Field Test Implementation of Variable Speed Advisory Control Strategy: A Case Study on SR-78E

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ABSTRACT
This paper presents the field implementation and testing of variable speed advisory (VSA) for bottleneck flow maximization based on speed and occupancy measurement. The test site was at the California State Route 78 Eastbound (SR-78E) corridor in San Diego, between Vista Village Drive in the City of Vista and U.S. Route 15 (US-15) interchange in the city of Escondido (Abs. PostMile 6.32 - 17.73). The test site is an 11-mile long corridor with 10 on-ramps and 10 off-ramps to which the VSA algorithm has been applied. By comparing the vehicle miles-travelled (VMT), vehicle-hours-travelled (VHT), and the ratio VMT/VHT (freeway efficiency) of PeMS data which is independent of the data from VSA system for objectivity in performance evaluation, the results for before and after VSA control implementation are analyzed in depth. During the morning peak hours (6:00 AM-9:00 AM), VMT/VHT increased by 8.71% on average, which indicating traffic efficiency improvement. During the evening peak hours (2:00 PM-7:00 PM), VMT/VHT increased only by 2.8% on average, which suggests a slight traffic efficiency improvement. The test results suggest that the proposed VSA algorithm can be deployed for heavily congested traffic to alleviate congestion. Findings of this field test will help to further develop VSA control algorithms and improve VSA traffic operations benefits.
INTRODUCTION
Variable Speed Advisory (VSA) control seeks to improve freeway efficiency by deferring the onset of congestion or increasing the effective throughput particularly at congested bottlenecks. Early research regarding Variable Speed Limit (VSL) focused on the concept of speed homogenization \[1\] \[2\]. This research shows that harmonizing the speed along the freeway and reducing speed differences in different lanes and for lane-changing can improve freeway efficiency \[3\]. In practice, VSL/VSA systems have been more widely deployed in Europe \[4\] than in the United States \[5\] \[6\]. VSL posts speed limits that drivers must obey, while VSA posts recommended driving speeds that are not legally enforced. Therefore, driver’s willingness to comply with these two types of methods of control could be different and produce different levels of driver compliance rates. By the type of control algorithm, VSL/VSA can be divided into two categories: rule-based \[7\] \[8\] and model-based control \[9\] \[10\]. Rule-based VSA system uses pre-defined logic rules and preselect parameter thresholds to create real-time traffic control, while model-based VSA system uses a pre-established optimization model with traffic measurement to obtain optimal control action. Rule-based VSA strategies have been deployed in the United States, namely in Washington \[11\], Minnesota \[12\] \[13\], Oregon \[14\] and Missouri \[15\], and in European countries such as the United Kingdom \[16\], Germany \[17\], and the Netherlands \[18\]. Few model-based VSA have been deployed in the real-world. Hegyi and Hoogendoorn have developed a SPECIALIST algorithm (SPEed ControllIng ALgorIthm using Shock wave Theory) and performed a field test on a 14 km long stretch on the Dutch A12 freeway \[19\]. This field test example was designed primarily to address recurrent bottlenecks or moving jams, in which an increase of throughput typically ranges from 5% to 15%, and to reduce of rear-end collisions.

In California, United States, most of the VSA deployments were originally designed for warning drivers of weather/road related hazardous conditions, visibility conditions, work zones, incidents, and on-ramp/off-ramp/lane closures. A temporary VSA deployment in these situations is used for managing non-recurring congestion and increasing freeway safety. However, there have been a few temporary VSA deployments for recurrent congestion in California. Developing an efficient variable speed advisory system that can regulate the traffic speed levels under the dynamically changing traffic conditions is necessary for improving freeway safety and alleviating recurrent congestion.

The main contribution of this paper: a variable speed advisory system was designed and evaluated in the field. The proposed VSA algorithm adopts occupancy and speed measurement from upstream and downstream of a VSA location that does not employ traffic models in calculating the time-variant advisory speed values. By providing advisory speed to the drivers on the freeway, the system is able to improve the most downstream bottleneck flow and reduce speed variations and the potential for rear-end collisions. The system was implemented during a four-week period from April 9 to May 4, 2018 on a test segment of SR 78 Eastbound, which is one of San Diego’s most congested interchanges. The field test effectiveness in reducing traffic congestion and improving freeway efficiency was evaluated using PeMS data which is independent of the data used by the VSA system for objectivity in the performance evaluation. The rest of the paper summarizes the test site traffic characteristics, the methodology of the proposed system, field implementations and performance evaluation results.
TEST SITE AND AVAILABLE DATA DESCRIPTION

The test site of the variable speed advisory (VSA) field implementation is on the SR-78E from Vista Village Drive in the City of Vista at absolute postmile 6.32 to the freeway interchange point of SR-78E, and U.S. Route 15 (US-15) in the city of Escondido, at absolute postmile 17.73. This test segment is a three-lane freeway with a posted speed limit of 65 mph and it has 10 on-ramps and 10 off-ramps. The available vehicle detector stations (VDS) are shown in Figure 1. A fixed message sign (FMS) displaying "FOLLOW ADVISORY SPEED" was placed at the starting point of the test site to instruct drivers to obey the speed posted by the downstream VSA. The posted speed on VSA during morning and evening peak hours is recommended to drivers but not enforced. The VDS are installed on the freeway mainline, on-ramps, and off-ramps to collect traffic data, namely volume, speed, and occupancy, every 30 seconds. This data is sent to PeMS for archiving and to our system for monitoring and controlling the freeway.

![FIGURE 1 SR-78E Network configuration and VDS deployment](image)

**Bottleneck Identification**

The scope of this field test is limited to reducing recurrent bottlenecks during morning and evening peak hours. From daily observation during weekdays, the morning peak hours range from 6:00 AM to 9:00 AM and the evening peak hours range from 2:00 PM to 19:00 PM. During peak hours, the speed drops from 60 mph to as low as 15 mph after the onset of the congestion. Figure 2 shows the speed contour for SR78 Eastbound, plotted from loop detector data on March 14, 2018. Two recurrent bottleneck locations are identifiable: Bottleneck 1, which is near San Marcos Blvd. (PM12.27); and Bottleneck 2, which is near the freeway interchange point of SR-78E and US-15 (PM 16.6). Bottleneck 2 (the downstream bottleneck) is caused by diverging traffic from SR-78E to US-15 NB and US-15 SB. This congestion may propagate back to midstream and activates bottleneck 1 at around PM 11, especially during morning peak hours, since high daily commuters
enter the following upstream on-ramps: Sycamore Ave., Las Posas Rd., and San Marcos Blvd. and it causes the onset of bottleneck 1. In summary, based on traffic characteristic studies and bottleneck identifications, the critical location for this VSA test is the most downstream segment around Barham Dr. and Nordahl Rd. Seven VSA signs were placed on the test site. The VSA locations, their posted speed ranges, and the corresponding mainline VDS number are listed in Table 1.

