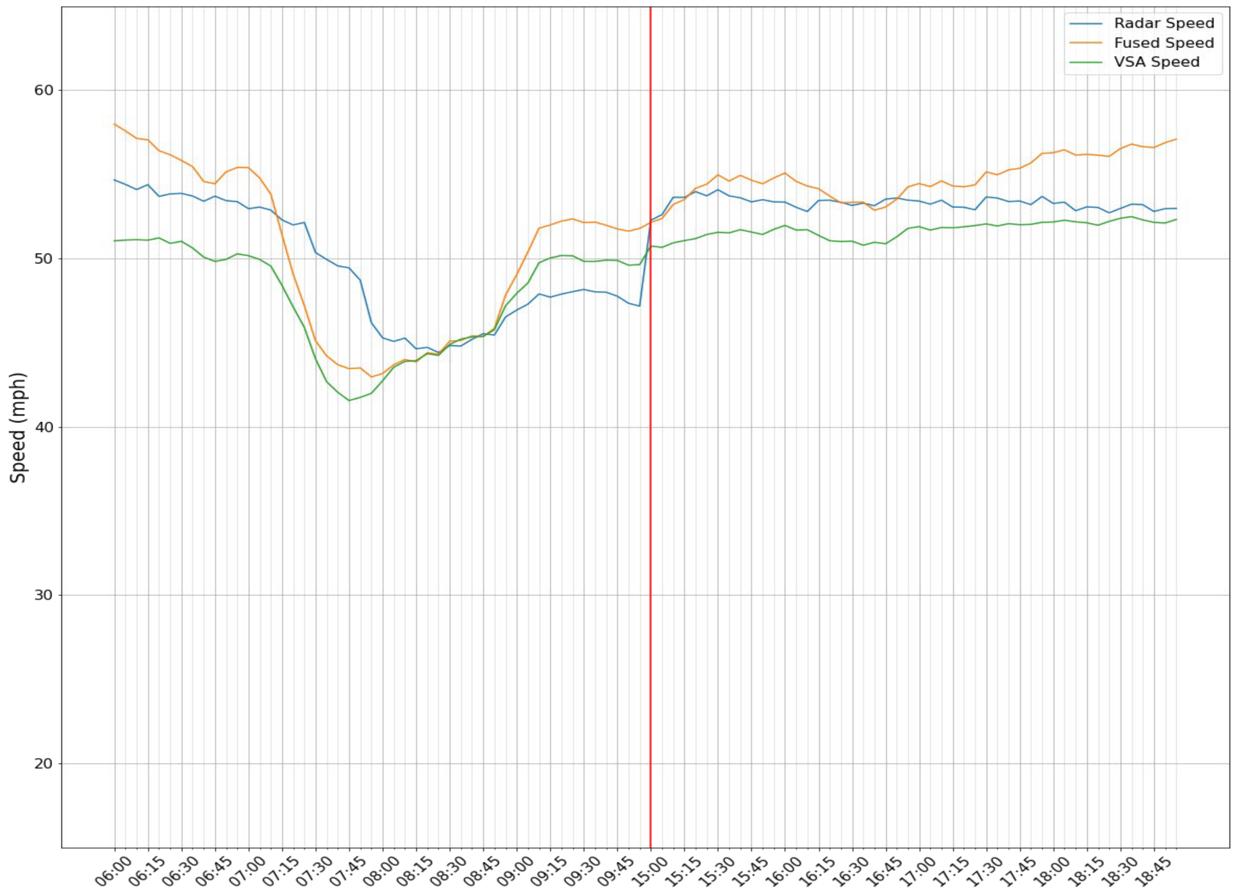



Figure 17. Speed comparison at VSA sign 6 (downstream of Mack Road WB onramp, 2nd sign)

It is interesting to observe from this plot (Figure 16) that there is a speed drop that usually happens in the AM peak in 7:00am – 9:15am. During that time, the VSA speed drops earlier than the fused speed and radar speed. This means that the driver response has a delay. Therefore, at the stage of traffic recovery from about 8:30am, the radar speed is below the VSA speed and the fused speed.

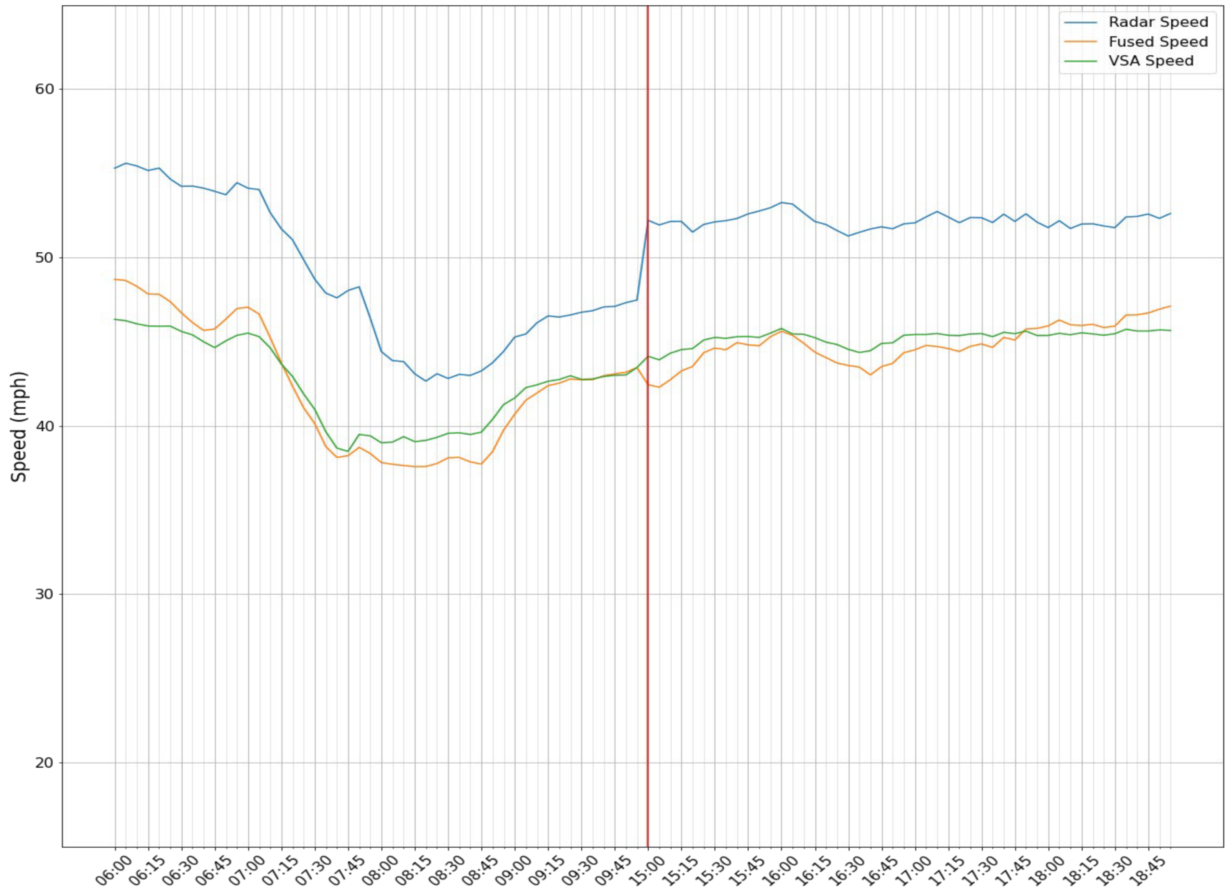



Figure 18. Speed comparison at VSA sign 7 (downstream of Florin WB onramp)

In this plot (Figure 17), the fused speed and VSA are pretty close, but the radar speed is rather high. This may mean that the radar perhaps only measured the nearside lane speed instead of the traffic in other lanes.

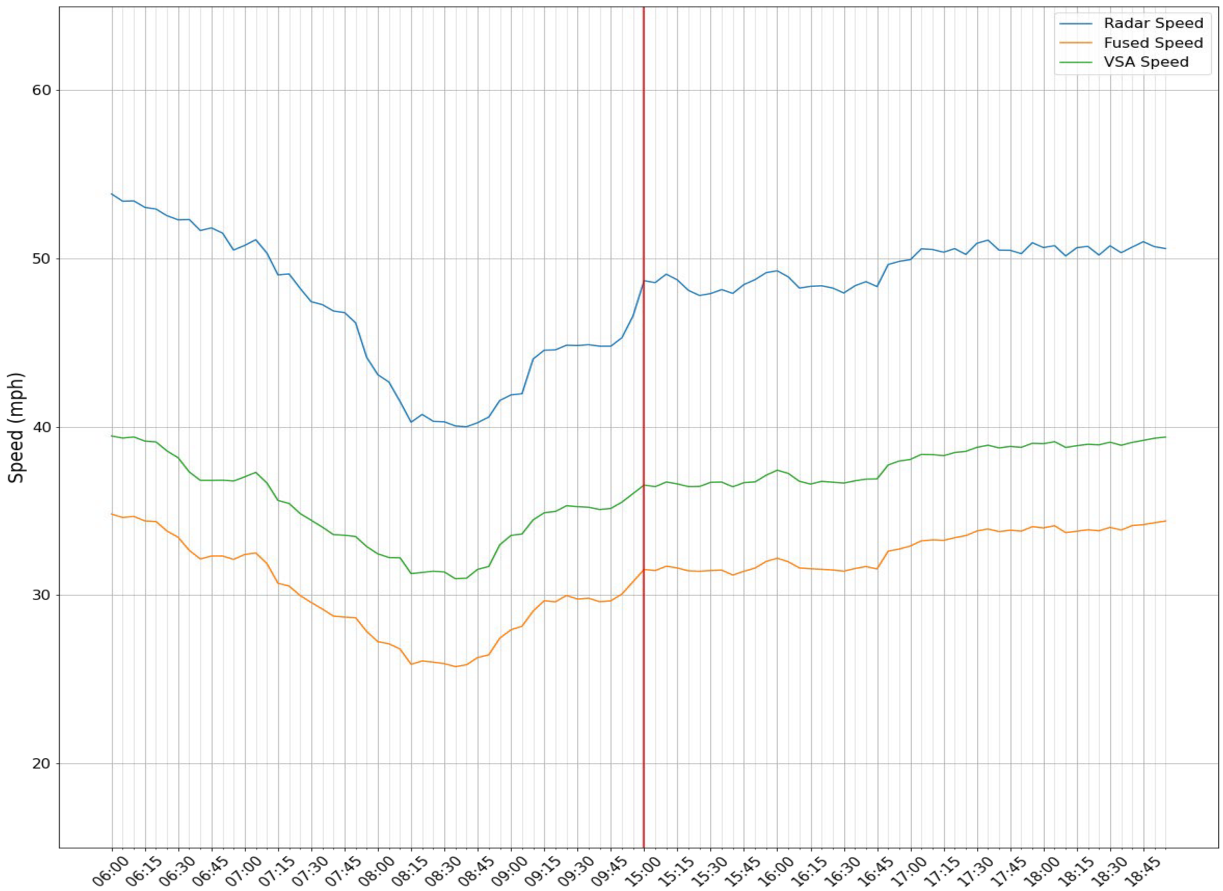


Figure 19. Speed comparison at VSA sign 8 (downstream of 47th Ave WB onramp)

The three speeds have similar pattern in Figure 19 and Figure 20 compared to the previous on in Figure 18 except that the radar speed is significantly higher.

