# Variable Speed Limits: Safety and Operational Impacts of a Candidate Control Strategy for Freeway Applications

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***Abstract*—Variable-speed limit sign (VSLS) systems enable transportation managers to dynamically change the posted speed limit in response to prevailing traffic and/or weather conditions. Although VSLSs have been implemented in a limited number of jurisdictions throughout the world, there is currently very limited documentation that describes quantitative safety and operational impacts. Furthermore, the impacts reported are primarily from systems in Europe and may not be directly transferable to other jurisdictions such as North America. This paper presents the results of an evaluation of a candidate VSLS system for an urban freeway in Toronto, ON, Canada. The evaluation was conducted using a microscopic simulation model combined with a categorical crash potential model for estimating safety impacts.**

***Index Terms*—Congestion management, microsimulation, safety, traffic control, variable speed limits.**

## I. Introduction

VARIABLE-SPEED limit sign (VSLS) systems consist of dynamic message signs (DMSs) that are deployed along a roadway and connected via a communication system to a traffic management center. The VSLSs are used to display a regulatory or advisory speed limit. Unlike typical static speed signs, the VSLS system enables transportation system managers to dynamically post a speed limit that is appropriate for current traffic, weather, or other conditions. VSLSs are thought to improve safety and reduce driving stress while improving traffic flow and travel times [1]. Worldwide, VSLS systems have been deployed in a limited number of jurisdictions, including the U.K., the Netherlands, the U.S., Germany, Australia, and New Zealand. To date, the only well-documented impact analyses for congestion management systems have been for the M25 Controlled Motorway in the U.K. [2] and for the A2 Motorway in the Netherlands [3]. The reported impacts for these systems are fairly consistent, citing reduced average speeds, reduced speed variation, improved lane utilization, and a calmer driving experience—all of which may contribute to measured reductions in crash frequency and severity. Although it is useful to have empirical impacts reported from these field deployments, these studies do not cater for the following tasks:

1) developing an understanding of the interaction between traffic flow changes and VSLS activity;
2) establishing relationships between VSLS activity and resulting safety improvements;
3) providing insights regarding the impacts of varying the parameters within the VSLS control strategies;
4) reporting benefits in terms of definitive quantitative evidence.

It is suspected that these limitations are, in part, due to the risk, expense, and effort that are involved in deploying live systems. In addition, before and after studies are difficult to control and can be hindered by confounding effects [4] such as temporal changes in crash risks, changes in traffic demands [3], and effects of enforcement policies during speed limit changes [5], [6].

Variable-speed limit systems have been modeled through microscopic simulation studies to address these limitations. Lee *et al.* [6], [12] and Abdel-Aty *et al.* [7] used microscopic simulations to test the impacts of VSLS responses to real-time measures of crash potential (CP). Lee *et al.* found that, for highly congested locations, VSLSs provided a reduction in CP of 25% but increased travel time. In contrast, Abdel-Aty *et al.* found that VSLSs provided a large reduction in CP during low loading (higher speed) conditions but had little impact for peak period conditions. Abdel-Aty *et al.* also found a consistent decrease in travel time during low loading conditions using VSLSs, although the relative change in travel time from the non-VSLS case to the VSLS case was very small. The discrepancy in these results causes the overall expected benefit of a VSLS application to remain unclear. Additionally, from a practical point of view, transportation authorities may be averse to adopting such VSLS strategies based on theoretical measures of CP.

The purpose of the current study was to quantify the safety and traffic flow impacts of candidate VSLS control strategies for an urban North American freeway section. This study differed from those described in the literature in that the VSLS control strategies evaluated were designed for the following reasons: 1) for practical implementation, i.e., by directly providing a dynamic response to loop detector data on 20-s intervals and by adhering to typical design standards with respect

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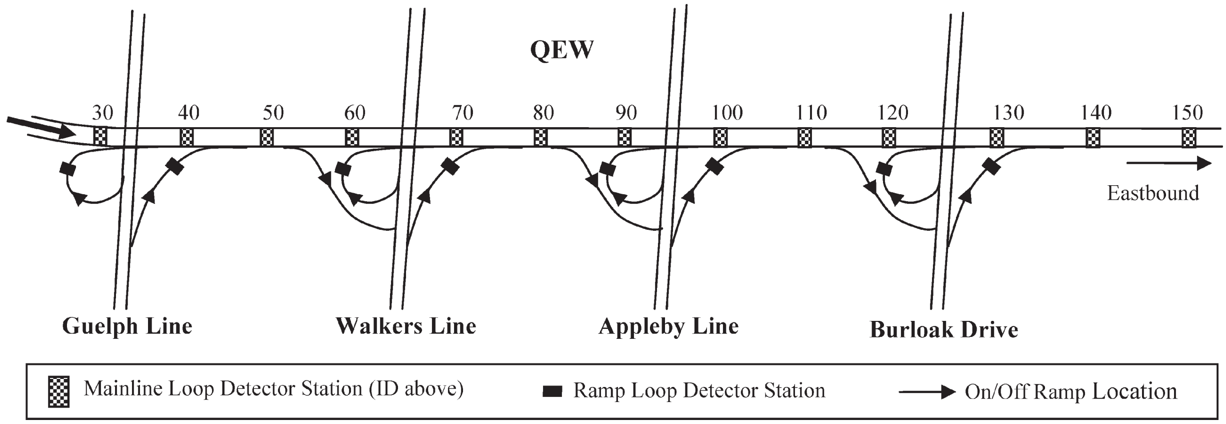


Fig. 1. Layout of the QEW study section.

to maximum speed limit reductions, etc., and 2) to be similar in structure to those already in use in the U.K. [2] and the Netherlands [3].