<table>
<thead>
<tr>
<th>Index</th>
<th>Abs. PM</th>
<th>Min. Speed</th>
<th>Max. Speed</th>
<th>VDS</th>
<th>Location</th>
<th>City</th>
</tr>
</thead>
<tbody>
<tr>
<td>FMS 1</td>
<td>6.316</td>
<td>N/A</td>
<td>N/A</td>
<td>1108635</td>
<td>Vista Village Dr.</td>
<td>Vista</td>
</tr>
<tr>
<td>VSA 1</td>
<td>6.822</td>
<td>5</td>
<td>65</td>
<td>1108633</td>
<td>Sunset/Escondido Dr.</td>
<td>Vista</td>
</tr>
<tr>
<td>VSA 2</td>
<td>9.214</td>
<td>5</td>
<td>65</td>
<td>1108645</td>
<td>Sycamore Ave.</td>
<td>Vista</td>
</tr>
<tr>
<td>VSA 3</td>
<td>11.36</td>
<td>5</td>
<td>65</td>
<td>1116449</td>
<td>Las Posas Rd.</td>
<td>San Marcos</td>
</tr>
<tr>
<td>VSA 4</td>
<td>12.27</td>
<td>5</td>
<td>65</td>
<td>1108601</td>
<td>San Marcos Blvd.</td>
<td>San Marcos</td>
</tr>
<tr>
<td>VSA 5</td>
<td>13.018</td>
<td>5</td>
<td>55</td>
<td>1108699</td>
<td>Twin Oaks Valley Rd.</td>
<td>San Marcos</td>
</tr>
<tr>
<td>VSA 6</td>
<td>14.856</td>
<td>5</td>
<td>55</td>
<td>1108702</td>
<td>Barham Dr.</td>
<td>San Marcos</td>
</tr>
<tr>
<td>VSA 7</td>
<td>15.593</td>
<td>5</td>
<td>65</td>
<td>1108706</td>
<td>Nordahl Rd.</td>
<td>San Marcos</td>
</tr>
</tbody>
</table>

**TABLE 1** VSA locations and its minimum and maximum advisory speed

**VARIABLE SPEED ADVISORY DESIGN**

**Traffic Flow Stabilization**

Consider the standard first order model for traffic flow on a single lane freeway parameterized by $x \in [0, L]$ and times $t$. The dynamics of the density on the freeway is given by Lighthill-Whitham-Richards (LWR) partial differential equation (PDE):

$$\frac{\partial}{\partial t} \rho(x,t) = -\frac{\partial}{\partial x} \{ \rho(x,t)v(x,t) \}.$$  \hspace{1cm} (1)

The control objective of variable speed limit control is to stabilize traffic flow by commanding a speed profile $v(x,t)$ such that the density profile $\rho(x,t)$ is close to a desired density profile
\( \rho_d(x,t) \) and the traffic moves at a desired speed \( v_d(x,t) > 0 \). The desired flow rate is determined by \( \phi_d(x,t) = \rho_d(x,t)v_d(x,t) \). For a single lane freeway, the following assumption is introduced.

**Assumption 1.**

1. The speed profile \( v(x,t) \) can be commanded.
2. The dynamics of the desired density and speed profile satisfies
   \[
   \frac{\partial}{\partial t} \rho_d(x,t) = - \frac{\partial}{\partial x} \{ \rho_d(x,t)v_d(x,t) \}. \tag{2}
   \]

Define the density error \( \tilde{\rho}(x,t) = \rho(x,t) - \rho_d(x,t) \) and consider the control law
\[
\begin{align*}
v(x,t) &= v_d(x,t) + v_f(x,t) \tag{3} \\
v_f(x,t) &= - \xi(x,t) \frac{\partial}{\partial x} \{ \rho_d(x,t)\tilde{\rho}(x,t) \} \tag{4}
\end{align*}
\]
where \( \xi(x,t) \geq 0 \).

The speed control laws in Eqs (3) - (4) was originally introduced by Li et al. in 1997 [20] for stabilizing traffic flow in Automated Highway Systems (AHS). The dynamics for the density error, obtained after substituting the control law in (3) and (4) into (1) and using (2), are
\[
\frac{\partial}{\partial t} \rho(x,t) = - \frac{\partial}{\partial x} \{ \rho(x,t)v_d(x,t) \} - \frac{\partial}{\partial x} \{ \rho(x,t)v_f(x,t) \}. \tag{5}
\]
For \( u : [0,L] \to \mathbb{R} \) a real valued function on \([0,L]\), denote the \( L_2 \) norm by \( ||u||_2^2 = \int_0^L u^2 dx \). The following theorem states that with (3) and (4) as the speed control, the desired traffic condition is stable in the \( L_2 \) sense.

**Theorem 1.** [20] Consider the single lane freeway model in (1). Suppose that the inlet flow rate is \( \phi(0,t) = \rho_d(0,t)v_d(0) \), then, under assumption 1, the control law in (3) and (4) with \( \xi(x,t) \geq 0 \) and \( \xi(0,t) = \xi(L,t) = 0 \), is such that the density error \( \tilde{\rho}(x,t) = 0 \forall x \in [0,L] \) is \( L_2 \) stable in time.