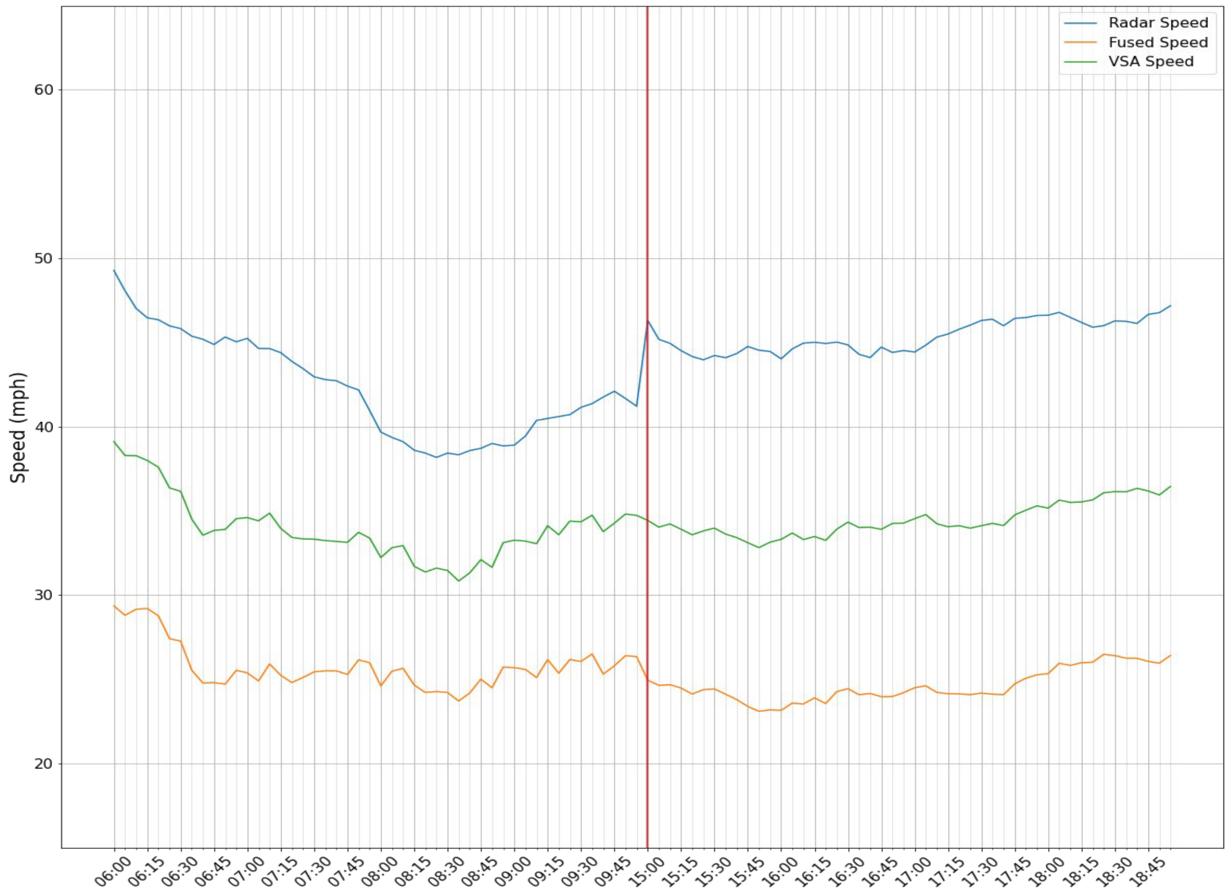


Figure 20. Speed comparison at VSA sign 9 (downstream of Fruitridge WB onramp)

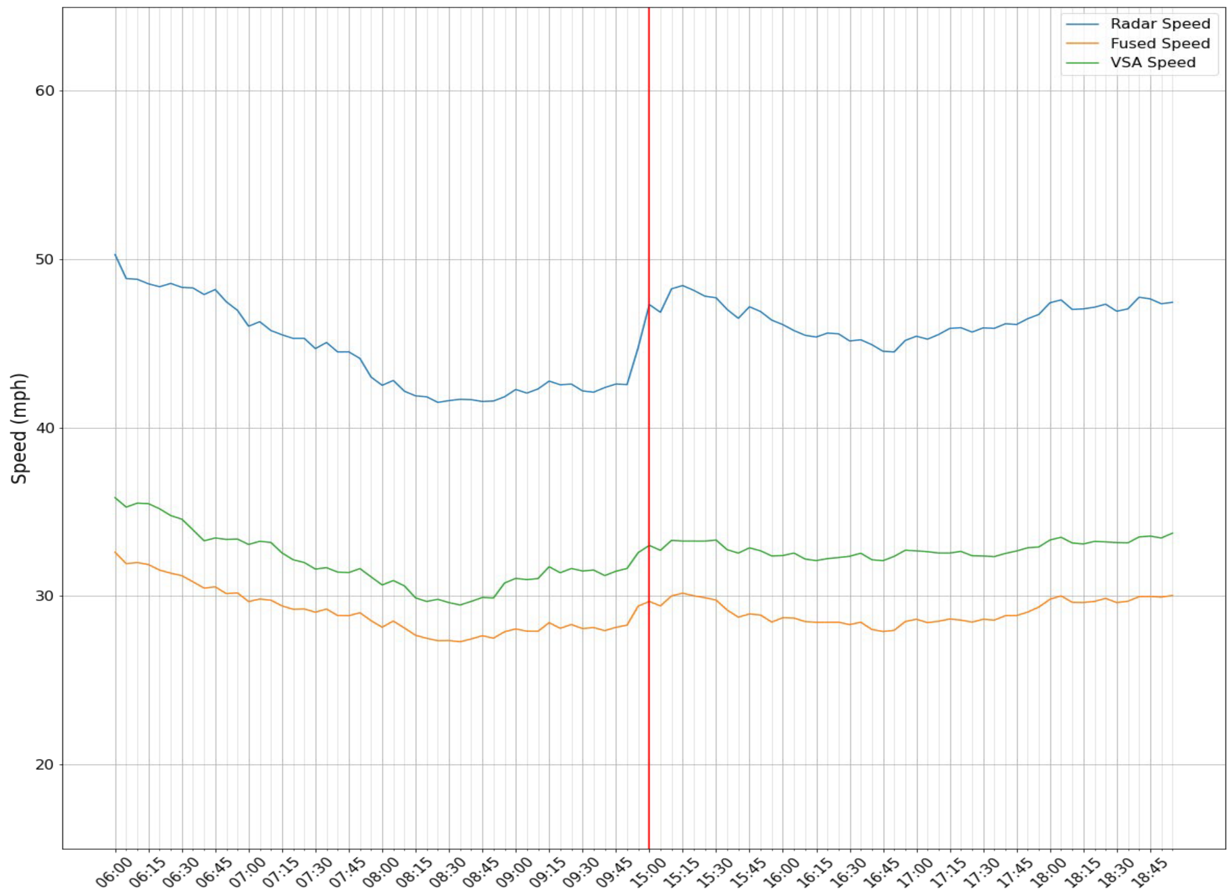


Figure 21. Speed comparison at VSA sign 10 (downstream of 12th Ave. onramp)

### *6.3.2 Percentage Comparison for 15 min Aggregated Data*

The following ten tables list the comparison of VSA speed with the radar speed and the fused speed, and the percentage differences. The percentage calculation is as follows:

Radar speed vs. VSA (%): (Radar Speed – VSA Speed)/VSA Speed
Fused speed vs. VSA (%): (Fused Speed – VSA Speed)/VSA Speed

Color code in the table:
**Black** means: nearly constant traffic speed or speed change is within 3 mph;
**Green** means: traffic deceleration with speed changes over 3 mph;
**Red** means: traffic acceleration with speed changes over 3 mph;

Note that the traffic data aggregation interval is 15 minutes.

Table 9. Percentage of speed difference for VSA compared to radar speed and fused speed at VSA sign 1 (Elk Grove)

| | 6:00 | 6:15 | 6:30 | 6:45 | 7:00 | 7:15 | 7:30 | 7:45 | 8:00 | 8:15 | 8:30 | 8:45 | 9:00 | 9:15 | 9:30 | 9:45 | 15:00 | 15:15 | 15:30 | 15:45 | 16:00 | 16:15 | 16:30 | 16:45 | 17:00 | 17:15 | 17:30 | 17:45 | 18:00 | 18:15 | 18:30 | 18:45 |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Radar Speed | 50.42 | 49.71 | 49.85 | 49.92 | 50.06 | 49.48 | 49.12 | 48.94 | 48.82 | 48.34 | 48.25 | 48.38 | 48.56 | 48.84 | 48.96 | 48.92 | 48.81 | 48.36 | 48.61 | 48.51 | 48.33 | 48.92 | 49.32 | 49.85 | 50.61 | 50.13 | 50.46 | 50.57 | 50.38 | 50.29 | 50.77 | 50.80 |
| Fused Speed | 48.47 | 49.29 | 49.33 | 49.45 | 48.87 | 46.37 | 47.00 | 48.73 | 48.43 | 47.84 | 47.23 | 47.63 | 48.13 | 48.31 | 48.38 | 48.20 | 43.24 | 45.80 | 46.45 | 46.68 | 46.96 | 47.73 | 47.79 | 48.62 | 48.93 | 48.78 | 49.21 | 49.46 | 49.30 | 49.39 | 49.80 | 49.77 |
| VSA Speed | 49.77 | 51.14 | 51.51 | 51.61 | 51.20 | 49.15 | 49.99 | 51.45 | 51.43 | 51.26 | 50.73 | 51.08 | 51.54 | 51.55 | 51.73 | 51.51 | 46.96 | 49.41 | 49.95 | 50.10 | 50.40 | 51.08 | 51.06 | 51.72 | 52.02 | 51.94 | 52.26 | 52.53 | 52.49 | 52.71 | 52.98 | 52.87 |
| Radar vs VSA | 1.32 | -2.80 | -3.22 | -3.28 | -2.23 | 0.67 | -1.74 | -4.88 | -5.06 | -5.70 | -4.90 | -5.29 | -5.78 | -5.25 | -5.36 | -5.03 | 3.93 | -2.12 | -2.69 | -3.17 | -4.10 | -4.24 | -3.40 | -3.60 | -2.71 | -3.50 | -3.44 | -3.72 | -4.03 | -4.60 | -4.17 | -3.93 |
| Fused vs VSA | -2.60 | -3.61 | -4.23 | -4.18 | -4.54 | -5.66 | -5.97 | -5.29 | -5.82 | -6.67 | -6.91 | -6.76 | -6.61 | -6.29 | -6.47 | -6.43 | -7.93 | -7.30 | -7.00 | -6.83 | -6.83 | -6.56 | -6.40 | -6.00 | -5.95 | -6.10 | -5.83 | -5.85 | -6.09 | -6.31 | -6.01 | -5.87 |
| Status | / | Const | Const | Const | Const | Const | Const | Const | Const | Const | Const | Const | Const | Const | Const | Const | / | Const | Const | Const | Const | Const | Const | Const | Const | Const | Const | Const | Const | Const | Const | Const |

Table 10. Percentage of speed difference for VSA compared to radar speed and fused speed at VSA sign 2 (Laguna Blvd WB)

| | 6:00 | 6:15 | 6:30 | 6:45 | 7:00 | 7:15 | 7:30 | 7:45 | 8:00 | 8:15 | 8:30 | 8:45 | 9:00 | 9:15 | 9:30 | 9:45 | 15:00 | 15:15 | 15:30 | 15:45 | 16:00 | 16:15 | 16:30 | 16:45 | 17:00 | 17:15 | 17:30 | 17:45 | 18:00 | 18:15 | 18:30 | 18:45 |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Radar Speed | 41.35 | 41.87 | 41.78 | 41.64 | 41.71 | 40.82 | 40.19 | 40.26 | 40.91 | 40.86 | 40.37 | 40.69 | 40.47 | 40.57 | 41.06 | 41.20 | 40.03 | 39.79 | 40.19 | 40.49 | 40.79 | 40.76 | 41.03 | 40.33 | 40.41 | 40.82 | 41.03 | 41.01 | 41.03 | 40.79 | 40.71 | 40.73 |
| Fused Speed | 40.37 | 45.30 | 46.04 | 46.20 | 45.49 | 42.43 | 42.51 | 45.73 | 45.74 | 45.20 | 44.62 | 45.21 | 45.31 | 45.18 | 45.16 | 45.48 | 40.01 | 42.32 | 43.94 | 44.48 | 44.32 | 45.37 | 45.35 | 44.98 | 45.46 | 45.93 | 46.98 | 47.02 | 46.86 | 46.57 | 46.23 | 46.45 |
| VSA Speed | 39.83 | 45.73 | 46.94 | 46.87 | 46.86 | 44.59 | 44.60 | 47.19 | 47.61 | 47.80 | 47.18 | 47.44 | 47.21 | 47.29 | 47.50 | 47.79 | 42.36 | 45.17 | 46.62 | 47.02 | 46.95 | 48.01 | 47.76 | 47.49 | 47.96 | 48.58 | 49.28 | 49.42 | 49.38 | 49.03 | 48.44 | 48.18 |
| Radar vs VSA | 3.83 | -8.43 | -10.99 | -11.15 | -11.00 | -8.45 | -9.88 | -14.69 | -14.07 | -14.51 | -14.43 | -14.23 | -14.28 | -14.22 | -13.56 | -13.78 | -5.50 | -11.91 | -13.79 | -13.90 | -13.13 | -15.09 | -14.10 | -15.07 | -15.73 | -15.97 | -16.73 | -17.01 | -16.90 | -16.81 | -15.95 | -15.48 |
| Fused vs VSA | 1.37 | -0.93 | -1.92 | -1.41 | -2.93 | -4.84 | -4.67 | -3.10 | -3.92 | -5.43 | -5.43 | -4.69 | -4.03 | -4.46 | -4.93 | -4.82 | -5.55 | -6.31 | -5.73 | -5.42 | -5.60 | -5.50 | -5.05 | -5.29 | -5.21 | -5.46 | -4.66 | -4.86 | -5.10 | -5.03 | -4.57 | -3.59 |
| Status | / | Accel | Const | Const | Const | Const | Const | Const | Const | Const | Const | Const | Const | Const | Const | Const | / | Const | Const | Const | Const | Const | Const | Const | Const | Const | Const | Const | Const | Const | Const | Const |