Three traffic scenarios were modeled, each under a different condition of recurrent congestion. An initial VSLS control strategy was designed, and its impacts on safety and system delay were evaluated using a microscopic simulation model (PARAMICS) combined with a categorical CP model. A sensitivity analysis was then conducted to investigate the effects of modifying parameters within the VSLS control algorithm. Descriptions of each aspect of the study and the results of the system evaluations are presented in the following sections.

## II. Description of the Study Network

An 8-km section of the eastbound Queen Elizabeth Way (QEW) located near Toronto, ON, Canada, was selected as the study network. The QEW services a large volume of commuter traffic in the morning and evening peak periods, resulting in heavy congestion and a high frequency of crashes. The study area features a posted speed limit of 100 km/h, has three mainline lanes, contains four interchanges, and experiences a directional annual average daily traffic of about 70 000 vehicles. The freeway is instrumented with dual-loop-detector stations in each mainline lane, spaced approximately 600 m apart, and single-loop stations on entrance and exit ramps (Fig. 1). Speed, volume, and occupancy are recorded every 20 s for all mainline stations, whereas volume is recorded for all ramp stations.

During the morning peak period (6:00–10:00 A.M.), this freeway section experiences high levels of recurrent congestion. The congestion is mainly caused by a bottleneck created at the most downstream interchange. At this location, a high volume of traffic ($\sim$1000 vehicles/h) entering the already-congested mainline results in reduced freeway speeds, queues, and an upstream-moving shockwave that penetrates much of the section. Freeway speeds through the bottleneck during this period typically range from 30 to 50 km, but at times, traffic is observed to be at a standstill.

A VSLS control strategy was designed to reduce vehicle speeds upstream of this bottleneck to test for the results of the following tasks: 1) providing safer deceleration for vehicles encountering the tail of the queue and 2) increasing the mean bottleneck speed by reducing stop–start conditions.

## III. Simulation Development: Base Model

The microscopic traffic simulator PARAMICS [8] was selected to perform the modeling work. PARAMICS was primarily chosen because it allows the user to implement custom control logic via an application programming interface (API). Through the API, the user-defined VSLS control algorithm overrides the standard code in PARAMICS to dynamically change link-based speed limits.

The modeled segment was coded using actual geometry and traffic volume data. An origin–destination (O–D) matrix was estimated from morning peak-period (6:00–10:00 A.M.) loop detector data averaged over ten nonincident weekdays. The days were chosen from November 2004 and April 2005 under the following conditions: 1) that the day was a weekday but not a Friday; 2) that no incidents were recorded during that day; 3) that the speed profile of the peak period exhibited congested conditions and a prolonged shockwave; and 4) that complete detector data were available for that day (i.e., no large blocks of missing data). A time series of O–D matrices were developed on the basis of the observed traffic volumes. Each matrix was applicable for a 30-min period so that the growth and dissipation of congestion could be adequately modeled.

Dual loop detectors were placed in the modeled network at approximately the same locations as those in the field and were programmed to report 20-s speed, volume, and occupancy data. A "base model" was established upon validation of existing (non-VSLS) conditions, based on temporal speed profiles produced from both observed and simulated data for each detector station. Simulation parameters were adjusted until the speed profiles adequately matched the observed profiles (within confidence limits of $\pm 2\sigma$). The simulation parameter values that produced the best results were 1.2 s for the mean target headway and 1.0 s for the driver's reaction time. The mean target headway was increased from the default value to promote the smooth prolonged shockwave that is evident from observed data. Driver aggressiveness was not changed from the default value, but driver awareness was increased to reflect

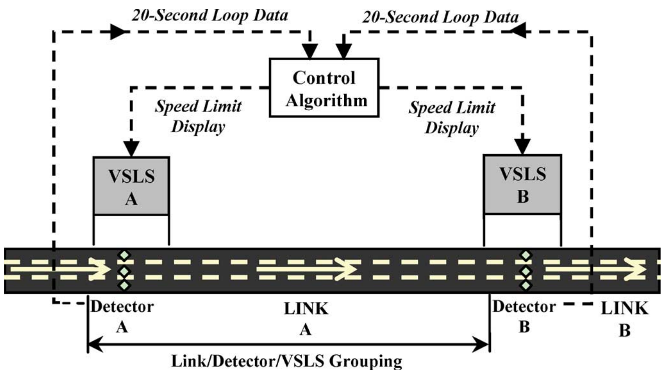


Fig. 2. Basic layout of link–detector–VSLS groupings.

the familiarity of commuters. Calibration parameters found in other PARAMICS calibration research [9], [10] were also tested, but these values produced model results that were not representative of the observed traffic conditions. Note also that behavioral parameters were not modified during active VSLS conditions due to limited documentation on a driver's response to a VSLS.

## IV. VSLS System Integration

The VSLS system infrastructure was represented within PARAMICS by 13 VSLSs, each placed next to a loop detector, spaced approximately 500–600 m apart. Since PARAMICS assigns speed limits by link, the mainline was coded as a series of links that correspond to each detector–VSLS pair. Each link–detector–VSLS set acted as its own entity—the detector gathered information about traffic conditions, the appropriate "condition-based" speed was assigned to the link, and the VSLS displayed the current speed limit for the benefit of the user/observer. Fig. 2 illustrates this layout. Based on traffic data received every 20 s from "loop detector A," a control algorithm determined the appropriate speed limit to be displayed at "VSLS A." This displayed speed limit governed until the end of "link A," at which point, a new displayed speed limit at "VSLS B" was determined by traffic data from "loop detector B."