**Proof.** Consider the following Lyapunov functional:
\[
W(t) = \frac{1}{2} \int_0^L \tilde{\rho}(x,t)^2 v_d(x,t) dx. \tag{6}
\]
Differentiating (6) with respect to time and using (5),
\[
\dot{W}(t) = \int_0^L \tilde{\rho}(x,t)\dot{\tilde{\rho}}(x,t)v_d(x,t) dx = - \int_0^L \tilde{\rho}(x,t)v_d(x,t) \frac{\partial}{\partial x} \{ \tilde{\rho}(x,t)v_d(x,t) \} dx
+ \tilde{\rho}(x,t)v_d(x,t) \frac{\partial}{\partial x} \{ \rho(x,t)v_f(x,t) \} dx. \tag{7}
\]
The first term in (7) is an exact differential:

\[
\frac{1}{2} \frac{\partial}{\partial x} \left\{ \bar{\rho}(x,t)v_d(x,t) \right\}^2 = \bar{\rho}(x,t)v_d(x,t) \frac{\partial}{\partial x} \left\{ \bar{\rho}(x,t)v_d(x,t) \right\}
\]

Using the Leibniz rule in the second term of (7) and substituting \( v_f(x,t) \), this term becomes

\[
- \int_0^L \bar{\rho}(x,t)v_d(x,t) \frac{\partial}{\partial x} \{ \rho(x,t)v_f(x,t) \} \, dx = - \frac{1}{2} \xi(x,t)\rho(x,t) \frac{\partial}{\partial x} \{ \bar{\rho}(x,t)v_d(x,t) \}^2 \bigg|_0^L
\]

\[
- \int_0^L \xi(x,t)\rho(x,t) \left\{ \frac{\partial}{\partial x} \{ \bar{\rho}(x,t)v_d(x,t) \} \right\}^2 \, dx.
\]

Substituting (8) and (9) into (7) yields

\[
\dot{W}(t) = - \frac{1}{2} \left[ \bar{\rho}(x,t)v_d(x,t) \right]^2 \bigg|_0^L - \frac{1}{2} \xi(x,t)\rho(x,t) \frac{\partial}{\partial x} \{ \bar{\rho}(x,t)v_d(x,t) \}^2 \bigg|_0^L
\]

\[
- \int_0^L \xi(x,t)\rho(x,t) \left\{ \frac{\partial}{\partial x} \{ \bar{\rho}(x,t)v_d(x,t) \} \right\}^2 \, dx.
\]

By the theorem’s assumptions, the boundary terms in (10) can be cancel out: \( \xi(0,t) = \xi(L,t) = 0 \) and \( \phi(0,t) = v_d(0)\rho_d(0,t) \), \( \xi(0,t) = 0 \) implies \( v(0,t) = v_d(0) \), and therefore \( \rho(0,t) = \rho_d(0,t) \). Hence,

\[
\dot{W}(t) \leq - \int_0^L \xi(x,t)\rho(x,t) \left\{ \frac{\partial}{\partial x} \{ \bar{\rho}(x,t)v_d(x,t) \} \right\}^2 \, dx \leq 0,
\]

since the density \( \rho(x,t) \geq 0 \). Then \( W(t) \leq W(0) \). Defining \( v_d = \inf_{(x,t) \in \mathcal{H}} v_d(x,t) \), and \( v_d = \sup_{(x,t) \in \mathcal{H}} v_d(x,t) \),

\[
v_d ||\bar{\rho}(\cdot,t)||_2^2 \leq W(t) \leq W(0) \leq v_d ||\bar{\rho}(\cdot,0)||_2^2.
\]

Thus, for all \( t \geq 0 \), \( ||\bar{\rho}(\cdot,t)||_2 \leq \alpha ||\bar{\rho}(\cdot,0)||_2 \) for \( \alpha = \sqrt{v_d/v_d} \), and therefore \( L_2 \) stability follows.

Consider the simplified case when both \( v_d \) and \( \rho_d \) are constant, the control becomes

\[
v(x,t) = v_d - \xi(x,t)v_d \frac{\partial}{\partial x} \rho(x,t).
\]

If the downstream density is higher than upstream, \( \frac{\partial}{\partial x} \rho(x,t) > 0 \), and the control law (12) decreases the speed, which prevents a pile-up downstream. Thus, the control law can be interpreted as a density homogenizing law.

If a freeway segment is divided into \( N \) sections for \( i = 0, \cdots, N \), let \( x = i\Delta x \), \( t = k\Delta t \) and \( \Delta x = x_{i+1} - x_i \), the discretization of (12) is

\[
v(i\Delta x,k\Delta t) = v_d - \xi(i\Delta x,k\Delta t)v_d \frac{\rho((i+1)\Delta x,k\Delta t) - \rho(i\Delta x,k\Delta t)}{\Delta x}
\]
Omitting $\Delta x$ and $\Delta t$ and using simplified notation $y(i\Delta x, k\Delta t) := y_i(k)$, (13) can be written as

$$v_i(k) = v_d - \xi_i(k)v_d \frac{\rho_{i+1}(k) - \rho_i(k)}{\Delta x}$$  \hspace{1cm} (14)

If we set $v_d = v_i(k-1)$, (14) becomes an integral type controller

$$\tilde{v}_i(k) = v_i(k-1) - L_i(k)(\rho_{i+1}(k) - \rho_i(k))$$  \hspace{1cm} (15)

where $\tilde{v}_i(k)$ is the calculated VSA of section $i$ at time step $k$, $v_i(k-1)$ is the applied speed command of section $i$ at time step $k-1$, and $L_i(k) = \xi_i(k)v_i(k-1)/\Delta x$ is the control gain. The speed command of section $i$, $v_i$, is able to respond to its downstream density changes. In practice, setting upper bound and lower bound on the speed commands of section $i$ is necessary, and then $v_i(k)$ must satisfy the following constraint

$$V_{\text{min},i} \leq v_i(k) \leq V_{\text{max},i}$$  \hspace{1cm} (16)

where $V_{\text{max},i}$ is the maximum speed limit allowed in section $i$, which is usually set to be the default speed limit, and $V_{\text{min},i}$ is the lowest speed limit we can apply. However, $\tilde{v}_i(k)$ calculated by (15) may cause unsafe changes of speed limits, two constraints (17) and (18) are applied to the advisory speed such that speed command has a smooth change: Speed difference between two consecutive time steps on the same location $i$ cannot be too large,

$$|v_i(k) - v_i(k-1)| \leq C_i$$  \hspace{1cm} (17)

where $C_i \geq 0$ is a positive constant represents the largest change of speed commands allowed between two consecutive time steps in section $i$. $C_i = 5 \sim 20 \text{ km/h}$ is a suggested value. Speed difference between two consecutive VSA locations during the same time interval $k$ cannot be too large,

$$|v_i(k) - v_{i+1}(k)| \leq D_i$$  \hspace{1cm} (18)

where $D_i \geq 0$ is a positive constant represents the largest change of speed commands allowed during the same time interval $k$ between section $i$ and $i+1$. $D_i = 5 \sim 20 \text{ km/h}$ is a suggested value.