Table 11. Percentage of speed difference for VSA compared to radar speed and fused speed at VSA sign 3 (Sheldon WB)

| | 6:00 | 6:15 | 6:30 | 6:45 | 7:00 | 7:15 | 7:30 | 7:45 | 8:00 | 8:15 | 8:30 | 8:45 | 9:00 | 9:15 | 9:30 | 9:45 |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Radar Speed | 54.95 | 54.16 | 54.44 | 54.95 | 54.83 | 51.69 | 50.69 | 51.76 | 52.03 | 52.23 | 52.05 | 52.66 | 53.15 | 53.38 | 54.00 | 53.48 |
| Fused Speed | 59.02 | 59.21 | 59.37 | 59.81 | 58.87 | 54.53 | 53.61 | 57.16 | 58.13 | 57.57 | 55.93 | 57.17 | 58.22 | 57.97 | 58.11 | 58.10 |
| VSA Speed | 51.70 | 55.55 | 56.11 | 56.32 | 55.72 | 53.22 | 52.41 | 55.30 | 56.21 | 56.27 | 55.16 | 55.60 | 56.12 | 55.88 | 56.06 | 56.30 |
| Radar vs VSA | 6.28 | -2.49 | -2.97 | -2.43 | -1.60 | -2.89 | -3.29 | -6.40 | -7.43 | -7.18 | -5.65 | -5.28 | -5.30 | -4.47 | -3.67 | -5.01 |
| Fused vs VSA | 14.16 | 6.60 | 5.82 | 6.21 | 5.65 | 2.46 | 2.30 | 3.37 | 3.42 | 2.31 | 1.38 | 2.82 | 3.74 | 3.74 | 3.65 | 3.19 |
| Status | / | Accel | Const | Const | Const | Const | Const | Const | Const | Const | Const | Const | Const | Const | Const | Const |

| | 15:00 | 15:15 | 15:30 | 15:45 | 16:00 | 16:15 | 16:30 | 16:45 | 17:00 | 17:15 | 17:30 | 17:45 | 18:00 | 18:15 | 18:30 | 18:45 |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Radar Speed | 51.85 | 51.71 | 52.31 | 52.56 | 52.83 | 53.05 | 53.13 | 53.30 | 53.21 | 53.28 | 53.25 | 53.39 | 52.84 | 52.97 | 53.01 | 53.30 |
| Fused Speed | 57.19 | 57.71 | 58.62 | 59.04 | 59.20 | 59.51 | 59.69 | 60.05 | 59.88 | 60.26 | 60.59 | 60.53 | 60.22 | 60.64 | 60.69 | 60.49 |
| VSA Speed | 53.53 | 55.39 | 56.52 | 56.81 | 56.88 | 57.50 | 57.29 | 57.04 | 57.14 | 57.81 | 58.36 | 58.37 | 58.38 | 58.43 | 57.95 | 57.53 |
| Radar vs VSA | -3.14 | -6.64 | -7.44 | -7.49 | -7.12 | -7.75 | -7.26 | -6.57 | -6.88 | -7.82 | -8.76 | -8.53 | -9.48 | -9.34 | -8.53 | -7.35 |
| Fused vs VSA | 6.82 | 4.17 | 3.71 | 3.93 | 4.09 | 3.49 | 4.21 | 5.27 | 4.80 | 4.25 | 3.82 | 3.70 | 3.16 | 3.79 | 4.73 | 5.13 |
| Status | / | Const | Const | Const | Const | Const | Const | Const | Const | Const | Const | Const | Const | Const | Const | Const |

Table 12. Percentage of speed difference for VSA compared to radar speed and fused speed at VSA sign 4 (Calvine WB)

| | 6:00 | 6:15 | 6:30 | 6:45 | 7:00 | 7:15 | 7:30 | 7:45 | 8:00 | 8:15 | 8:30 | 8:45 | 9:00 | 9:15 | 9:30 | 9:45 |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Radar Speed | 39.31 | 38.31 | 38.30 | 38.23 | 38.19 | 38.14 | 37.92 | 37.76 | 38.23 | 38.52 | 38.29 | 38.49 | 39.05 | 38.18 | 38.32 | 38.28 |
| Fused Speed | 64.02 | 64.00 | 64.05 | 63.89 | 63.85 | 62.82 | 58.61 | 59.41 | 61.74 | 61.54 | 60.15 | 61.79 | 63.66 | 63.92 | 63.69 | 63.56 |
| VSA Speed | 51.56 | 54.88 | 55.34 | 54.52 | 54.93 | 54.57 | 51.24 | 50.57 | 53.06 | 54.64 | 55.83 | 56.28 | 56.68 | 58.22 | 58.67 | 58.81 |
| Radar vs VSA | -23.76 | -30.20 | -30.80 | -29.87 | -30.48 | -30.11 | -26.00 | -25.32 | -27.95 | -29.49 | -31.43 | -31.60 | -31.10 | -34.42 | -34.68 | -34.91 |
| Fused vs VSA | 24.16 | 16.62 | 15.75 | 17.19 | 16.24 | 15.12 | 14.38 | 17.50 | 16.35 | 12.63 | 7.73 | 9.79 | 12.32 | 9.80 | 8.57 | 8.07 |
| Status | / | Accel | Const | Const | Const | Const | Decel | Const | Const | Const | Const | Const | Const | Const | Const | Const |

| | 15:00 | 15:15 | 15:30 | 15:45 | 16:00 | 16:15 | 16:30 | 16:45 | 17:00 | 17:15 | 17:30 | 17:45 | 18:00 | 18:15 | 18:30 | 18:45 |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Radar Speed | 38.85 | 38.37 | 38.09 | 38.11 | 38.42 | 38.55 | 38.56 | 38.72 | 38.83 | 38.55 | 38.34 | 38.48 | 38.32 | 37.86 | 38.02 | 38.18 |
| Fused Speed | 57.16 | 61.16 | 62.68 | 63.46 | 63.85 | 64.26 | 64.10 | 64.03 | 63.78 | 63.81 | 63.93 | 64.06 | 63.89 | 63.85 | 63.74 | 63.62 |
| VSA Speed | 53.35 | 56.96 | 58.56 | 59.35 | 58.96 | 59.61 | 59.02 | 58.63 | 58.78 | 59.39 | 59.31 | 58.99 | 58.64 | 58.63 | 56.98 | 55.53 |
| Radar vs VSA | -27.17 | -32.64 | -34.94 | -35.79 | -34.83 | -35.34 | -34.66 | -33.96 | -33.94 | -35.08 | -35.36 | -34.78 | -34.64 | -35.42 | -33.28 | -31.24 |
| Fused vs VSA | 7.16 | 7.37 | 7.05 | 6.93 | 8.29 | 7.79 | 8.61 | 9.22 | 8.50 | 7.45 | 7.80 | 8.58 | 8.95 | 8.90 | 11.86 | 14.58 |
| Status | / | Accel | Const | Const | Const | Const | Const | Const | Const | Const | Const | Const | Const | Const | Const | Const |

Table 13. Percentage of speed difference for VSA compared to radar speed and fused speed at VSA sign 5 (Mack Road WB 1st)

| | 6:00 | 6:15 | 6:30 | 6:45 | 7:00 | 7:15 | 7:30 | 7:45 | 8:00 | 8:15 | 8:30 | 8:45 | 9:00 | 9:15 | 9:30 | 9:45 | 15:00 | 15:15 | 15:30 | 15:45 | 16:00 | 16:15 | 16:30 | 16:45 | 17:00 | 17:15 | 17:30 | 17:45 | 18:00 | 18:15 | 18:30 | 18:45 |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Radar Speed | 28.13 | 28.13 | 28.13 | 28.13 | 28.13 | 28.13 | 28.13 | 28.13 | 28.13 | 28.13 | 28.13 | 28.13 | 28.13 | 28.13 | 28.13 | 28.13 | 28.13 | 28.13 | 28.13 | 28.13 | 28.13 | 28.13 | 28.13 | 28.13 | 28.13 | 28.13 | 28.13 | 28.13 | 28.13 | 28.13 | 28.13 | 28.13 |
| Fused Speed | 57.97 | 57.31 | 55.70 | 54.62 | 54.34 | 42.56 | 32.99 | 32.83 | 37.32 | 39.99 | 42.73 | 44.83 | 51.29 | 54.59 | 54.16 | 54.12 | 56.77 | 58.01 | 59.31 | 58.90 | 59.55 | 58.32 | 58.37 | 58.96 | 60.20 | 59.95 | 60.91 | 61.13 | 60.82 | 60.89 | 61.62 | 60.87 |
| VSA Speed | 54.98 | 56.49 | 55.89 | 54.43 | 54.90 | 45.71 | 37.81 | 37.62 | 41.93 | 44.52 | 47.02 | 49.09 | 53.87 | 57.15 | 57.43 | 57.19 | 57.86 | 59.63 | 60.91 | 60.53 | 60.58 | 59.78 | 59.52 | 59.42 | 60.55 | 60.53 | 60.94 | 60.84 | 60.72 | 60.60 | 60.25 | 59.00 |
| Radar vs VSA | -48.85 | -50.21 | -49.68 | -48.33 | -48.77 | -38.47 | -25.61 | -25.24 | -32.93 | -36.83 | -40.19 | -42.71 | -47.79 | -50.79 | -51.03 | -50.82 | -51.39 | -52.83 | -53.82 | -53.53 | -53.57 | -52.95 | -52.75 | -52.66 | -53.55 | -53.53 | -53.85 | -53.77 | -53.68 | -53.59 | -53.32 | -52.33 |
| Fused vs VSA | 5.44 | 1.46 | -0.34 | 0.35 | -1.02 | -6.89 | -12.75 | -12.74 | -11.01 | -10.18 | -9.13 | -8.68 | -4.78 | -4.48 | -5.70 | -5.37 | -1.89 | -2.71 | -2.62 | -2.68 | -1.70 | -2.44 | -1.94 | -0.77 | -0.58 | -0.95 | -0.05 | 0.48 | 0.16 | 0.48 | 2.28 | 3.16 |
| Status | / | Const | Const | Const | Const | Decel | Decel | Const | Accel | Const | Const | Const | Accel | Accel | Const | Const | / | Const | Const | Const | Const | Const | Const | Const | Const | Const | Const | Const | Const | Const | Const | Const |

Table 14. Percentage of speed difference for VSA compared to radar speed and fused speed at VSA sign 6 (Mack Road WB 2nd)

| | 6:00 | 6:15 | 6:30 | 6:45 | 7:00 | 7:15 | 7:30 | 7:45 | 8:00 | 8:15 | 8:30 | 8:45 | 9:00 | 9:15 | 9:30 | 9:45 | 15:00 | 15:15 | 15:30 | 15:45 | 16:00 | 16:15 | 16:30 | 16:45 | 17:00 | 17:15 | 17:30 | 17:45 | 18:00 | 18:15 | 18:30 | 18:45 |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Radar Speed | 54.39 | 53.97 | 53.66 | 53.51 | 52.97 | 52.15 | 49.95 | 48.12 | 45.21 | 44.59 | 44.94 | 45.84 | 47.38 | 47.88 | 48.06 | 47.43 | 52.84 | 53.78 | 53.81 | 53.41 | 53.06 | 53.42 | 53.19 | 53.53 | 53.37 | 53.00 | 53.55 | 53.44 | 53.15 | 52.94 | 53.14 | 52.91 |
| Fused Speed | 57.57 | 56.54 | 55.29 | 55.00 | 54.67 | 49.24 | 44.34 | 43.31 | 43.62 | 44.19 | 45.21 | 46.35 | 50.41 | 52.19 | 52.09 | 51.73 | 52.58 | 54.03 | 54.84 | 54.63 | 54.66 | 53.72 | 53.19 | 53.61 | 54.45 | 54.32 | 55.13 | 55.77 | 56.30 | 56.13 | 56.66 | 56.86 |
| VSA Speed | 51.09 | 51.07 | 50.58 | 50.02 | 49.89 | 47.15 | 42.92 | 41.77 | 43.39 | 44.18 | 45.15 | 46.11 | 48.74 | 50.12 | 49.85 | 49.71 | 50.78 | 51.23 | 51.60 | 51.58 | 51.79 | 51.15 | 50.93 | 51.32 | 51.81 | 51.89 | 52.02 | 52.06 | 52.21 | 52.10 | 52.39 | 52.19 |
| Radar vs VSA | 6.46 | 5.68 | 6.09 | 6.98 | 6.16 | 10.60 | 16.38 | 15.20 | 4.20 | 0.94 | -0.46 | -0.58 | -2.81 | -4.49 | -3.60 | -4.59 | 4.06 | 4.98 | 4.28 | 3.55 | 2.46 | 4.44 | 4.45 | 4.31 | 3.01 | 2.14 | 2.93 | 2.64 | 1.81 | 1.61 | 1.42 | 1.38 |
| Fused vs VSA | 12.68 | 10.71 | 9.31 | 9.96 | 9.59 | 4.43 | 3.30 | 3.69 | 0.53 | 0.03 | 0.13 | 0.53 | 3.43 | 4.12 | 4.49 | 4.05 | 3.55 | 5.48 | 6.28 | 5.91 | 5.53 | 5.04 | 4.43 | 4.47 | 5.09 | 4.68 | 5.98 | 7.11 | 7.83 | 7.73 | 8.14 | 8.94 |
| Status | / | Const | Const | Const | Const | Const | Decel | Const | Const | Const | Const | Const | Const | Const | Const | Const | / | Const | Const | Const | Const | Const | Const | Const | Const | Const | Const | Const | Const | Const | Const | Const |