The original VSLS control algorithm employed in this study was introduced as an initial concept for a candidate control algorithm that could be implemented in practice. The algorithm was designed to select speed limits based on measures of average station volume, speed, and occupancy. This design incorporates the state of the practice of existing first-generation VSLS systems. For example, the M25 Controlled Motorways in the U.K. operate VSLSs triggered by volume thresholds (e.g., when loop detector station volumes reach 1650 vehicles per hour per lane (vphpl), the speed limits reduce to 60 mi/h from a default of 70 mi/h). On the A2 motorway in the Netherlands, VSLSs reduce to either 90 or 70 km/h, based on 1-min average measures of loop detector station volume and speed.

The parameter values for this control algorithm were selected on the basis of engineering principles. A volume threshold of 1600 vphpl was selected as it represents a freeway level of service C (as specified in the Highway Capacity Manual 2000); an occupancy threshold of 15% was selected as traffic data plots

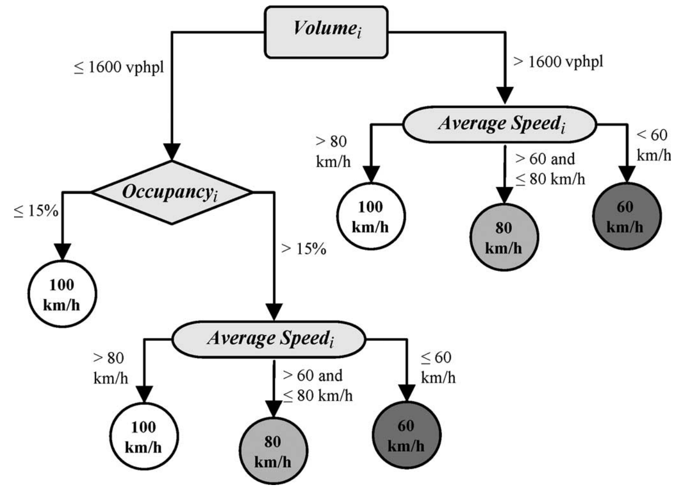


Fig. 3. Decision path for determining the new posted speed of the trigger $\mathrm{VSLS}_i$.

revealed that this threshold approximates the critical occupancy at which traffic flow breakdown occurs for this section of the road; and the response patterns of VSLSs were selected to reduce traffic speeds well in advance of a congested location (and be consistent with current static speed limit signing guidelines in terms of maximum speed reductions per sign, etc.).

The algorithm was designed to determine an appropriate speed limit using tree logic based on 20-s speed, volume, and occupancy loop detector data (Fig. 3). Based on the selected parameter values, each combination of volume, occupancy, and speed data fell within a particular traffic condition. Note that since this algorithm was only an initial concept, the algorithm structure and parameter values only represented starting points for evaluation and not an optimal strategy.

Fig. 3 shows the four conditions that resulted in a VSLS speed limit reduction, which were termed *trigger conditions*. Upon detection of a trigger condition at detector $i$, the speed limit displayed at $\mathrm{VSLS}_i$ (the *trigger VSLS*) was decremented to the appropriate speed. Only speed limits of 100 km/h, 80 km/h (i.e., 20-km/h decrement), and 60 km/h (i.e., 40-km/h decrement) were tested in this study.

Once the speed limit was determined for the trigger VSLS, the speeds displayed for its upstream speed signs were determined based on a *response zone*, a *transition zone*, and a *temporal countdown*, which are described as follows.

1) *Response zone:* This included the two nearest upstream speed signs. These displayed the same speed limit as the trigger VSLS.
2) *Transition zone:* If the posted speed limit was reduced from 100 to 60 km/h at the response zone, then the third upstream sign (one upstream of the response zone) displayed 80 km/h to provide a gradual transition for drivers who are required to slow from 100 km/h.
3) *Temporal countdown:* If the posted speed limit was reduced from 100 to 60 km/h, then the VSLS signs displayed 80 km/h for 10 s prior to displaying 60 km/h.

After a reduction in the displayed speed limit had occurred, the speed limit could not be incremented until three consecutive 20-s intervals of traffic flow improvement were detected. Traffic

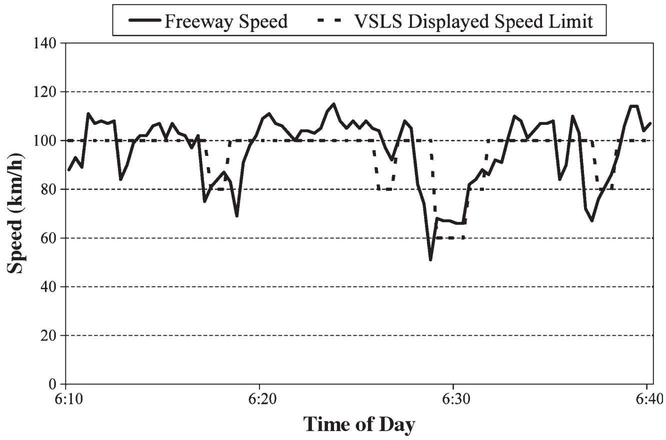


Fig. 4. VSLS response to freeway traffic conditions.

flow improvement was indicated by detector occupancies less than 15%, the threshold at which flow breakdown was found to occur for this study section. VSLSs were not required to be incremented in the same sequence as they were decremented and could be incremented individually; however, a VSLS could not display a speed that is more than 20 km/h higher than the displayed speed of its next downstream VSLS.