If the average vehicle length is known, the density can be estimated by occupancy measurements [21] and (15) can be written as

$$\tilde{v}_i(k) = v_i(k-1) - G_i(k)(\bar{\omega}_{i+1}(k) - \bar{\omega}_i(k))$$  \hspace{1cm} (19)

where $\bar{\omega}_i(k)$ is the occupancy of section $i$ at time step $k$ and $G_i(k)$ is the control gain.

In practice, the shockwave propagation speed on freeway needs to be considered when developing the VSA system. The shockwave speed was constant about 13 mph (or 5.8 m/s) as analyzed in the following reference [22] based on NGSIM data. Since the VSA algorithm is based on the traffic detection of downstream, the occupancy or density increase indicates the congestion happens downstream. The VSA algorithm looking ahead at least 2 ~ 3 sections downstream, and the control update time interval is 30 seconds during which the shockwave could propagate about 175 meters, the VSA upstream should be able to respond to it by reducing the feeding flow (or reducing the advisory speed). Therefore, the shockwave was under detection. However, there could be a time delay depending on sensor (loop detector) density; the higher density in traffic detector, the less time delay.
Heuristic Bottleneck Flow Maximization Strategy

In the previous section, a mainline traffic flow stabilization controller was synthesized using Lyapunov’s direct method. The main goal of advisory speed is bottleneck flow maximization. From the controller structure, the advisory speed of section $i$ is determined by the occupancy $o_i(k)$ at section $i$ and its immediately downstream occupancy $o_{i+1}(k)$. It is possible to propose different types of advisory speed strategy based on the adjacent occupancy measurement of section $i$.

If the advisory speed of section $i$ is determined by the next $n$ downstream occupancy measurements of section $i$, it can be calculated as

$$\bar{v}_i(k) = \frac{\alpha_i}{\omega_i(k)}, \quad (20)$$

$$\omega_i(k) = p_{i0}o_i(k) + p_{i1}o_{i+1}(k) + \cdots + p_{in}o_{i+n}(k), 0 \leq n \leq N \quad (21)$$

$$p_{i0} + p_{i1} + \cdots + p_{in} = 1 \quad (22)$$

where $\alpha_i$ is a parameter and $\omega_i$ is the weighted occupancy by parameters $p_{ij}, j = 0, \ldots, n$. The parameter $p_{ij}$ can be determined by

$$p_{ij}(k) = \frac{o_j(k)}{\sum_{k=0}^{n} o_k(k)}, j = 0, \ldots, n. \quad (23)$$

Similarly, if the advisory speed of section $i$ can be determined by the next $n$ downstream speed measurement of section $i, v_i^m$, it can be calculated as

$$\bar{v}_i(k) = \beta_i V_i^m(k), \quad (24)$$

$$V_i^m(k) = p_{i0}v_i^m(k) + p_{i1}v_{i+1}^m(k) + \cdots + p_{in}v_{i+n}^m(k), 0 \leq n \leq N \quad (25)$$

$$p_{i0} + p_{i1} + \cdots + p_{in} = 1 \quad (26)$$

where $\beta_i$ is a parameter and $V_i^m$ is the weighted speed by parameters $p_{ij}, j = 0, \ldots, n$.

FIELD IMPLEMENTATION

Hardware Architecture

Seven Variable Message Signs (VMS) with modified firmware were distributed along a 10.8-mile stretch of California State Route 78 near San Diego, which is shown in Figure 3. The firmware and back-end were modified by the manufacturer (TrafficLogix Corp.) to accommodate the faster update rate needed for timely traffic data acquisition and sign control. The TrafficLogix Safepace 650 Variable Message Sign was used in this project for several reasons:

1. Capability of changing the speed advisory remotely.
2. Integrated radar for sensing traffic speed.
4. Speed display update rate of 30 seconds.
5. Solar powered charging system that allowed for continuous operation.

In its standard configuration, suitable for normal traffic operations, the Safepace 650 has an update interval of 5 minutes. Simulation studies performed at PATH indicated that traffic patterns can...
change much faster than 5 minutes, so the engineering staff at TrafficLogix was asked to modify the firmware on the signs and the back-end server to allow for 30 second intervals. They also provided an applications programming interface that allowed software control by the user. When this was done, the signs were successfully deployed.

**Software Architectures**

Software was constructed as a sequence of processes executed by a parent script. The child processes communicated with each other via a publish/subscribe database, temporary data files, and php scripts. This software structure was largely dictated by two different sources of data (a data feed from Caltrans containing occupancy, flow, and speed over the loops embedded in the highway, and radar data from the signs transmitted from the TrafficLogix data server located in New York) and one control channel (Variable Speed Advisories that were output from the control algorithm and sent to the web server in New York for transmission to the VSA signs).

Variable speed advisories were calculated using an algorithm that applied the most recent data from the two data sources, namely radar speed from the VSA signs and loop data from the Caltrans data feed. The occupancy measurement based VSA rules in Eqs. (19)-(23) and its constraints in Eqs. (16)-(18) was implemented in this field test. Since the update rate of the two data streams was 30 seconds, the data was read and analyzed every 30 seconds. Upon calculation of the variable speed advisories, the VSAs were sent to the TrafficLogix application server for display on the VSA signs. The software architecture is shown in Figure 4. VDS data from loop detectors (bottom data stream) was collected by Caltrans into an XML file and sent to PATH. Radar statistics from the VSA signs (upper data stream) were received from TrafficLogix’ web server and forwarded to PATH. Variable Speed Advisories are calculated in the PATH server and sent to the VSA signs via the TrafficLogix server. The data collected from the field, as well as the VSAs, were sent to the VSA web page for display.