Table 15. Percentage of speed difference for VSA compared to radar speed and fused speed at VSA sign 7 (Florin WB)

| | 6:00 | 6:15 | 6:30 | 6:45 | 7:00 | 7:15 | 7:30 | 7:45 | 8:00 | 8:15 | 8:30 | 8:45 | 9:00 | 9:15 | 9:30 | 9:45 |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Radar Speed | 55.45 | 55.04 | 54.19 | 54.03 | 53.60 | 50.87 | 48.07 | 47.56 | 44.03 | 42.95 | 42.96 | 43.81 | 45.62 | 46.53 | 46.88 | 47.29 |
| Fused Speed | 48.54 | 47.68 | 46.17 | 46.35 | 46.31 | 42.39 | 39.01 | 38.44 | 37.73 | 37.64 | 38.03 | 38.65 | 41.39 | 42.57 | 42.82 | 43.24 |
| VSA Speed | 46.21 | 45.93 | 45.34 | 45.02 | 45.15 | 42.84 | 39.77 | 39.13 | 39.13 | 39.17 | 39.54 | 40.43 | 42.12 | 42.79 | 42.82 | 43.17 |
| Radar vs VSA | 19.99 | 19.86 | 19.54 | 20.01 | 18.73 | 18.76 | 20.86 | 21.57 | 12.53 | 9.64 | 8.63 | 8.37 | 8.30 | 8.72 | 9.48 | 9.57 |
| Fused vs VSA | 5.05 | 3.81 | 1.85 | 2.95 | 2.57 | -1.04 | -1.91 | -1.76 | -3.58 | -3.90 | -3.83 | -4.39 | -1.74 | -0.52 | -0.01 | 0.18 |
| Status | / | Const | Const | Const | Const | Const | Decel | Const | Const | Const | Const | Const | Const | Const | Const | Const |

| | 15:00 | 15:15 | 15:30 | 15:45 | 16:00 | 16:15 | 16:30 | 16:45 | 17:00 | 17:15 | 17:30 | 17:45 | 18:00 | 18:15 | 18:30 | 18:45 |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Radar Speed | 52.09 | 51.87 | 52.21 | 52.77 | 53.03 | 51.90 | 51.49 | 51.84 | 52.40 | 52.28 | 52.34 | 52.28 | 51.89 | 51.95 | 52.20 | 52.51 |
| Fused Speed | 42.49 | 43.71 | 44.69 | 44.95 | 45.30 | 44.06 | 43.37 | 43.86 | 44.67 | 44.58 | 44.93 | 45.55 | 46.08 | 45.94 | 46.36 | 46.91 |
| VSA Speed | 44.12 | 44.74 | 45.25 | 45.35 | 45.56 | 45.01 | 44.46 | 45.07 | 45.45 | 45.40 | 45.45 | 45.49 | 45.43 | 45.46 | 45.62 | 45.67 |
| Radar vs VSA | 18.06 | 15.94 | 15.38 | 16.35 | 16.39 | 15.30 | 15.81 | 15.02 | 15.29 | 15.16 | 15.17 | 14.92 | 14.24 | 14.29 | 14.45 | 14.97 |
| Fused vs VSA | -3.70 | -2.30 | -1.22 | -0.89 | -0.57 | -2.13 | -2.45 | -2.69 | -1.71 | -1.81 | -1.14 | 0.13 | 1.43 | 1.07 | 1.64 | 2.73 |
| Status | / | Const | Const | Const | Const | Const | Const | Const | Const | Const | Const | Const | Const | Const | Const | Const |

Table 16. Percentage of speed difference for VSA compared to radar speed and fused speed at VSA sign 8 (47th Ave WB)

| | 6:00 | 6:15 | 6:30 | 6:45 | 7:00 | 7:15 | 7:30 | 7:45 | 8:00 | 8:15 | 8:30 | 8:45 | 9:00 | 9:15 | 9:30 | 9:45 |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Radar Speed | 53.56 | 52.84 | 52.10 | 51.28 | 50.74 | 48.78 | 47.19 | 45.70 | 42.42 | 40.45 | 40.12 | 40.80 | 42.63 | 44.66 | 44.83 | 45.56 |
| Fused Speed | 34.70 | 34.20 | 32.75 | 32.26 | 32.27 | 30.41 | 29.16 | 28.40 | 27.05 | 26.00 | 25.85 | 26.73 | 28.38 | 29.75 | 29.73 | 30.17 |
| VSA Speed | 39.40 | 38.94 | 37.44 | 36.81 | 37.00 | 35.31 | 34.03 | 33.31 | 32.31 | 31.35 | 31.12 | 32.08 | 33.89 | 35.06 | 35.19 | 35.57 |
| Radar vs VSA | 35.94 | 35.69 | 39.16 | 39.31 | 37.15 | 38.16 | 38.68 | 37.19 | 31.32 | 29.01 | 28.91 | 27.19 | 25.81 | 27.38 | 27.40 | 28.07 |
| Fused vs VSA | -11.91 | -12.18 | -12.51 | -12.36 | -12.78 | -13.88 | -14.30 | -14.74 | -16.27 | -17.06 | -16.94 | -16.66 | -16.24 | -15.14 | -15.51 | -15.17 |
| Status | / | Const | Const | Const | Const | Const | Const | Const | Const | Const | Const | Const | Const | Const | Const | Const |

| | 15:00 | 15:15 | 15:30 | 15:45 | 16:00 | 16:15 | 16:30 | 16:45 | 17:00 | 17:15 | 17:30 | 17:45 | 18:00 | 18:15 | 18:30 | 18:45 |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Radar Speed | 48.78 | 48.21 | 48.00 | 48.79 | 48.81 | 48.33 | 48.32 | 49.27 | 50.35 | 50.40 | 50.83 | 50.57 | 50.52 | 50.52 | 50.60 | 50.77 |
| Fused Speed | 31.57 | 31.49 | 31.38 | 31.68 | 31.93 | 31.53 | 31.57 | 32.30 | 33.15 | 33.40 | 33.84 | 33.91 | 33.95 | 33.83 | 34.01 | 34.30 |
| VSA Speed | 36.57 | 36.51 | 36.62 | 36.85 | 37.14 | 36.69 | 36.78 | 37.54 | 38.26 | 38.43 | 38.81 | 38.88 | 38.97 | 38.92 | 39.02 | 39.30 |
| Radar vs VSA | 33.37 | 32.07 | 31.08 | 32.40 | 31.41 | 31.71 | 31.37 | 31.25 | 31.59 | 31.14 | 30.96 | 30.07 | 29.66 | 29.80 | 29.65 | 29.16 |
| Fused vs VSA | -13.67 | -13.73 | -14.30 | -14.03 | -14.03 | -14.05 | -14.17 | -13.95 | -13.37 | -13.09 | -12.82 | -12.79 | -12.88 | -13.08 | -12.85 | -12.74 |
| Status | / | Const | Const | Const | Const | Const | Const | Const | Const | Const | Const | Const | Const | Const | Const | Const |

Table 17. Percentage of speed difference for VSA compared to radar speed and fused speed at VSA sign 9 (Fruitridge WB)

| | 6:00 | 6:15 | 6:30 | 6:45 | 7:00 | 7:15 | 7:30 | 7:45 | 8:00 | 8:15 | 8:30 | 8:45 | 9:00 | 9:15 | 9:30 | 9:45 | 15:00 | 15:15 | 15:30 | 15:45 | 16:00 | 16:15 | 16:30 | 16:45 | 17:00 | 17:15 | 17:30 | 17:45 | 18:00 | 18:15 | 18:30 | 18:45 |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Radar Speed | 48.12 | 46.27 | 45.46 | 45.08 | 44.84 | 43.91 | 42.83 | 41.85 | 39.39 | 38.41 | 38.45 | 38.86 | 39.58 | 40.60 | 41.43 | 41.67 | 45.48 | 44.22 | 44.22 | 44.59 | 44.54 | 44.99 | 44.42 | 44.55 | 44.87 | 45.77 | 46.23 | 46.51 | 46.63 | 46.03 | 46.22 | 46.87 |
| Fused Speed | 29.11 | 28.47 | 25.87 | 25.02 | 25.40 | 25.06 | 25.49 | 25.81 | 25.25 | 24.39 | 24.05 | 25.09 | 25.47 | 25.91 | 25.96 | 26.19 | 24.76 | 24.34 | 24.12 | 23.23 | 23.43 | 23.92 | 24.24 | 24.06 | 24.45 | 24.13 | 24.14 | 25.03 | 25.71 | 26.17 | 26.31 | 26.15 |
| VSA Speed | 38.56 | 37.32 | 34.75 | 34.10 | 34.63 | 33.58 | 33.25 | 33.42 | 32.67 | 31.57 | 31.21 | 32.29 | 33.18 | 34.04 | 34.29 | 34.61 | 34.24 | 33.77 | 33.68 | 33.03 | 33.44 | 33.55 | 34.13 | 34.15 | 34.52 | 34.05 | 34.17 | 35.04 | 35.44 | 35.76 | 36.21 | 36.20 |
| Radar vs VSA | 24.79 | 23.97 | 30.85 | 32.23 | 29.50 | 30.77 | 28.81 | 25.23 | 20.58 | 21.67 | 23.19 | 20.34 | 19.29 | 19.29 | 20.81 | 20.39 | 32.85 | 30.94 | 31.32 | 35.01 | 33.20 | 34.10 | 30.15 | 30.47 | 29.96 | 34.41 | 35.27 | 32.73 | 31.58 | 28.74 | 27.65 | 29.50 |
| Fused vs VSA | -24.50 | -23.72 | -25.55 | -26.61 | -26.64 | -25.38 | -23.35 | -22.76 | -22.69 | -22.73 | -22.96 | -22.32 | -23.24 | -23.89 | -24.28 | -24.34 | -27.67 | -27.93 | -28.38 | -29.66 | -29.91 | -28.72 | -28.99 | -29.56 | -29.17 | -29.15 | -29.37 | -28.57 | -27.45 | -26.82 | -27.34 | -27.75 |
| Status | / | Const | Const | Const | Const | Const | Const | Const | Const | Const | Const | Const | Const | Const | Const | Const | / | Const | Const | Const | Const | Const | Const | Const | Const | Const | Const | Const | Const | Const | Const | Const |

Table 18. Percentage of speed difference for VSA compared to radar speed and fused speed at VSA sign 10 (12th Ave)

| | 6:00 | 6:15 | 6:30 | 6:45 | 7:00 | 7:15 | 7:30 | 7:45 | 8:00 | 8:15 | 8:30 | 8:45 | 9:00 | 9:15 | 9:30 | 9:45 | 15:00 | 15:15 | 15:30 | 15:45 | 16:00 | 16:15 | 16:30 | 16:45 | 17:00 | 17:15 | 17:30 | 17:45 | 18:00 | 18:15 | 18:30 | 18:45 |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Radar Speed | 49.32 | 48.49 | 48.18 | 47.55 | 46.03 | 45.37 | 44.75 | 43.87 | 42.50 | 41.74 | 41.65 | 41.66 | 42.21 | 42.63 | 42.22 | 43.30 | 47.47 | 48.13 | 47.07 | 46.82 | 45.79 | 45.52 | 45.10 | 44.74 | 45.41 | 45.84 | 46.00 | 46.44 | 47.34 | 47.18 | 47.24 | 47.48 |
| Fused Speed | 32.18 | 31.59 | 30.85 | 30.29 | 29.75 | 29.29 | 29.04 | 28.80 | 28.26 | 27.51 | 27.37 | 27.68 | 27.96 | 28.27 | 28.05 | 28.61 | 29.70 | 30.03 | 29.23 | 28.76 | 28.63 | 28.45 | 28.26 | 28.12 | 28.52 | 28.56 | 28.68 | 29.08 | 29.82 | 29.72 | 29.76 | 29.98 |
| VSA Speed | 35.55 | 35.15 | 33.93 | 33.40 | 33.17 | 32.24 | 31.57 | 31.39 | 30.73 | 29.79 | 29.59 | 30.19 | 31.02 | 31.59 | 31.42 | 31.90 | 33.01 | 33.27 | 32.88 | 32.65 | 32.39 | 32.21 | 32.36 | 32.39 | 32.63 | 32.54 | 32.42 | 32.82 | 33.33 | 33.19 | 33.28 | 33.58 |
| Radar vs VSA | 38.73 | 37.95 | 42.00 | 42.35 | 38.77 | 40.74 | 41.74 | 39.77 | 38.29 | 40.10 | 40.76 | 37.97 | 36.05 | 34.96 | 34.39 | 35.75 | 43.80 | 44.69 | 43.18 | 43.42 | 41.39 | 41.35 | 39.38 | 38.11 | 39.17 | 40.88 | 41.88 | 41.50 | 42.05 | 42.16 | 41.93 | 41.39 |
| Fused vs VSA | -9.49 | -10.12 | -9.09 | -9.30 | -10.30 | -9.14 | -8.02 | -8.26 | -8.04 | -7.68 | -7.51 | -8.33 | -9.88 | -10.50 | -10.72 | -10.32 | -10.02 | -9.72 | -11.11 | -11.91 | -11.59 | -11.67 | -12.67 | -13.20 | -12.59 | -12.23 | -11.54 | -11.40 | -10.53 | -10.44 | -10.59 | -10.72 |
| Status | / | Const | Const | Const | Const | Const | Const | Const | Const | Const | Const | Const | Const | Const | Const | Const | / | Const | Const | Const | Const | Const | Const | Const | Const | Const | Const | Const | Const | Const | Const | Const |

### 6.4 Conclusion and Lesson Learned

Based on the engineering data, it is difficult to quantify the driver compliance rate for all VSA signs since they may be different at different locations.