Fig. 4 shows the dynamic response of a VSLS's displayed speed limit to changing traffic conditions (measured at a detector station).

## V. Categorical CP Model

### A. Model Overview

The crash model employed in this study was introduced in 2003 by Lee *et al.* [11]. The model uses a calibrated log-linear function to determine a relative CP based on exposure, control factors, and categorized levels of time-varying traffic conditions. These traffic conditions, termed crash precursors, are related to the turbulence experienced within a traffic stream. More turbulent levels of crash precursors correspond to a higher likelihood of an impending crash situation. The three crash precursors can be calculated from loop detector data and are described as follows.

1) *The coefficient of variation of speed (CVS)* measures the average speed variation within each lane at a particular location.
2) *The spatial variation of speed (Q)* measures the difference between the average speeds at upstream and downstream locations.
3) *The covariance of volume (COVV)* measures the difference in the average covariance of volume (between adjacent lanes) upstream and downstream from a location (surrogate measure for lane-changing activity).

The model was calibrated through log-linear regression to find a disparity between precursors that exist prior to a crash and those that exist during noncrash conditions. Traffic data for crash conditions were compiled from loop detector data preceding 299 crashes on the QEW between 1998 and 2003. Noncrash conditions were compiled from loop data of 12 nonincident days.

### B. Application of the CP Model

The advantage of this crash model is that it can provide a dynamic relative measure of crash risks with changing traffic conditions by being updated as often as new traffic data become available (i.e., 20-s loop detector intervals). Furthermore, the model can capture the spatial or temporal changes in crash risks that may exist between adjacent road sections based on the introduction of a traffic control/management system such as the VSLS.

In this study, the safety impact of VSLSs was measured by calculating the relative change in CP from the non-VSLS case to the VSLS case. Ten simulation runs were performed for the non-VSLS case and ten for the VSLS case. The same set of ten seed values was used for the VSLS and non-VSLS runs. For each simulation run, at each station, a value of CP was calculated from crash precursor values in 20-s intervals. Then, average values of station CP (SCP) were obtained for each run over the simulation period by

$$\mathrm{SCP}_i = \frac{1}{n}\sum_{j=1}^{n}\mathrm{CP}_{ij} \qquad (1)$$

where

$\mathrm{SCP}_i$ SCP for station $i$ (in crashes per million vehicles-kilometer);

$\mathrm{CP}_{ij}$ CP for station $i$ at a 20-s interval $j$ (in crashes per million vehicles-kilometer);

$n$ number of 20-s intervals in the period (720 for a 4-h period).

Since the non-VSLS and VSLS cases differed only by the introduction of the VSLS system, the SCP values could be paired by a simulation run. A paired two-tailed Student's $t$-test was used to test for the significance of the change in SCP (or VSLS impact) at the 95% level of confidence. If the difference was found to be significant, the relative safety benefit (RSB) was calculated using (2). A positive RSB represented a decrease in CP. We define

$$\mathrm{RSB}_i = \left(\frac{\mathrm{ASCP}_i(\text{non-VSLS}) - \mathrm{ASCP}_i(\text{VSLS})}{\mathrm{ASCP}_i(\text{non-VSLS})}\right) \times 100 \qquad (2)$$

where

$\mathrm{RSB}_i$ RSB at station $i$ (in percent);

$\mathrm{ASCP}_i$ average SCP (over $x$ simulation runs) at station $i$ (in crashes per million vehicles-kilometer).

## VI. VSLS Impact Results

The VSLS impact analyses were performed on three traffic scenarios of varying levels of congestion—heavy, moderate, and light. These scenarios were termed *peak*, *near-peak*, and *off-peak*, respectively. The validated simulation model from the observed morning peak period conditions represented the peak traffic scenario. The near- and off-peak scenarios were represented by approximately 90% and 75%, respectively, of the peak volumes. These scenarios were not calibrated for existing conditions, as their purpose was to investigate and understand the varying reactions of the VSLS system to