**RESULTS AND DISCUSSION**

**Flow Study**

Since traffic flow fluctuates day to day, this study averages the flow on weekdays during the field test to compare the change in flow patterns under VSA control. For the no-control period, no VSA signs were placed on the freeway shoulder. In the field test period, VSA signs were placed and activated during morning peak hours (from 6:00 AM to 9:00 AM) and evening peak hours (from 2:00 PM to 7:00 PM). The VSA field test were implemented from April 9 to May 4, 2018. Recurrent morning congestion happened at San Marcos Blvd. (the location of VSA 4 near bottleneck 1) and at Nordahl Rd. (the location of VSA 7 near bottleneck 2). Figure 5 (a) and (b) show 5 minutes aggregated flow from all mainline loop detectors near VSA during morning and evening peak hours, respectively. These figures present no VSA control (average weekday flow from May 7 to May 11, 2018) and VSA control (average weekday flow from April 9 to May 4, 2018) cases, respectively. Except for the flow near San Marcos Blvd. (VSA 4), these plots indicate that the flow patterns are similar in the no control and VSA control cases, which indicates that traffic demand was stable and comparable in the no control and VSA control cases. As shown in Figure 5 (a), the average flow of morning peak hours near San Marcos Blvd. (VSA 4) increased from 4100 vph to 4500 vph after the VSA deployment and the average flow near Nordahl Rd. (VSA 7) also increased slightly. As shown in Figure 5 (b), the average flow of evening peak hour near San Marcos Blvd. (VSA 4) increased from 2700 vph to 3200 vph. This observation indicates that the traffic flow near
FIGURE 3  TrafficLogix Safepace 650 Variable Message Sign

FIGURE 4  Software architecture of the variable speed advisory system
San Marcos Blvd. (the midstream bottleneck 1) was improved.

**Speed Study**

When vehicles pass a congestion bottleneck, the deceleration and acceleration cause a capacity drop. Ideally, if drivers follow the advisory speed posted by VSA, the upstream discharge flow can be reduced by lowering the driving speed limit, and then gradually raising speed limits after vehicles pass downstream bottlenecks. In this way, VSA reduces the occurrence of congestion, stop-and-go conditions, shock waves, and capacity drop. Figure 7 (a) and (b) present the 5 minutes aggregated speed profile at each VSA location during morning and evening peak hours, respectively. These figures present no VSA control (average weekday speed from May 7 to May 11, 2018) and VSA control (average weekday speed from April 9 to May 4, 2018) cases, respectively. The morning mainline speed profile in Figure 7 (a) shows that downstream speeds at the VSA 5, VSA 6, and VSA 7 locations under VSA control were higher than those under no control scenario. For the upstream mainline speeds at the VSA 2, VSA 3 and VSA 4 locations, although the speeds were lower than those under no control scenario, the upstream speeds were maintained around 55 mph from 7:30 AM to 9:00 AM, which is desirable since the upstream speed slowed down and kept a stable speed to delay the downstream congestion onset. Therefore, the downstream bottleneck (bottleneck 2) the downstream bottleneck speed were increased by VSA control and it also prevented drastic speed drops in the most downstream during the morning peak hours. The evening mainline speed profile in Figure 7 (b) shows that speed in all VSA locations under VSA control was only slightly higher than those under no control scenario. However, the speed variations at the VSA 4, VSA 5, VSA 6 locations from 3:00 PM to 6:00 PM under VSA control were lower than those no control scenario, which indicates that advisory speeds can smooth speed transitions.

Figure 8 (a) and (b) present the 30 second speed data and advisory speed at each VSA location on April 26, 2018 during morning and evening peaks, respectively. The morning peak hours from 7:00 AM to 9:00 AM in Figure 8 (a) show that the advisory speed at the VSA 7 location became lower than the measured speed when the most downstream congestion onset at 6:30 AM and those upstream VSA also recommended deceleration from 6:30 AM to 8:00 AM. The speeds during the evening peak in Figure 8 (b) shows that the advisory speed was generally lower than the measured speed when congestion onset at the VSA 4, VSA 5, VSA 6, and VSA 7 locations from 3:00 PM to 5:30 PM and then the advisory speed was gradually raising after 5:30 PM (the congestion dissipates). The comparison in Figure 8 shows that the advisory speed is reasonable and achievable, which encourage drivers to follow the VSA and therefore improves freeway mobility, rather than confuse them and reduce traffic performance.

**Compliance per VSA speed**

Figure 6 shows a box plot of the speed compliance at each of the advisory speeds from April 23, 2018 to April 27, 2018. The driver compliance $s_i(k)$ of section $i$ at time step $k$ is defined as

$$s_i(k) = \bar{v}_i(k) - v_{m_i}^i(k)$$

(27)

where $\bar{v}_i(k)$ is the VSA of section $i$ and $v_{m_i}^i(k)$ is measured speed of section $i$. The median compliance slightly less than zero means that vehicles are traveling at speeds lower than the advisory speed. At times when the VSA displays a speed above 50 mph (65, 60, 55, and 50 mph), the compliance level is between 10 mph and $-10$ mph and it is acceptable. The relationship between the displayed advisory speed and the compliance level is a subject that should be analyzed further.
FIGURE 5 Comparison of flow between no control and VSA control: (a) during morning peak (b) during evening peak
FIGURE 6   Compliance (advisory speed minus measured speed) in 30 second data from 4/23/2018 to 4/27/2018: (a) during morning peak (b) during evening peak
FIGURE 7 Comparison of speed between no control and VSA control: (a) during morning peak (b) during evening peak
FIGURE 8  Comparison between speed profiles and advisory speed (30 second data) in April 26, 2018: (a) during morning peak (b) during evening peak
Freeway Performance Study

Variable speed advisory (VSA) was introduced mainly for alleviating freeway congestion and improving safety by homogenizing vehicle speeds. In order to study the influence of VSA control, three main freeway performance indices: VMT, VHT, and Q (freeway efficiency) [23] were considered in this research using data obtained from PeMS [24].