The major lesson we have learned for the field test is that the VSA signs on the shoulder lane may not be noticed by some drivers, which could significantly affect the drivers' compliance. It it is available, overhead gantries would have better view to all the drivers without much distraction.

As for the location of VSA signs, we most selected the location about 100~200 m downstream of the onramp considering that the traffic from the onramp could be immediately affected by the VSA. During the test, after several crashes of the driver onto the trailers at least 3 locations of the VSA signs, we recognized that the downstream of the onramp might not be a good location since the drivers may have been paying more attention to the lane merge maneuver to get into the mainline traffic. Therefore, less attention to the VSA sign could possibly lead to some driver crash. Of course, if the overhead gantries are available, there would not be such a problem.

# 7 References

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# 8 Appendix 1. VSA Field Test Permission Application to FHWA

***Caltrans Division of Research, Innovation, and System Information (DRISI) is requesting permission to experiment with Variable Speed Advisory (VSA) signs***

***Project Title:*** *Field Test of Combined Coordinated Ramp Metering (CRM) and Variable Speed Advisory (VSA) for Freeway Traffic Control*

***Contract Number:*** *65A0743*

***Project Manager:*** *Hassan Aboukhadijeh, (916) 227-6216*

***Test Corridor:*** *State Route 99 northbound from Elk Grove Blvd. to State Route 50 interchange in Caltrans District 3, Sacramento, a 13 miles long corridor with 16 on-ramps and 11 off-ramps.*

***Number of VSA signs:*** *15*

***Proposed Test Period:*** *10/12/20 to 9/12//21; 12 months*

***Test time:*** *AM peak hour (6:00 –9: 00am) on workdays which has higher traffic demand than the PM peak hours; off on the weekends*

***Dimensions of the Signs:*** *48" (W)x (60)" H*

***Display Type and Color:*** *The electronic variable speed display portion are orange LED numbers, on black background. The phrase "ADVISORY SPEED" will be displayed in capital letters on the fixed portion of the sign (Black on Yellow)*

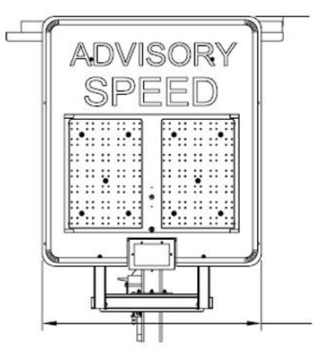




Figure 22 *Proposed VSA Style, Size and the Color Schemes*

***Other Components:***

- *Radar to provide aggregated traffic speed data every 30 [s]; data passing through modem.*
- *Modem and internet connection between PATH computer, the Cloud and the VSA signs in the field – update every 30 [s].*
- *Solar panel and batteries to provide sustainable power for operation on each unit for the proposed test period on workdays.*

***VSA Sign Locations:*** *The following 4 figures shows the preliminarily suggested locations based on the exact road geometry and roadside available spaces.*

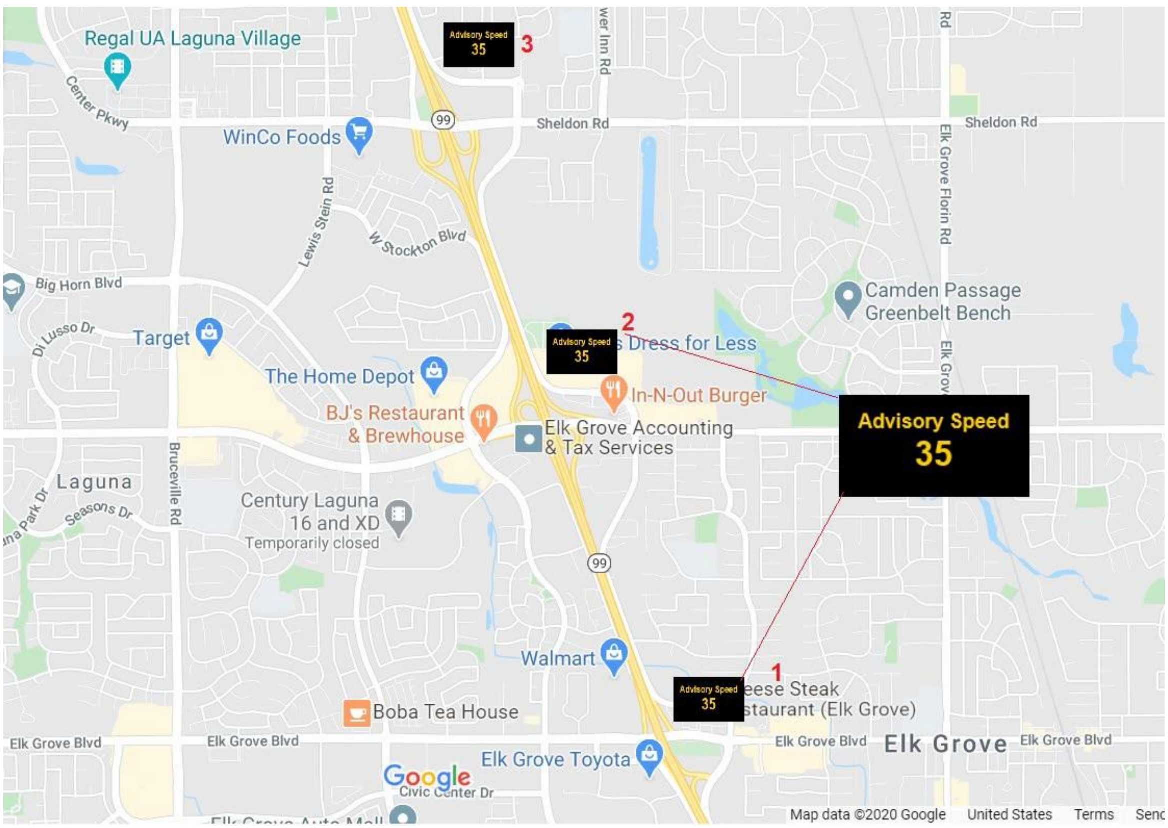



Figure 23. SR-99 NB Road Geometry and the schematic locations of VSA signs.

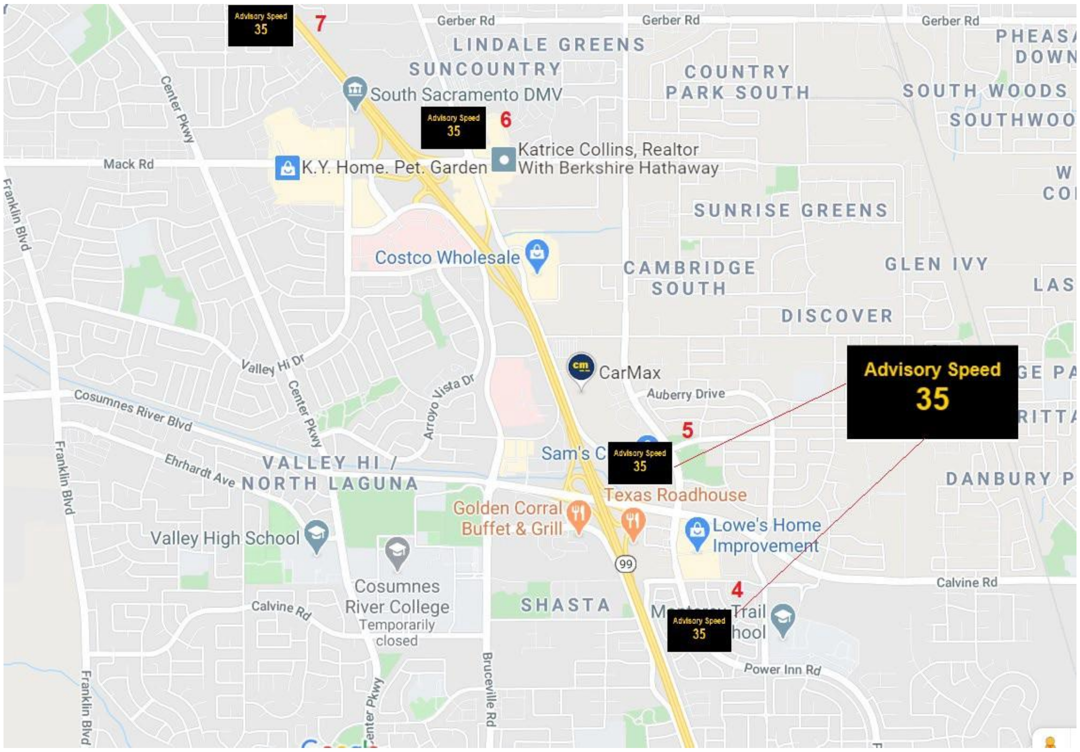



Figure 24. SR-99 NB Road Geometry and the schematic locations of VSA signs.

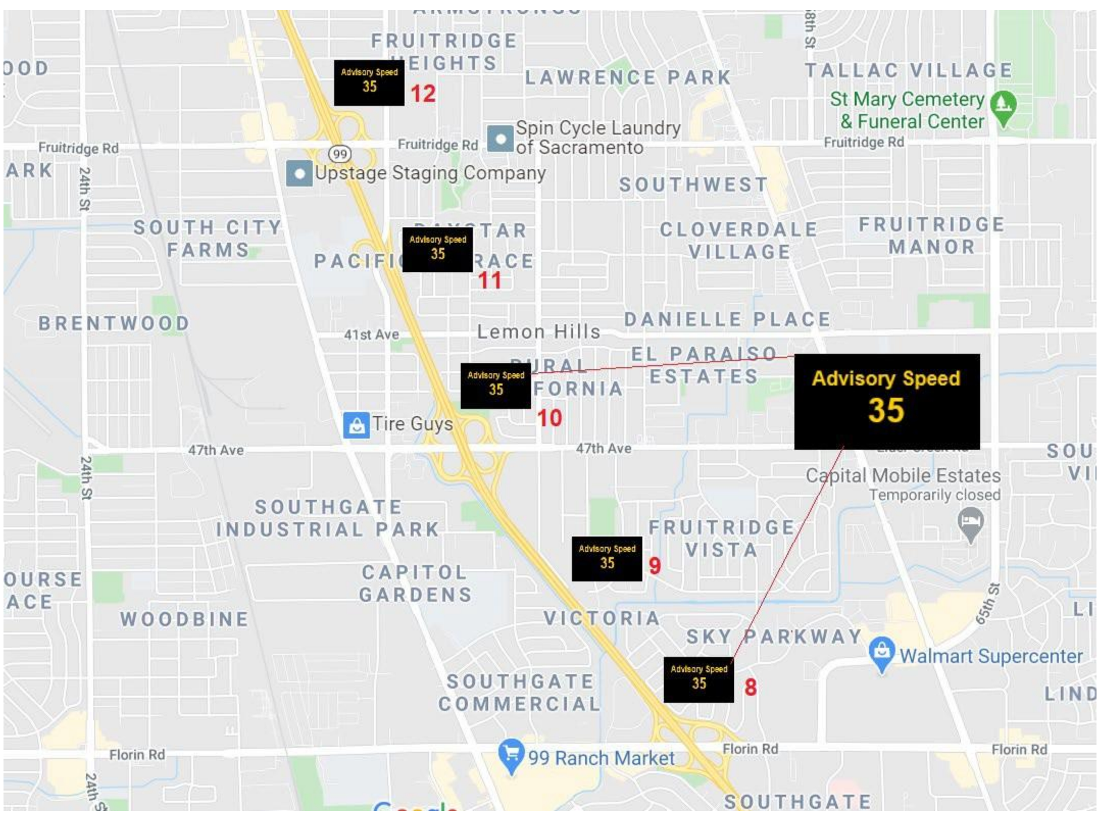



Figure 25. SR-99 NB Road Geometry and the schematic locations of VSA signs.