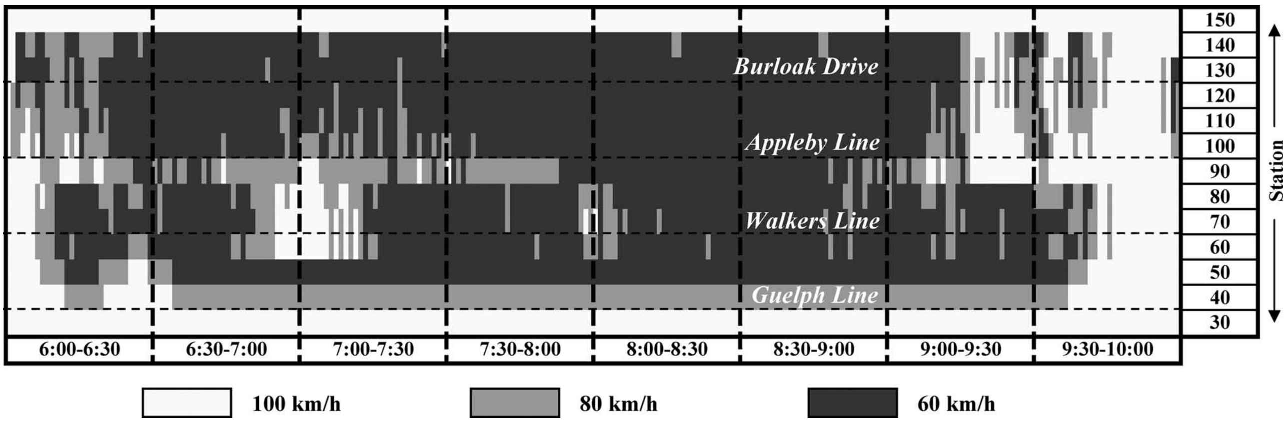


Fig. 5. Mapping of VSLS displayed speeds for the near-peak scenario.

TABLE I
VSLS COVERAGE

| Displayed Speed | % Time Speed Limit is Displayed | | |
|---|---|---|---|
| | *Peak* | *Near-Peak* | *Off-Peak* |
| 100 km/h | 5 | 15 | 92 |
| 80 km/h | 7 | 17 | 6 |
| 60 km/h | 88 | 68 | 2 |

TABLE II
VSLS SAFETY IMPACT SUMMARY

| Station ID | Relative Safety Benefit (RSB) of VSLS | | |
|---|---|---|---|
| | *Peak* | *Near-Peak* | *Off-Peak* |
| 50 | 44% | 27% | -8% |
| 60 | 45% | 43% | *N.S.* |
| 70 | 40% | 25% | *N.S.* |
| 80 | 43% | *N.S.* | *N.S.* |
| 90 | 37% | *N.S.* | *N.S.* |
| 100 | 26% | *N.S.* | -49% |
| 110 | 36% | 30% | -24% |
| 120 | 29% | 25% | 14% |
| 130 | 57% | 38% | 13% |
| 140 | 44% | 46% | *N.S.* |
| **Network RSB** | **+39%** | **+27%** | **-5%** |

*N.S.* = Results not found to be significant.

changes in congestion, rather than to replicate real traffic conditions. The VSLS impact was quantified in terms of the relative changes in safety (CP) and vehicle travel times before and after the implementation of the VSLS control strategy. The results of the VSLS activity, safety impacts, and travel time impacts of the three traffic scenarios under the original VSLS algorithm are presented in the following sections.

### *A. VSLS Activity*

During the peak scenario, the degree of congestion was severe enough that all VSLSs displayed 60 km/h for the majority of the period, whereas the off-peak scenario experienced very little VSLS activity. The near-peak scenario provided the most dynamic VSLS response. Although 60 km/h was the most frequently displayed speed limit, opportunities for speed limit recoveries and fluctuations were more readily available than during the peak scenario. Fig. 5 depicts the speed limits that are implemented by the VSLS for a single simulation run over the 4-h simulated period for the near-peak scenario. Table I shows the average network VSLS coverage for each of the three scenarios in terms of the percent of time that a speed limit was displayed.

### *B. VSLS Safety Impact*

Examination of the safety impact results revealed that the RSBs achieved by the VSLSs varied widely by the amount of congestion experienced within the network. For the peak scenario, a network average RSB of 40% was achieved with the implementation of the VSLS (Table II). Furthermore, all stations but one experienced a significant reduction in CP. Much of the safety benefit from the peak scenario was realized from reduced turbulence within the traffic stream, particularly the reduction in freeway speed variability. This was evident in the changes in the spatial speed differential measured by reductions in crash precursor $Q$ and in the in-lane speed variation measured by reductions in crash precursor CVS.

The near- and off-peak scenarios experienced diminishing safety benefits from the VSLS, as well as fewer stations that achieved significant results. Although the near-peak scenario experienced a positive network RSB of 27%, the results varied widely between simulation runs. Over the ten runs, the individual network RSBs ranged from $-4\%$ to $+47\%$. It was also discovered that for the near-peak scenario, more randomness existed within the simulation, producing varying levels of congestion for each run.

The most positive safety benefits were experienced during periods with high congestion. Further analysis of the data revealed a strong linear relationship $(R^2 = 0.9)$ between the mean network speed over the 4-h period (a surrogate measure of congestion) without the VSLS system active and the safety benefit achieved after VSLS implementation. This relationship indicates a diminishing safety benefit as a VSLS responds to periods of lower congestion (higher mean speeds). This result raises concerns regarding the current control strategy and its ability to provide a desirable response to temporal variations in traffic conditions.

The negative safety benefit (increase in CP) result for the off-peak scenario may provide some explanation for the

TABLE III
VSLS TRAVEL TIME IMPACT SUMMARY

| | Average Network Travel Time (min/vehicle) | | |
|---|---|---|---|
| | *Peak* | *Near-Peak* | *Off-Peak* |
| Non-VLS | 13.2 | 6.1 | 4.0 |
| VSLS | 14.6 | 7.6 | 4.1 |
| **Change** | **1.4** | **1.5** | **0.1** |
| **% Increase** | **11%** | **25%** | **1.3%** |

undesirable VSLS impact during periods of low congestion. The negative result is mainly due to the relatively large negative benefits experienced by stations 100 and 110. During this scenario, relatively few trigger conditions arose, but those that did occur happened between stations 140 and 130. Spatial speed differentials that arise between the resulting response zones and upstream stations 100 and 110 caused an increase in CP. Note, however, that the absolute values of CP for this scenario were much lower than those for the peak and near-peak scenarios, which means that the relative changes represent smaller changes in absolute value.