VMT is the sum of distance (in miles) traveled by each vehicle on the given section of freeway over a given time period. Consider a freeway partitioned into \( N \) segments each with length \( L_i \) for the \( i \)-th segment where each segment contains at least one loop detector. VMT is computed by

\[
VMT = \sum_{i=1}^{N} VMT_i,
\]

where \( VMT_i(k) = \tilde{f}_i(k)L_i \) and \( \tilde{f}_i(k) \) is flow measurement at segment \( i \).

VHT is the sum of all trip times (in hours) spent by each vehicle on the given section of freeway over a given time period. VHT is computed by

\[
VHT = \sum_{i=1}^{N} VHT_i,
\]

where \( VHT_i(k) = \frac{VMT_i(k)}{v_i(k)} \) and \( v_i(k) \) is the speed at the \( i \)-th segment.

Freeway efficiency (mean speed) is expressed in miles per hour (mph) and is defined as

\[
Q = \frac{VMT}{VHT}.
\]

Hourly PeMS data for the segment of test site SR-78E from postmile 6.316 to postmile 15.593 was used to compute VMT, VHT, and Q in this study. The VSA test duration in this study was the morning peak hours and afternoon peak hours on weekdays from April 9, 2018 to May 4, 2018, which constituted four weeks of VSA test in total. The morning VSA activation time was from 6:00 AM to 9:00 AM. The evening VSA activation time was from 2:00 PM to 7:00 PM. Two weeks of weekday data (without VSA control): from March 12, 2018 to March 16, 2018 and from May 7, 2018 to May 11, 2018 were selected as baselines for freeway performance comparison. The improvement of an index \( x \) is computed by

\[
\Delta x = \frac{x_{\text{with VSA}} - x_{\text{without VSA}}}{x_{\text{without VSA}}}.
\]

Since the traffic behavior during weekday is similar with each other, we aggregated the data as hourly averages for multiple days and the main freeway performances are still representative. Table 2 shows the average of VMT, VHT, and Q along the test site during the morning and evening field test periods. The morning average VMT is 50957.70 Veh-Miles and the evening average VMT is 47261.71 Veh-Miles. The morning average VHT is 979.07 Veh-Hours and the evening average VHT is 1208.45 Veh-Hours. The morning average Q is 53.22 mph and the evening average Q is 44.65 mph.

In order to study the field test result, the data without VSA activation before and after the VSA field test listed in Table 3 is selected as baselines for evaluation. The comparison of freeway
TABLE 2 Summary of both AM and PM hourly performance during VSA testing: (a) VMT (b) VHT (c) Q

(a)

<table>
<thead>
<tr>
<th>Test week, VMT (Veh-Miles)</th>
<th>6-7 AM</th>
<th>7-8 AM</th>
<th>8-9 AM</th>
<th>2-3 PM</th>
<th>3-4 PM</th>
<th>4-5 PM</th>
<th>5-6 PM</th>
<th>6-7 PM</th>
</tr>
</thead>
<tbody>
<tr>
<td>4/9/2018 - 4/13/2018</td>
<td>54 429.26</td>
<td>50 702.52</td>
<td>46 996.44</td>
<td>48 852.64</td>
<td>50 468.84</td>
<td>51 000</td>
<td>47 226.16</td>
<td>40 287.66</td>
</tr>
<tr>
<td>4/16/2018 - 4/20/2018</td>
<td>55 351.58</td>
<td>50 822.68</td>
<td>47 635.83</td>
<td>50 646.44</td>
<td>50 315.38</td>
<td>50 742.84</td>
<td>45 592.64</td>
<td>37 976.38</td>
</tr>
<tr>
<td>4/23/2018 - 4/27/2018</td>
<td>55 419.54</td>
<td>51 389.82</td>
<td>46 979.72</td>
<td>48 593.16</td>
<td>47 882.56</td>
<td>50 223.76</td>
<td>46 286.16</td>
<td>37 519.84</td>
</tr>
<tr>
<td>4/30/2018 - 5/4/2018</td>
<td>54 871.28</td>
<td>51 273.84</td>
<td>46 002.02</td>
<td>52 655.9</td>
<td>52 344.86</td>
<td>52 429.5</td>
<td>47 111.34</td>
<td>37 258.7</td>
</tr>
<tr>
<td>Average VMT</td>
<td>55 017.91</td>
<td>51 047.21</td>
<td>46 807.98</td>
<td>50 187.03</td>
<td>50 252.91</td>
<td>51 098.88</td>
<td>46 854.07</td>
<td>38 215.64</td>
</tr>
</tbody>
</table>

(b)

<table>
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<tr>
<th>Test week, VHT (Veh-Hours)</th>
<th>6-7 AM</th>
<th>7-8 AM</th>
<th>8-9 AM</th>
<th>2-3 PM</th>
<th>3-4 PM</th>
<th>4-5 PM</th>
<th>5-6 PM</th>
<th>6-7 PM</th>
</tr>
</thead>
<tbody>
<tr>
<td>4/9/2018 - 4/13/2018</td>
<td>1129.22</td>
<td>966.26</td>
<td>806.22</td>
<td>1710.02</td>
<td>1687.46</td>
<td>1554.5</td>
<td>915.9</td>
<td>626.96</td>
</tr>
<tr>
<td>4/16/2018 - 4/20/2018</td>
<td>1137.18</td>
<td>1004</td>
<td>816.7</td>
<td>1554.98</td>
<td>1630.1</td>
<td>1434.7</td>
<td>819.48</td>
<td>575.58</td>
</tr>
<tr>
<td>4/23/2018 - 4/27/2018</td>
<td>1096.34</td>
<td>1031.12</td>
<td>776.12</td>
<td>1482.34</td>
<td>1712.56</td>
<td>1538.96</td>
<td>877.26</td>
<td>569.8</td>
</tr>
<tr>
<td>4/30/2018 - 5/4/2018</td>
<td>1152.66</td>
<td>1041.02</td>
<td>792.06</td>
<td>1482.22</td>
<td>1417.74</td>
<td>1219.1</td>
<td>799.04</td>
<td>560.38</td>
</tr>
<tr>
<td>Average VHT</td>
<td>1128.85</td>
<td>1010.6</td>
<td>797.77</td>
<td>1557.39</td>
<td>1436.815</td>
<td>1436.815</td>
<td>825.92</td>
<td>583.18</td>
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</tbody>
</table>

(c)