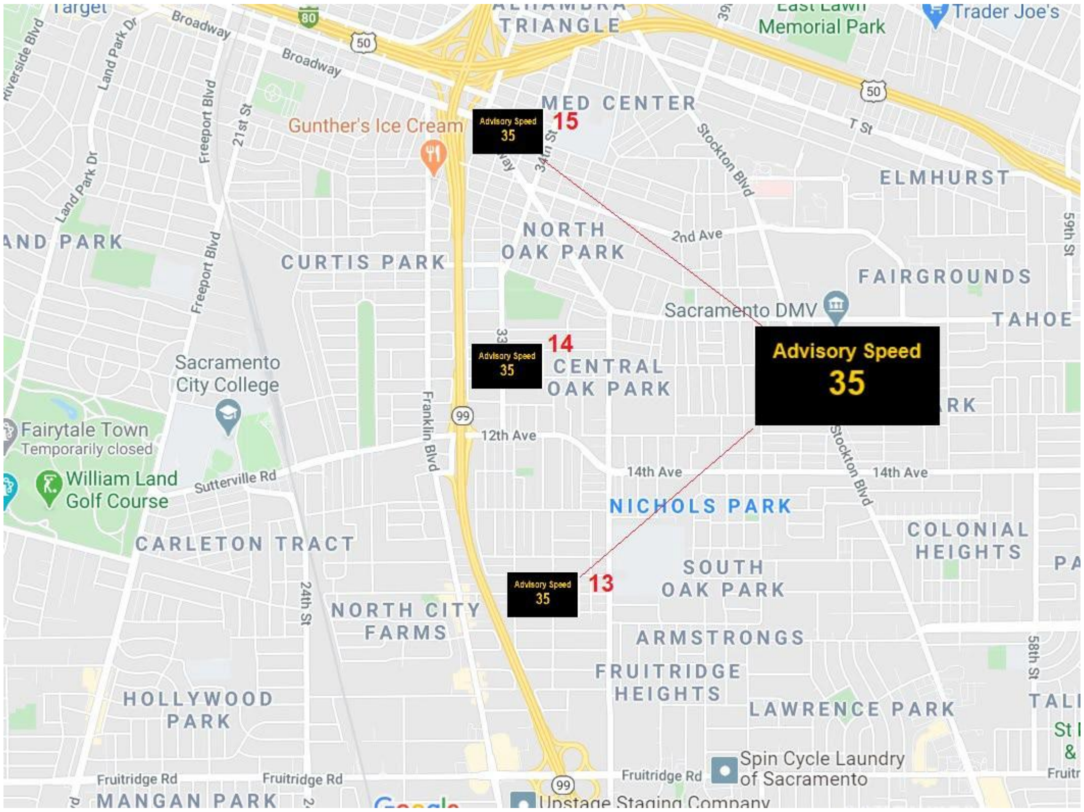



Figure 26. SR-99 NB Road Geometry and the schematic locations of VSA signs.

# 7 Appendix 2: Permission Application from CA CTCDC

**To:** Vijay Talada, P.E.
CA MUTCD Editor
Division of Traffic Operations
CA Dept of Transportation
1120 N Street, MS 36, Room 4500
Sacramento, CA 95814

**Date:** May 11, 2020

**From:** Hassan Aboukhadijeh
Office of Traffic Operations Research
Division of Research, Innovation, and System Information (DRISI)
CA Dept of Transportation
1727 30th Street,
Sacramento, CA 95816

**Subject: REQUEST TO TEST AND EVALUATE THE PERFORMANCE OF TraffiCalm™**

In accordance with the Manual of Uniform Traffic Control Devices (MUTCS), the Division of Research, Innovation, and System Information (DRISI) is applying for Request to test and evaluate the performance of Variable Speed Advisory (VSA) on State Route 99, northbound corridor from Elk Grove Blvd. to State Route 50 interchange in Caltrans District 3 in Sacramento. Similar signs have been used in previous studies in Caltrans District D11. UC Berkeley PATH project team has developed a simple, practical VSA algorithm that should improve bottleneck flow and reduce shockwaves along this freeway well known for congestion. This has generated promising results but still needs to be field tested to determine its success.

Attached is the project scope along with information for the temporary use of the VSA signs that will be acquired from TraffiCalm™.

Please contact Hassan Aboukhadijeh if you have any questions at (916) 227-6216.

**Request to Experiment**

Project Title: Field Test of Combined Coordinated Ramp Metering (CRM) and Variable Speed Advisory (VSA) for Freeway Traffic Control, Contract Number 65A0743

Caltrans Division of Research, Innovation, and System Information is requesting permission to experiment with TraffiCalm™ Variable Speed Advisory (VSA) signs on northbound on State Route 99 from Elk Grove Blvd. to State Route 50 interchange in Caltrans District 3 in Sacramento. This is a 13 miles long corridor with 16 on-ramps and 11 off-ramps. It is expected to use 15 VSA signs along the corridor. We plan to test these signs for 12 months so that the public drivers, particularly the commuters, can adapt to the system. The VSA signs will be tested mainly for AM peak hour (6:00 – 9:00am) which has higher traffic demand than the PM peak hours.

**Proposal**

Caltrans and UC Berkeley researchers are proposing to experiment with Variable Speed Advisory (VSA) in areas well known for congestion or traffic incidents, which can improve bottleneck flow and reduce shockwaves along the freeway. The VSA algorithm will use data from traffic sensors and radar to advise drivers of the optimum speed to improve traffic flow, reduce travel time, and improve roadway safety.

**A. A statement indicating the nature of the problem**

Typically, driver behavior is the main cause of traffic on the freeways. To better control this, Coordinated Ramp Metering (CRM) and Variable Speed Advisory (VSA) were introduced onto California freeway corridors. Ramp Metering controls the demand onto the freeway, and Variable Speed Advisory attempts to control driver behavior. UC Berkeley project team has developed a simple, practical VSA algorithm that should improve bottleneck flow and reduce shockwaves along the freeway. This has generated promising results but still needs to be field tested to determine its success.

**B. A description of the proposed change, how it was developed, the manner in which it deviates from the standard, and how it is expected to be an improvement over existing standards.**

The proposed overall control systems structure and the preliminary Concept of Operation (ConOps) are shown in Figure 1 below.

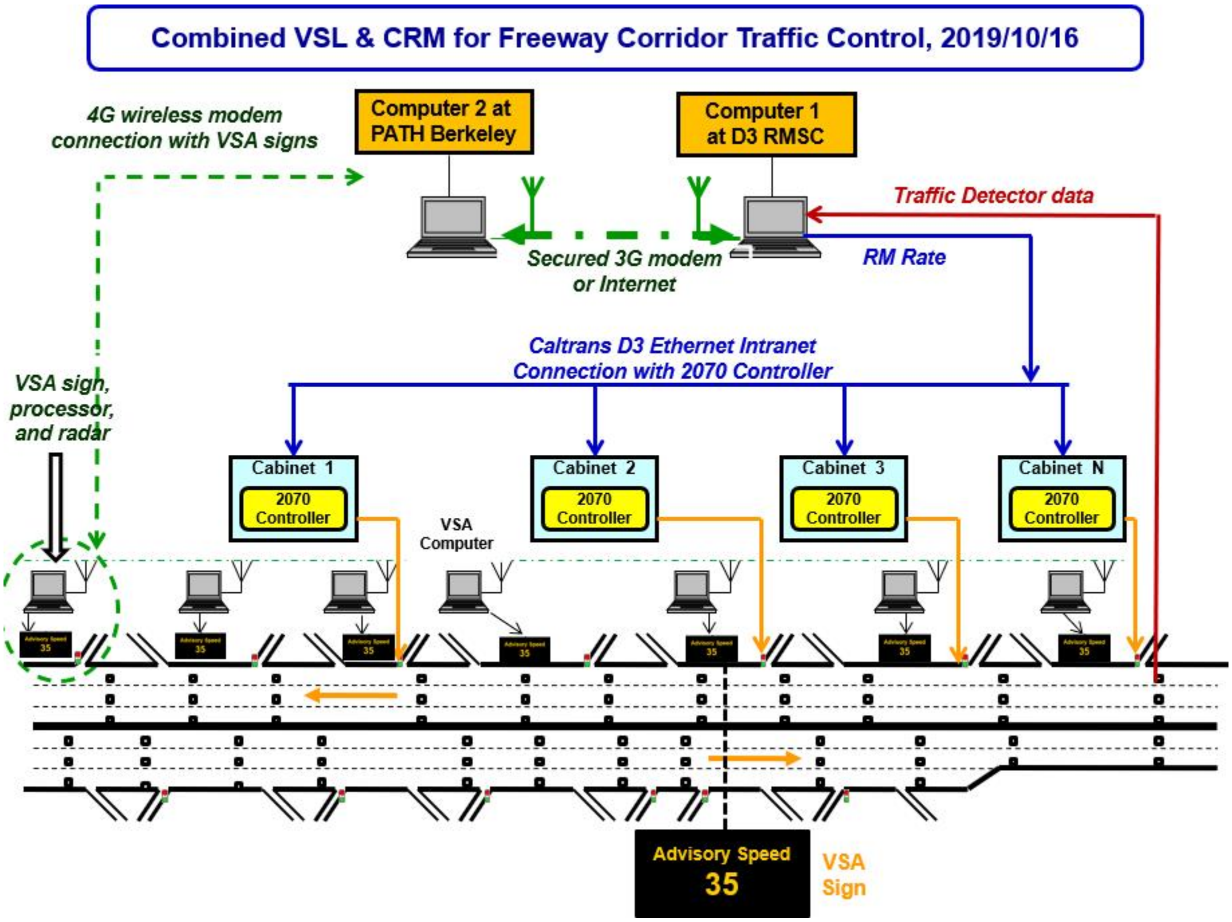



Figure 27 Proposed ConOps System Structure for Combined CRM and VSA

Note: currently, District 3 is using the Coordinated Ramp Metering (CRM) algorithm developed by UC Berkeley PATH. The control computer located in Caltrans District 3 TMC linked with 2070 controllers in the field for daily operation. This computer directly linked through Caltrans intranet with the 2070 traffic controllers on the SR-99 NB corridor for data acquisition, ramp meter rate calculation and sending back the rate for execution. This configuration will be kept for this this project of combined CRM and VSA project.

The main functions of the proposed TraffiCalm™ VSA signs are listed below:

- Large enough size for LED display
- With solar panel and battery for sustainable power supply; solar panel will charge the battery; the number of batteries is flexible
- Change message in real-time: update rate less than 10 second
- Mounted on trailer already, which meet Caltrans (California Department of Transportation) traffic safety requirement
- Modem connection for remote control; we can add the modem

- Radar interface: we can add the radar unit for traffic detection; but the processor needs to be powerful enough for raw radar data processing

### C. Any illustration, photograph, or videos, which would help, explain the experimental device or use of this device.

The proposed TraffiCalm™ VSA Sign that meet all the project technical requirement is shown in Figure 2 below.

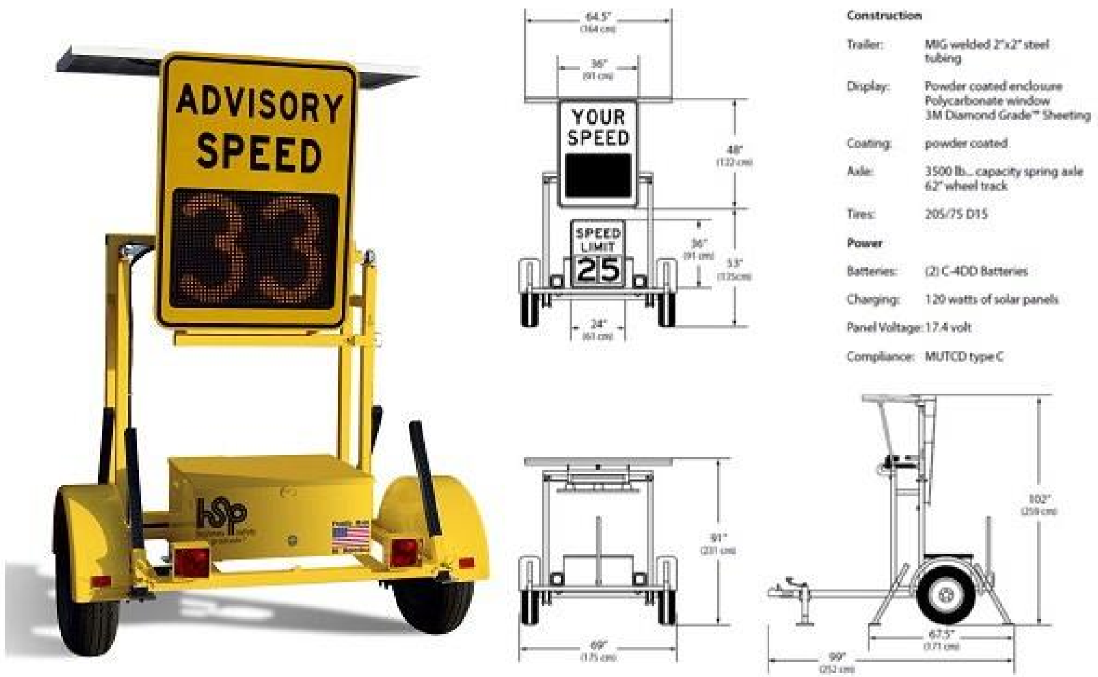



Figure 28. TraffiCalm™ VSA Sign -dimensions with Black on Yellow Background

It is noted that this trailer has been approved and used by Caltrans before. Mr. Yong Pak of Caltrans has utilized these trailers on his projects:

Mr. Yong Pak
I-5 North Coast Corridor
Phone: 858-688-1481
Email: yong.pak@dot.ca.gov

### D. Any supporting data as to how the experimental device was developed, if it has been tried, in what ways it was found to be adequate or inadequate, and how was this choice of device or application arrived at.

The following two previous projects generated promising results that need to be field tested.

- Caltrans initiated a Variable Speed Advisory (VSA) pilot project on State Route 78 in District 11 to help manage vehicle speeds in areas well known for congestion or traffic incidents. The VSA algorithm used data from traffic sensors to advise drivers of the optimum speed to improve traffic flow, reduce travel time; minimize traffic delays caused by incidents. The variable speed advisory system that was developed increased morning traffic efficiency by 8.71% and afternoon by 2.8%.