### C. VSLS Travel Time Impact

The travel time impacts of VSLS implementation were measured by the relative change in the average network travel time per vehicle from the non-VSLS case. For all three scenarios, the implementation of the VSLS resulted in an increase in the average travel time (Table III), which is significant at a 95% level of confidence.

The increase in travel time was largest for the near-peak scenario. The absolute magnitude of the impact (i.e., 1.5 min/veh) was almost the same as for the peak scenario (1.4 min/veh) but more than twice as large (25% versus 11%) when computed as a relative impact.

The off-peak scenario experienced far fewer travel time impacts largely because of the low activity of the VSLS.

These results seem to suggest that the evaluated VSLS control strategy may not respond well under conditions of localized intermittent congestion.

These results were somewhat troubling, as they imply that the use of the evaluated VSLS control algorithm can create sustained congestion for some locations when no sustained congestion would have occurred if the VSLS system had not been implemented. An investigation of the data revealed the cause of these results. Early in the simulation, congestion sporadically occurred in very short periods. In the absence of VSLS control, this congestion cleared very quickly. However, when the VSLS was implemented, the control algorithm responded to the detected congestion and reduced the speed limit. Due to response zone requirements, the reduced speed limit cascaded upstream.

These intermittent periods of localized congestion tended to occur most frequently in the near-peak scenario, causing the relatively large increase in travel time.

### D. Conclusions of Preliminary Analysis

The most desirable outcomes for VSLS impacts were a large decrease in CP associated with a decrease in travel time. Overall, the results of the preliminary analysis provided no clear indication that the implementation of a VSLS system under the original control algorithm would positively impact safety and travel efficiency measures for all traffic scenarios. However, the analyses of the VSLS impacts under this control algorithm did provide evidence that suggests the following.

1) Traffic scenarios that experience higher congestion were more likely to benefit from the VSLS system in terms of higher positive RSBs and fewer negative travel time impacts than traffic scenarios with less congestion. These benefits appeared to occur, at least in part, as a result of the reduction in the frequency and severity of shockwaves in the congested traffic (i.e., damping of the stop-and-go oscillations).
2) The most congested locations, or locations that triggered speed limit decrements, were more likely to experience positive RSBs with less impact to travel time.
3) For less congested conditions, stations upstream from VSLS response zones were more likely to experience negative RSBs.
4) Vehicles that make longer trips were more likely to experience negative travel time impacts under the current VSLS control algorithm than vehicles that make shorter trips.

The most desirable results (both positive safety and positive travel time impacts) were usually observed under moderately congested scenarios during which the VSLS response exhibited frequent speed limit decrements and frequent recoveries. The least desirable results were usually observed under conditions that caused prolonged speed limit reductions and, thus, lower freeway speeds than would have been observed without a VSLS. This suggests that the tested VSLS control algorithm was able to provide large safety benefits with no significant travel time penalty but only for a limited range of traffic conditions. The tested algorithm appears to be insufficiently robust to effectively operate over a wide range of traffic conditions. It was anticipated that modifications to the algorithm could result in a VSLS system that is able to operate over a wide range of traffic conditions and provide more consistent safety and travel time benefits. Several modifications to the parameter values were tested, and the performance impacts were analyzed using the same methodology as was applied for the original algorithm. A description of the modifications and the impacts to performance are provided in Section VII.

## VII. MODIFICATION TO CONTROL ALGORITHM PARAMETERS

The original variable-speed limit control algorithm was developed only as a preliminary design for practical applications. The algorithm parameter values were not optimized but were selected on the basis of engineering judgment, as described in Section IV. Consequently, it was unknown prior to the analysis whether these were the parameter values that would produce the most favorable results. The results of the preliminary analysis revealed that the original algorithm does have the potential to favorably operate during some conditions but produces inconsistent and undesirable results during the near- and off-peak

TABLE IV
MODIFICATIONS OF PARAMETER VALUES FOR SENSITIVITY ANALYSIS

| Case | Parameters for Speed Limit Reduction | | | Parameters for Speed Limit Increase |
|---|---|---|---|---|
| | Occupancy Threshold | Volume Threshold | # of Responding VSLS* | Occupancy Threshold |
| **Original** | 15% | 1600 | 80-60-60-60; 80-80-80 | 15% |
| **Modification 1** | 20% | 1600 | 80-60-60-60; 80-80-80 | 20% |
| **Modification 2** | 20% | 1600 | 80-60-60-60; 80-80-80 | 15% |
| **Modification 3** | 15% | 1800 | 80-60-60-60; 80-80-80 | 15% |
| **Modification 4** | 15% | 1600 | 80-60; 80-80 | 15% |
| **Modification 5** | 20% | 1800 | 80-60; 80-80 | 15% |