<table>
<thead>
<tr>
<th>Test week, Q (mph)</th>
<th>6-7 AM</th>
<th>7-8 AM</th>
<th>8-9 AM</th>
<th>2-3 PM</th>
<th>3-4 PM</th>
<th>4-5 PM</th>
<th>5-6 PM</th>
<th>6-7 PM</th>
</tr>
</thead>
<tbody>
<tr>
<td>4/9/2018 - 4/13/2018</td>
<td>48.71</td>
<td>53.21</td>
<td>58.45</td>
<td>29.44</td>
<td>30.79</td>
<td>33.62</td>
<td>52.29</td>
<td>64.28</td>
</tr>
<tr>
<td>4/16/2018 - 4/20/2018</td>
<td>49.76</td>
<td>51.58</td>
<td>58.44</td>
<td>33.52</td>
<td>31.46</td>
<td>35.86</td>
<td>55.81</td>
<td>65.73</td>
</tr>
<tr>
<td>4/23/2018 - 4/27/2018</td>
<td>51.13</td>
<td>51.63</td>
<td>60.15</td>
<td>32.82</td>
<td>29.67</td>
<td>34.07</td>
<td>53.69</td>
<td>65.84</td>
</tr>
<tr>
<td>4/30/2018 - 5/4/2018</td>
<td>47.73</td>
<td>49.68</td>
<td>58.22</td>
<td>36.38</td>
<td>38.38</td>
<td>43.79</td>
<td>59.08</td>
<td>66.58</td>
</tr>
<tr>
<td>Average Q</td>
<td>49.33</td>
<td>51.52</td>
<td>58.81</td>
<td>33.04</td>
<td>32.57</td>
<td>36.83</td>
<td>55.21</td>
<td>65.60</td>
</tr>
</tbody>
</table>

TABLE 3 Summary of both AM and PM hourly VHT, VMT and Q during no VSA testing: (a) March 12, 2018 - March 16, 2018 (before field test) (b) May 7, 2018 - May 11, 2018 (after field test)

(a)

<table>
<thead>
<tr>
<th>Test week, VMT (Veh-Miles)</th>
<th>6-7 AM</th>
<th>7-8 AM</th>
<th>8-9 AM</th>
<th>2-3 PM</th>
<th>3-4 PM</th>
<th>4-5 PM</th>
<th>5-6 PM</th>
<th>6-7 PM</th>
</tr>
</thead>
<tbody>
<tr>
<td>Baseline 3/12/2018 - 3/16/2018</td>
<td>51 713.88</td>
<td>48 239.8</td>
<td>46 757.66</td>
<td>52 521.58</td>
<td>50 946.14</td>
<td>51 431.44</td>
<td>46 941.72</td>
<td>37 900.66</td>
</tr>
<tr>
<td>Baseline 3/12/2018 - 3/16/2018</td>
<td>1340.3</td>
<td>1267.5</td>
<td>869.24</td>
<td>1470.82</td>
<td>1507.84</td>
<td>1453.76</td>
<td>868.18</td>
<td>642.64</td>
</tr>
<tr>
<td>Baseline 3/12/2018 - 3/16/2018</td>
<td>39.8</td>
<td>42.3</td>
<td>54.77</td>
<td>36.29</td>
<td>33.86</td>
<td>35.47</td>
<td>54.23</td>
<td>60.86</td>
</tr>
<tr>
<td>Baseline 3/12/2018 - 3/16/2018</td>
<td>49.33</td>
<td>51.52</td>
<td>58.81</td>
<td>33.04</td>
<td>32.57</td>
<td>36.83</td>
<td>55.21</td>
<td>65.60</td>
</tr>
</tbody>
</table>

(b)

<table>
<thead>
<tr>
<th>Test week, VMT (Veh-Miles)</th>
<th>6-7 AM</th>
<th>7-8 AM</th>
<th>8-9 AM</th>
<th>2-3 PM</th>
<th>3-4 PM</th>
<th>4-5 PM</th>
<th>5-6 PM</th>
<th>6-7 PM</th>
</tr>
</thead>
<tbody>
<tr>
<td>Baseline 5/7/2018 - 5/11/2018</td>
<td>54 502.2</td>
<td>51 302.9</td>
<td>45 197.48</td>
<td>50 323.46</td>
<td>48 961.12</td>
<td>50 683.56</td>
<td>46 360.28</td>
<td>37 512.9</td>
</tr>
<tr>
<td>Baseline 5/7/2018 - 5/11/2018</td>
<td>1134.48</td>
<td>1015.3</td>
<td>741.84</td>
<td>1520.7</td>
<td>1639.06</td>
<td>1534.4</td>
<td>946.18</td>
<td>582.56</td>
</tr>
<tr>
<td>Baseline 5/7/2018 - 5/11/2018</td>
<td>48.50</td>
<td>51.02</td>
<td>60.97</td>
<td>33.77</td>
<td>30.33</td>
<td>33.32</td>
<td>50.07</td>
<td>64.76</td>
</tr>
</tbody>
</table>
performance between the average of four VSA field test week and baseline data is demonstrated in Table 4 (using data from March 12, 2018 to March 16, 2018 as a baseline and data from May 7, 2018 to May 11, 2018 as a baseline), where \textbf{bold text} indicates improvement of the networks performance and \textit{italic text} means deterioration of performance. In Table 4 (a), the morning average ΔVMT is 4.10% and the evening average ΔVMT is -1.28%; the morning average ΔVHT is -14.75% and the evening average ΔVHT is 0.12%; the morning average ΔQ is 17.71% and the evening average ΔQ is 0.14%. In Table 4 (b), the morning average ΔVMT is 1.33% and the evening average ΔVMT is 1.09%; the morning average ΔVHT is 2.19% and the evening average ΔVHT is -3.07%; the morning average ΔQ is -0.27% and the evening average ΔQ is 5.47%. By averaging the improvement of performance index in Table 4 (a) and (b), the overall performance evaluation results are summarized as follows:

Morning variable speed advisory performance:

• VMT increased by 2.72% on average.
• VHT decreased by 6.28% on average.
• Q increased by 8.71% on average.

Since VMT and Q increased and VHT decreased, we conclude that VSA improved the traffic during morning peak hours (from 6:00 AM to 9:00 AM).