- In addition, Caltrans tested Coordinated Ramp Metering (CRM) on SR99 NB in Sacramento. The CRM that we used controlled a series of ramps to help improve efficiency and safety of the entire freeway system. Caltrans District 3 traffic engineers monitored traffic on SR99 and determined that Coordinated Ramp Metering (CRM) strategy algorithm showed positive results, increasing system efficiency by 7.25% over locally traffic responsive ramp metering.

Since CRM and VSA affect the freeway traffic from different aspects, it would make sense to test those two freeway traffic management measures jointly on a freeway corridor and evaluate the performance for traffic improvement.

**E. A legally binding statement certifying that the concept of the traffic control device is not protected by a patent or copyright**

To the best of our knowledge, the concept of using CRM/VSA algorithm to for freeway traffic control are not protected by patents or copyrights.

**F. The time period and location(s) of the experiment.**

The experiment will be for a one-year period.

**G. A detailed research or evaluation plan that must provide for close monitoring of the experimentation, especially in the early stages of its field implementation. The evaluation plan should include before and after studies as well as quantitative data describing the performance of the experimental device.**

Figure 3 shows the proposed locations of VSA signs on Caltrans District 3 SR-99 NB Corridor. Based on the road geometry, exact location of each sign will be determined with Caltrans Regional Transportation Management Center (RTMC) in District 3. UC Berkeley PATH will provide semi-annual progress reports for the duration of the experiment. The above information will be presented in a final report within 3 months following the completion of the experiment. We plan to use 15 VSA signs to cover the whole corridor as shown in Figure 3. The following is a tentative short-term schedule for system preparation:

| Actions/Activities | Start date | End Date | Comments |
|---|---|---|---|
| First VSA sign acquisition | 4/15/20 | 6/15/20 | |
| System development | 6/15/20 | 8/15/20 | |
| Acquisition of the rest 14 VSA sign | 7/15/20 | 8/15/20 | Ready to go to field |
| John to work at D3 Maintenance Yards for system integration | 8/15/20 | 9/4/20 | VSA ready for installation in the field |
| Trailers and VSA signs to be mounted in the field | 9/7/20 | 9/11/20 | VSA signs ready in field |
| System integration and verification in the field | 9/14/20 | 9/25/20 | VSA signs ready for test |
| Preliminary test | 9/28/20 | 10/9/20 | System tuning |
| Extensive formal tests | 10/12/20 | 9/12//21 | 12 months field tests |
| Remove trailers from field to D3 Maintenance Yards | 9/12/21 | 9/20/21 | |

**H. An agreement to restore the site of the experiment to a condition that complies with the provisions of this Manual within 3 months following the end of the time period of the experiment. This agreement must also provide that the agency sponsoring the experimentation will terminate the experimentation at any time that it determines significant safety concerns are directly or indirectly attributable to the experimentation. The FHWA's Office of Transportation Operations has the right to terminate approval of the experimentation at any time if there is an indication of safety concerns. If, as a result of the experimentation, a request is made that this Manual be changed to include the device or application being experimented with, the device or application will be permitted to remain in place until an official rulemaking action has occurred.**

Caltrans DRISI and UC Berkeley PATH agree to the above conditions.

**I. An agreement to provide a progress report at 6 months for the experimentation and an agreement to provide a copy of the final results of the experimentation to the FHWA's Office of Transportation Operations within 3 months following completion of the experimentation. The FHWA's Office of Transportation Operations has the right to terminate approval of the experimentation if reports are not provided in accordance with this schedule.**

Caltrans DRISI and UC Berkeley PATH agree to the above conditions, however based on the information that FHWA is looking to collect, all of this will be available within the final report.

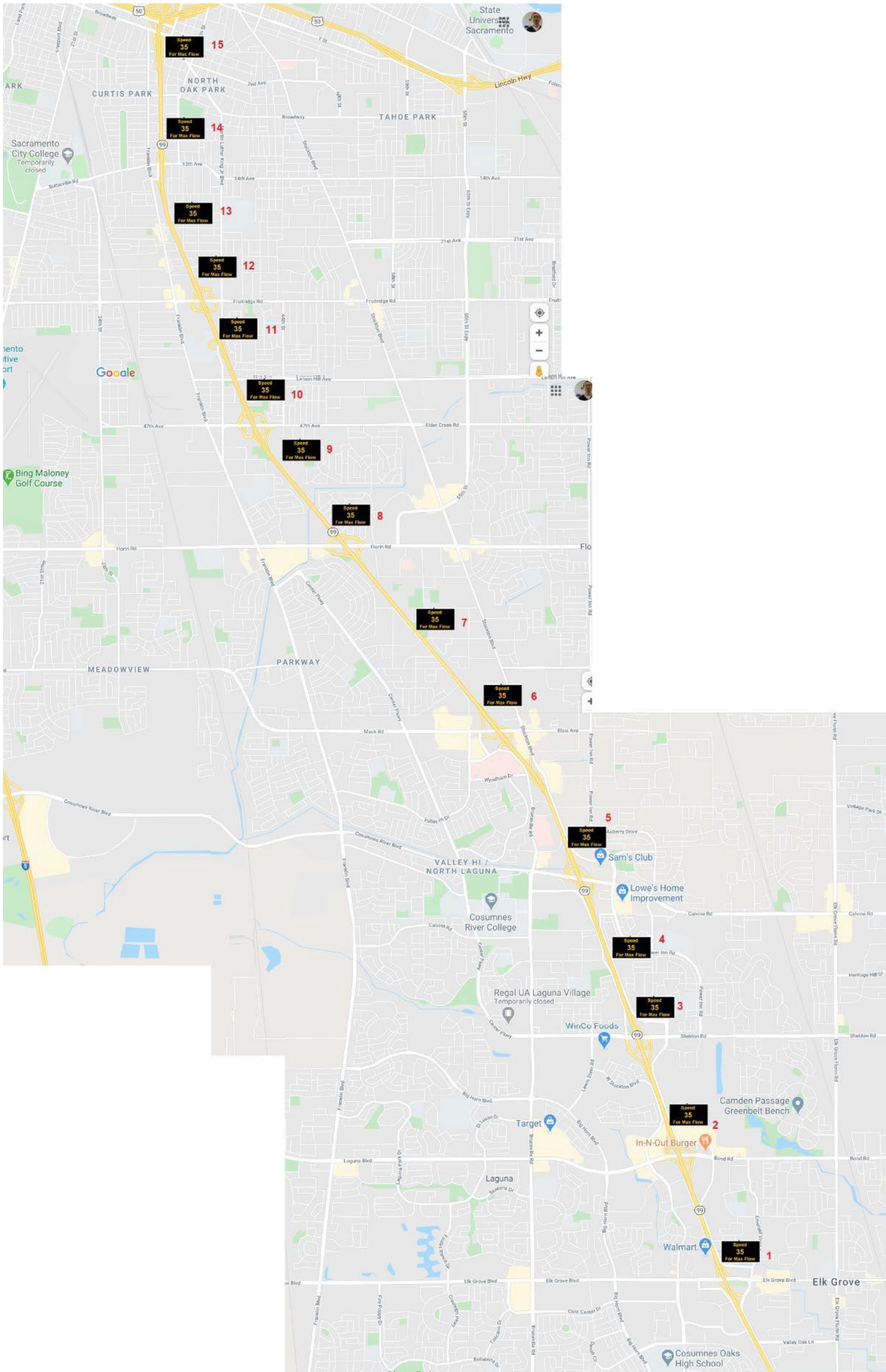



Figure 29. SR-99 NB Road Geometry and the schematic locations of VSA signs.

# 8 Appendix 3: Bird-view of VSA Sign Locations over Google Map


Figure 30. Location of VSA sign 1 (downstream of Elk Grove onramp)

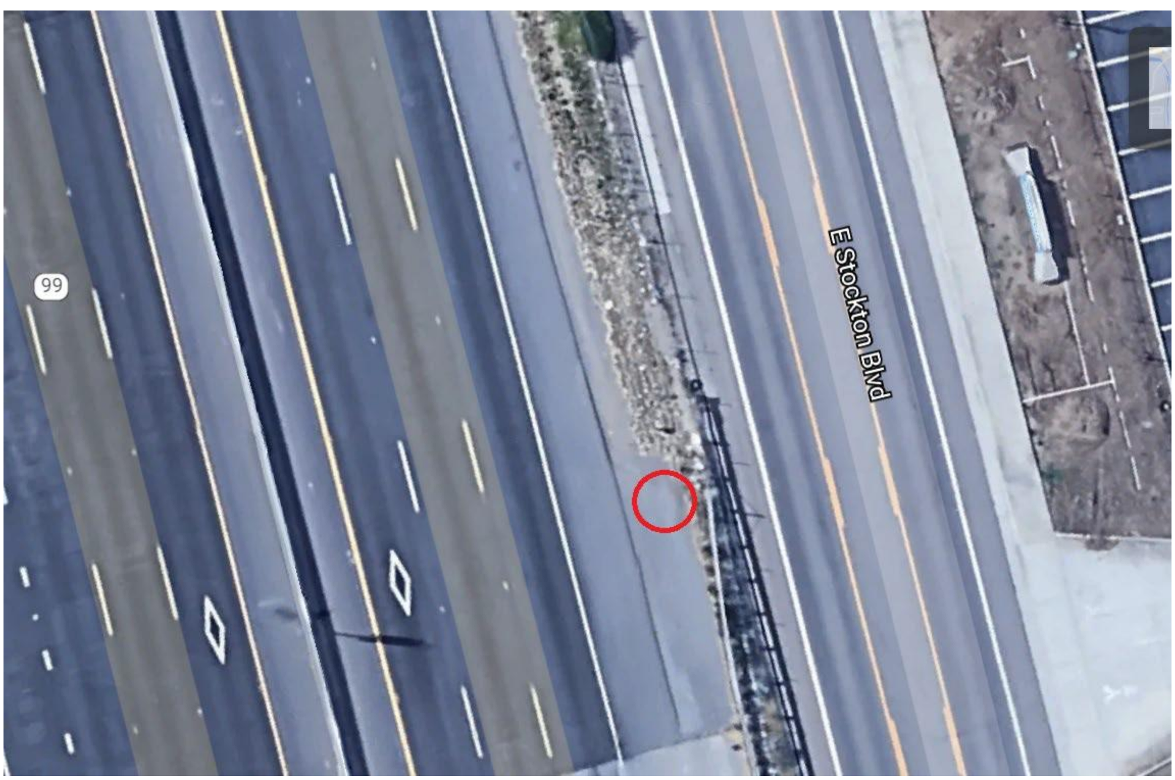



Figure 31. Location of VSA sign 2 (downstream of Laguna Blvd WB onramp)

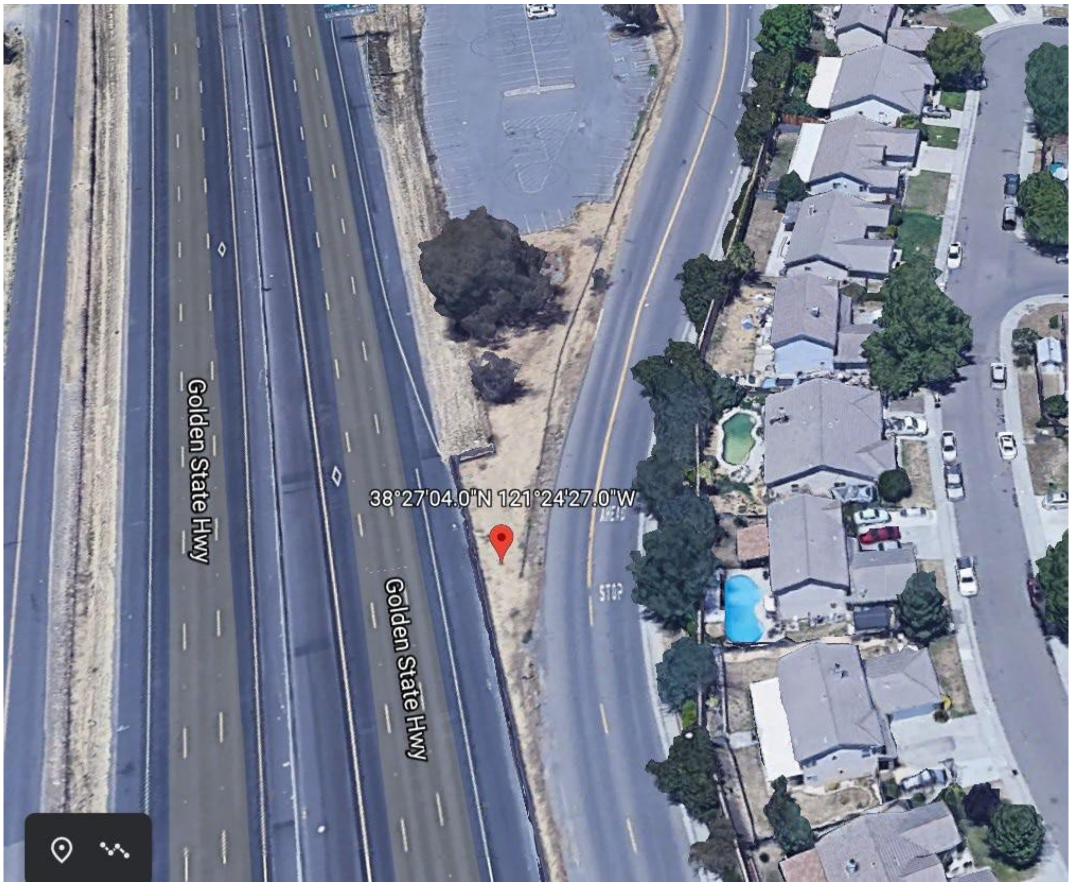



Figure 32. Location of VSA sign 3 (downstream of Sheldon WB onramp)