TABLE V
VSLS ACTIVITY AS A RESULT OF PARAMETER MODIFICATIONS

| Case | Proportion of Time Speed Limit is Displayed | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| | Peak | | | Near Peak | | | Off Peak | | |
| | 100 km/h | 80 km/h | 60 km/h | 100 km/h | 80 km/h | 60 km/h | 100 km/h | 80 km/h | 60 km/h |
| **Original** | 5% | 7% | 88% | 15% | 17% | 68% | 92% | 6% | 2% |
| **Modification 1** | 4% | 15% | 81% | 17% | 21% | 62% | 95% | 4% | 1% |
| **Modification 2** | 7% | 10% | 83% | 23% | 23% | 54% | 95% | 4% | 1% |
| **Modification 3** | 5% | 9% | 86% | 19% | 18% | 63% | 94% | 5% | 1% |
| **Modification 4** | 15% | 16% | 69% | 45% | 20% | 35% | 95% | 4% | 1% |
| **Modification 5** | 21% | 16% | 63% | 52% | 16% | 32% | 98% | 2% | 0% |

scenarios. It was suspected that changes in the original algorithm could result in improvements to the overall VSLS impact results. Therefore, the last stage of this study was to perform a preliminary sensitivity analysis on modifications to the parameter values within the algorithm. The objective of this analysis was not to identify an optimal algorithm but to identify any patterns in the changes in safety and travel time impacts following different modifications to the parameter values.

The sensitivity analysis investigated the resulting impacts of modifications to the following parameters values:

1) occupancy threshold for triggering a speed limit reduction;
2) occupancy threshold for allowing reduced speeds limits to increase;
3) volume threshold for triggering a speed limit reduction;
4) number of VSLSs included in response to a speed limit reduction.

Five modifications were tested, each varying one or more of the above parameter values to analyze the sensitivity to both individual and combined modifications. The modifications are displayed in Table IV. These modifications were selected to address the issues raised in the preliminary conclusions (Section VI-D), which indicated that the original algorithm might have responded at times or locations where a response was not truly warranted. The following modification objectives were established with the expectation of achieving a more targeted VSLS response:

1) raising the minimum level of congestion to which VSLSs respond, thus reducing the overall degree of the VSLS response and eliminating the VSLS response to brief pockets of light turbulence;
2) reducing the number of upstream VSLSs included in a response, thus limiting the distance affected by the VSLS and reducing the undesired cascading effect that was previously noted.

Cells in Table IV that are shaded indicate the parameter that was modified. For each of the modifications listed in Table IV, ten simulations were performed using the same simulation volumes and random number seed values as the original analysis. The overall results for VSLS activity, safety impacts, and travel time impacts for each modification were compiled in the same manner as the original analysis and are presented in Tables V and VI.

The results of the modification cases vary. *Modification 5* exhibited the most improvement from the results of the original algorithm, followed by *Modification 2*. The primary benefits from these modifications were a reduction in the travel time penalty for each scenario without a significant reduction to the net safety impacts.

Under *Modification 5*, the travel time increase was nearly erased without impacting the net decrease in CP of 39% during the peak scenario. The near-peak scenario also experienced positive results, with a reduction in travel time penalty from 23% to 13% while maintaining a 19% RSB. Furthermore, the negative safety impact for the off-peak scenario was improved from a 5% increase in CP to a 1% increase in CP.

A primary explanation for the improvement in travel time impact for both *Modification 2* and *Modification 5* was

TABLE VI
OVERALL NETWORK SAFETY AND TRAVEL TIME IMPACTS AS A RESULT OF PARAMETER MODIFICATIONS

| Case | Relative Safety Impact | | | Relative Travel Time Impact | | |
|---|---|---|---|---|---|---|
| | Peak | Near-Peak | Off-peak | Peak | Near-Peak | Off-peak |
| **Original** | 39% | 27% | -5% | 11% | 23% | 1% |
| **Modification 1** | 35% | 6% | -4% | 9% | 25% | 1% |
| **Modification 2** | 41% | 20% | -6% | 5% | 15% | 1% |
| **Modification 3** | 41% | 23% | -4% | 4% | 22% | 1% |
| **Modification 4** | 31% | 7% | -4% | 6% | 23% | 1% |
| **Modification 5** | 39% | 19% | -1% | 1% | 13% | 0% |