Evening variable speed advisory performance:

• VMT decreased by 0.096% on average.
• VHT decreased by 1.47% on average.
• Q increased by 2.80% on average.

Since the change in both VMT, VHT and Q was marginal, we conclude that VSA did not improve traffic during the evening peak hours (from 2:00 PM to 7:00 PM).

TABLE 4 Summary of both AM and PM hourly performance comparison: (a) March 12, 2018 - March 16, 2018 (b) comparing to May 7, 2018 - May 11, 2018

(a)

<table>
<thead>
<tr>
<th></th>
<th>6-7 AM</th>
<th>7-8 AM</th>
<th>8-9 AM</th>
<th>2-3 PM</th>
<th>3-4 PM</th>
<th>4-5 PM</th>
<th>5-6 PM</th>
<th>6-7 PM</th>
</tr>
</thead>
<tbody>
<tr>
<td>Δ VMT</td>
<td>6.38%</td>
<td>5.81%</td>
<td>0.10%</td>
<td>−4.44%</td>
<td>−1.36%</td>
<td>−0.64%</td>
<td>−0.82%</td>
<td>0.83%</td>
</tr>
<tr>
<td>Δ VHT</td>
<td>−15.77%</td>
<td>−20.26%</td>
<td>−8.22%</td>
<td>5.88%</td>
<td>6.90%</td>
<td>−1.16%</td>
<td>−1.75%</td>
<td>−9.25%</td>
</tr>
<tr>
<td>Δ Q</td>
<td>23.95%</td>
<td>21.80%</td>
<td>7.38%</td>
<td>−8.95%</td>
<td>−3.79%</td>
<td>3.84%</td>
<td>1.82%</td>
<td>7.80%</td>
</tr>
</tbody>
</table>

(b)

<table>
<thead>
<tr>
<th></th>
<th>6-7 AM</th>
<th>7-8 AM</th>
<th>8-9 AM</th>
<th>2-3 PM</th>
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<th>4-5 PM</th>
<th>5-6 PM</th>
<th>6-7 PM</th>
</tr>
</thead>
<tbody>
<tr>
<td>Δ VMT</td>
<td>0.94%</td>
<td>−0.49%</td>
<td>3.56%</td>
<td>−0.27%</td>
<td>2.63%</td>
<td>0.81%</td>
<td>0.41%</td>
<td>1.87%</td>
</tr>
<tr>
<td>Δ VHT</td>
<td>−0.49%</td>
<td>−0.46%</td>
<td>7.54%</td>
<td>2.41%</td>
<td>−1.65%</td>
<td>−6.35%</td>
<td>−9.85%</td>
<td>0.10%</td>
</tr>
<tr>
<td>Δ Q</td>
<td>1.71%</td>
<td>0.98%</td>
<td>−3.53%</td>
<td>−2.16%</td>
<td>7.40%</td>
<td>10.54%</td>
<td>10.28%</td>
<td>1.30%</td>
</tr>
</tbody>
</table>
CONCLUSIONS
In this study, the variable speed advisory freeway traffic management based on occupancy and speed measurement was developed and implemented at the stretch of SR-78E between Vista Village Drive and the interchange with US-15, which is one of the most congestion interchanges in San Diego. At the test site, seven VSA signs, which were updated every 30 seconds in real-time, were deployed at the shoulder of the road for advisory speed display. The VSA system was activated during the morning peak periods of 6:00 AM - 9:00 AM and evening peak periods of 2:00 PM - 7:00 PM on weekdays. After the control system was implemented, a progressive test procedure was conducted for the field tests. First, a dry-run (VSA was calculated and saved but not displayed) was conducted for the first 2 weeks to verify that the overall system was running well. Then, after 4 weeks of tests and data collection, PeMS hourly VHT and VMT data were used for performance evaluation. It was noted that PeMS data is completely independent from the data in PATH computer obtained directly from the 2070 controllers in the field. By using PeMS data, the project team intended to obtain objective performance results to the greatest extent possible. To address demand fluctuation, the freeway efficiency (VMT to VHT ratio) was used as the performance parameter, which could be understood as the average speed. We believed that this ratio could reasonably accommodate traffic demand fluctuation. The data used for VSA OFF was collected in the week (3/12-3/16, 2018) right before VSA signs were mounted, and the week (5/7-5/11, 2018) right after VSA signs were removed. The aggregated data over four weeks when VSA was ON compared to the data with VSA OFF for average speed (freeway efficiency) increased by 8.71% for morning peak hours, which indicates an improvement in congested traffic. For evening peak hours, average speed (freeway efficiency) increased by 2.8%, which is marginal. This suggests that the algorithm is effective for congested traffic caused by high demand. The simplicity of the advisory speed strategy developed in this study and the flexibility of the hardware/software system used for the field test indicate the possibility of adopting the proposed variable advisory speed system as one of the regular tools for freeway management.

Future research includes safety impact brought by VSA deployment. Safety evaluation of VSA was not within the scope of this study. The impact of VSA on reducing primary and secondary incidents can be evaluated to obtain safety benefits. In addition, the scope of this research limited to recurrent bottlenecks. Developing VSA algorithm that can handle situations causing non-recurrent bottlenecks, such as incidents, accidents, and inclement weather conditions, are also a major concern for freeway operation.

ACKNOWLEDGMENT
This work is supported by the State of California Transportation Agency, Department of Transportation under award number: 65A0587 and project title: Combined Variable Speed Limit and Coordinated Ramp Metering for Freeway Traffic Control-Phase III: Field Experiment of Variable Speed Advisory (VSA). The contents of this paper reflect the views of the authors, who are responsible for the facts and accuracy of the data presented herein. The contents do not necessarily reflect the official views or policies of the State of California.

AUTHOR CONTRIBUTION STATEMENT
The authors confirm contribution to the paper as follows: study conception and design: Cheng-Ju Wu, Xiao-Yun Lu, John Spring and Roberto Horowitz; data collection: Cheng-Ju Wu and John Spring; analysis and interpretation of results: Cheng-Ju Wu and Xiao-Yun Lu; draft manuscript
preparation: Cheng-Ju Wu. All authors reviewed the results and approved the final version of the manuscript.

REFERENCES