Figure 33. Location of VSA sign 4 (downstream of Calvine WB onramp)

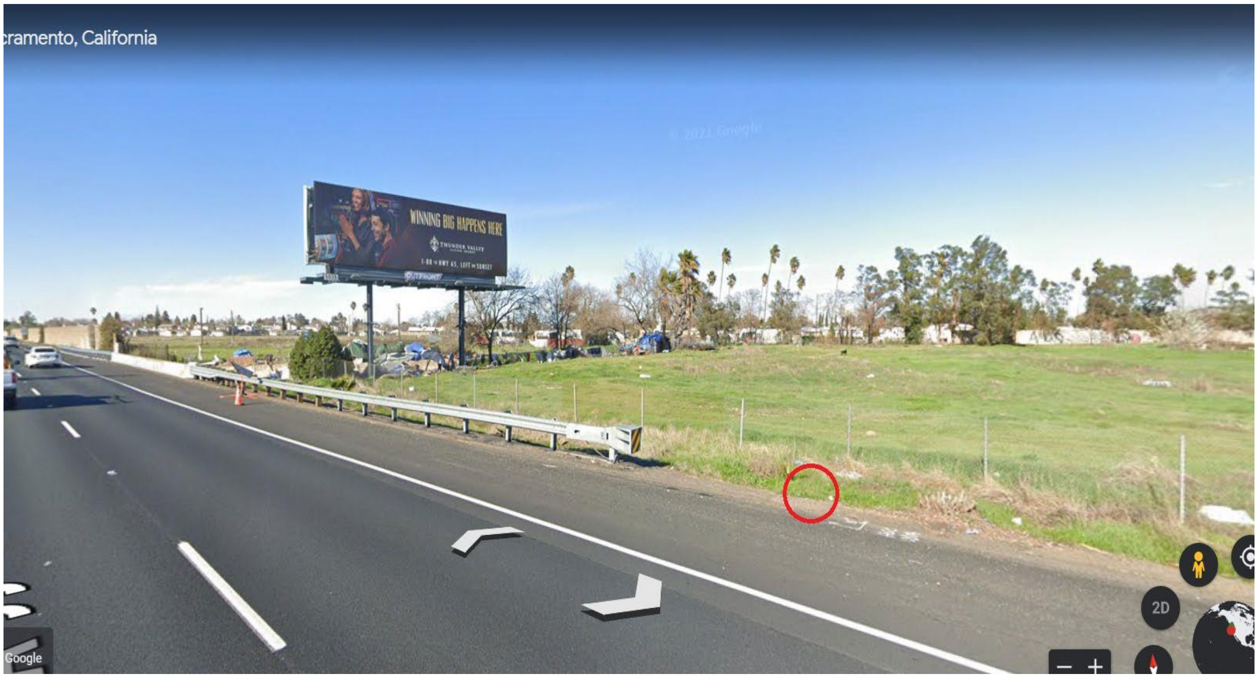
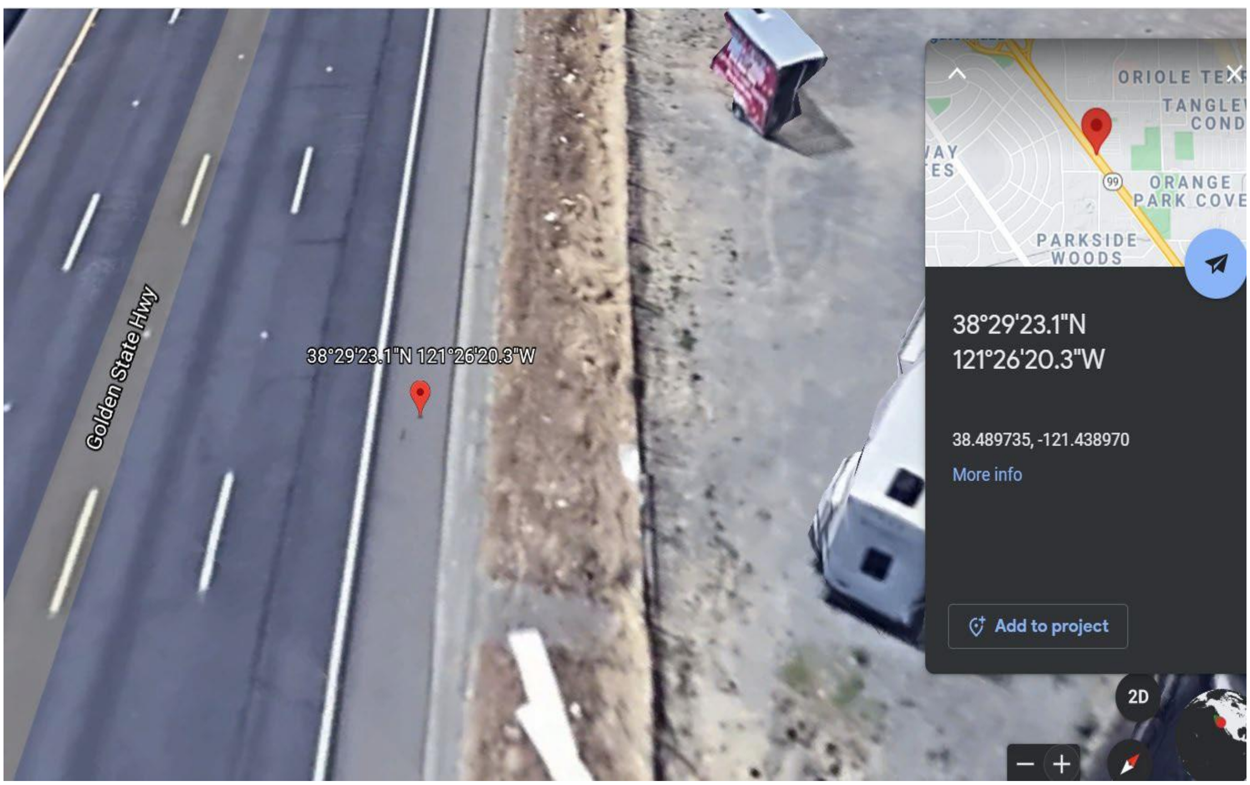



Figure 34. Location of VSA sign 5 (downstream of Mack Road WB onramp, 1st sign)




Location of VSA sign 6 (downstream of Mack Road WB onramp, 2nd sign)

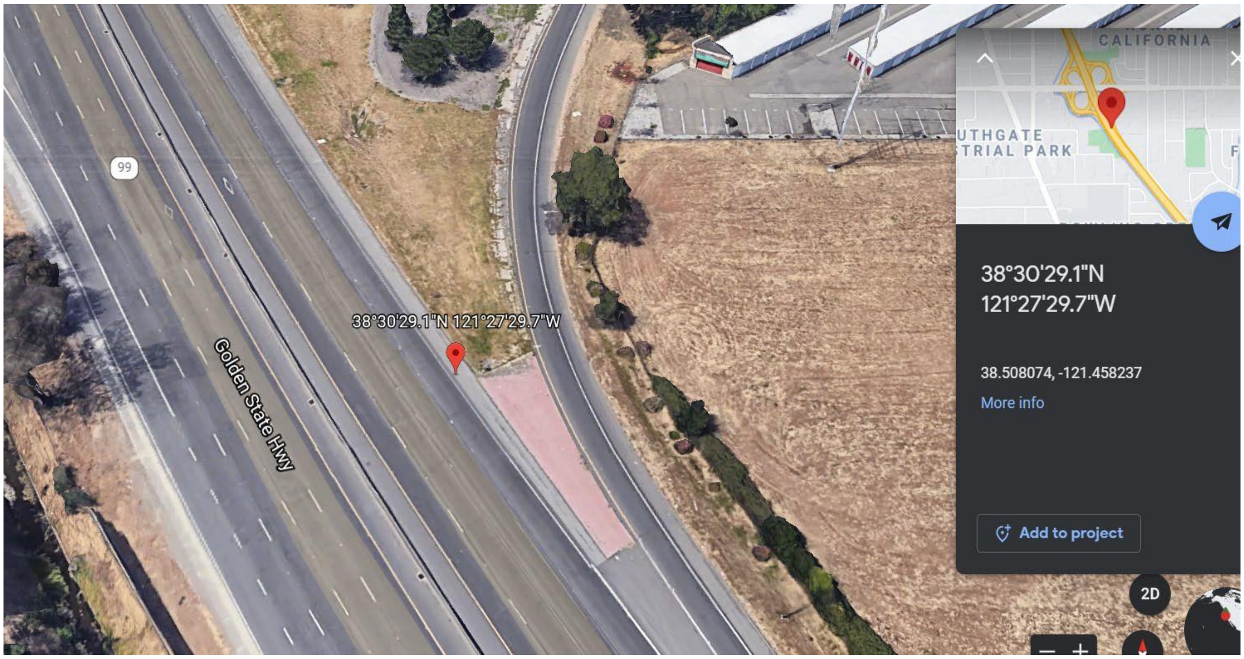



Figure 35. Location of VSA sign 7 (downstream of Florin WB onramp)


Figure 36. Location of VSA sign 8 (downstream of 47th Ave WB onramp)

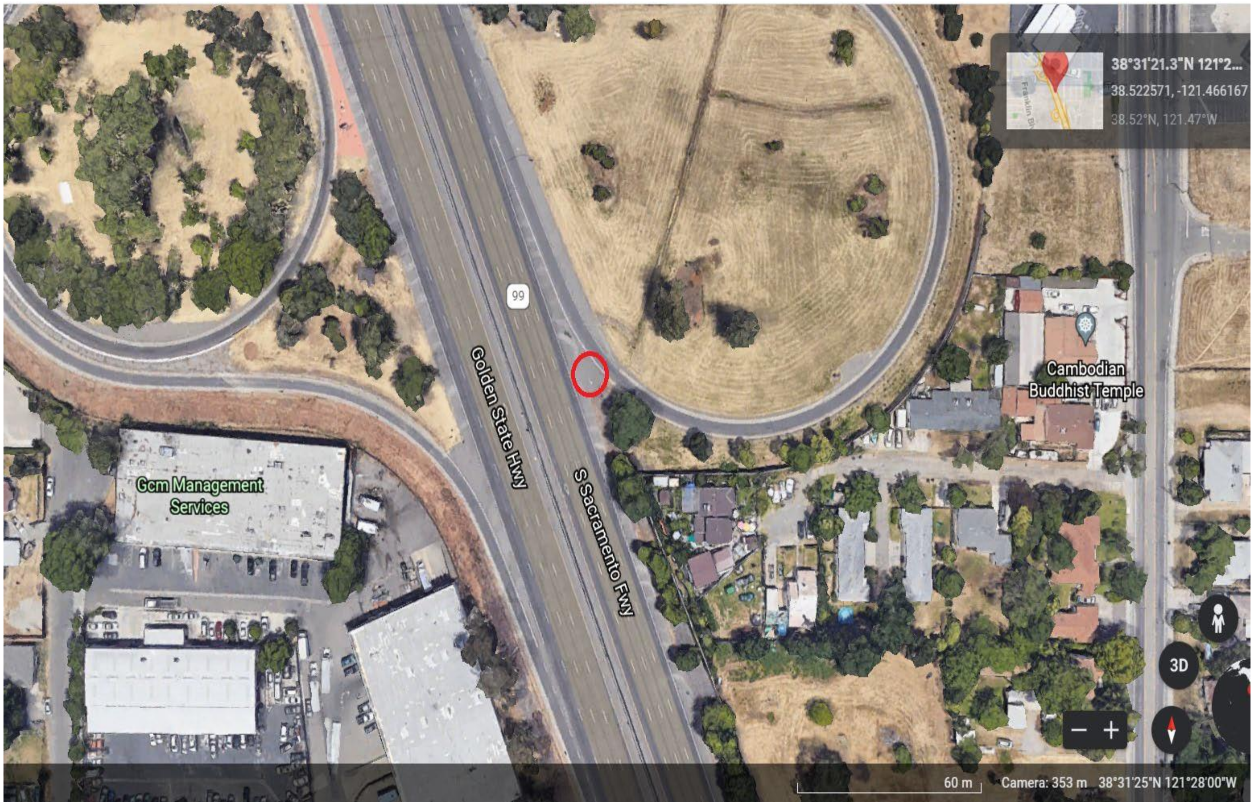



Figure 37. Location of VSA sign 9 (downstream of Fruitridge WB onramp)


Figure 38. Location of VSA sign 10 (downstream of 12th Ave. onramp)