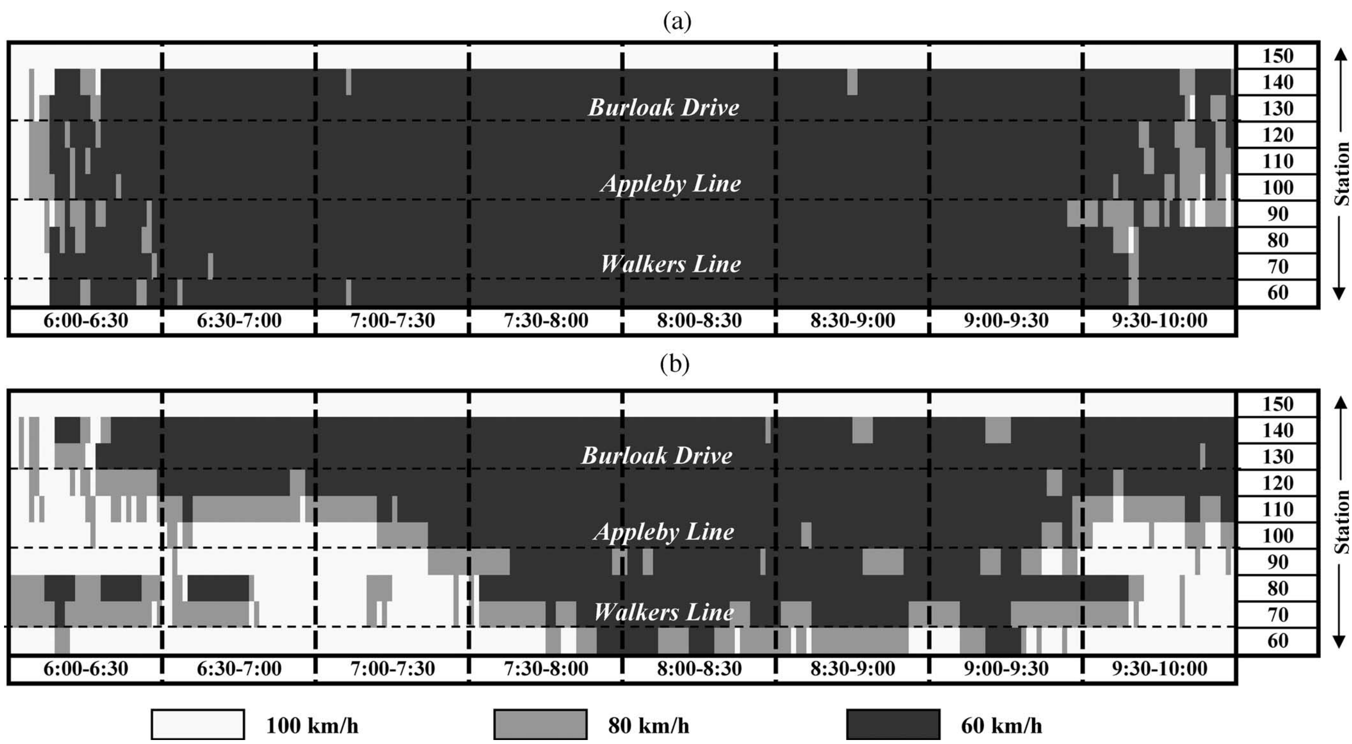


Fig. 6. Mapping of VSLS displayed speeds for the peak scenario. (a) Performance of the original algorithm. (b) Performance of the algorithm under *Modification 5*.

the reduction in the number of VSLS responses during the simulation period. It was evident from the original analysis that the VSLS frequently responded to short-term pockets of congestion and, due to the response zone requirements, speed limit reductions cascaded upstream, and the VSLSs were unable to recover. This resulted in prolonged speed reductions for much of the network, even in the absence of turbulence. Upon the introduction of *Modification 5*, the percent time of the simulation period during which a 60-km/h speed limit was displayed was reduced from 88% to 63% for the peak scenario. For the near-peak scenario, it was reduced from 68% to 32%. Achieving such reductions in VSLS activity, without compromising the safety benefit, indicates that the original control algorithm caused many VSLS responses that were unnecessary. It should also be noted that during the off-peak scenario under *Modification 5*, the VSLS system was mostly inactive—only reductions to 80-km/h speed limits were triggered, and only for 2% of the time of the entire simulation period. These results suggest that this algorithm was successful in achieving a positive response during highly congested conditions and an idle response during uncongested conditions—a desirable observation for a system that is expected to operate full time in an automatic state.

Fig. 6(a) shows the mapping of the VSLS displayed speed limits during peak scenario simulation runs before and after *Modification 5* (with identical seed values). Note that under the original algorithm [Fig. 6(a)], the VSLS responded to congestion early in the period and were unable to recover. In contrast, after *Modification 5* [Fig. 6(b)], the VSLS provided a consistent response to the downstream congestion with less impact to the upstream end of the network.

An examination of the results for the remaining three modifications revealed no clear improvements in performance. The results for *Modification 3* show very little change in any measure from the original case. A data log of the VSLS response triggers showed that volume-related responses were reduced, but occupancy-related responses increased by approximately the same degree. Consequently, the overall VSLS impact remained largely unchanged. The results for *Modification 4* show a modest reduction in travel time impact for the peak scenario but had no positive impact on the travel time for the near-peak scenario. This is somewhat surprising, considering the significant reduction in VSLS activity, and it is unclear as to why the travel time impact was not reduced. Examination of the traffic conditions for the near-peak scenario before and after the modification revealed that the level of congestion in the network remained largely unchanged. It is possible that the limiting factors for traffic throughput were the trigger zones, which responded to the same levels of volume and occupancy in this modification as in the original algorithm.

The only modification that resulted in a clear deterioration in performance was *Modification 1*, which exhibited no improvements in travel time and a reduction in safety benefit. Examination of the data revealed that permitting reduced speed limits to increment upon occupancies of 20% contributed to increased speed limit fluctuations and increased turbulence. It is suspected that this relaxed threshold may have induced premature increases in reduced speed limits. As a result, vehicles increased their speeds only to encounter more congestion downstream—a possible explanation for the increased turbulence. Interestingly, after returning the occupancy threshold for a speed limit increase to 15% in *Modification 2*, the performance results considerably improved.

## VIII. Conclusion

Although a number of studies, both empirical and theoretical, have reported impacts of VSLS control strategies that aim to increase safety and reduce congestion, little has been documented that quantifies the expected benefits of a practical VSLS control strategy in terms of VSLS response activity and upon modifications to the control algorithm parameters. The objectives of this study were to design an evaluation framework for a candidate VSLS control algorithm on a congested North American freeway, to perform an extensive analysis on a proposed algorithm, and to test the sensitivity in performance changes in control algorithm parameter values.

The evaluation framework consisted of a microscopic simulation model combined with a categorical crash model. Relative safety and travel time impacts were quantified for three scenarios of traffic congestion following the implementation of the VSLS system. In addition to the quantification of these benefits, the simulation model reported a significant amount of information useful for tracking and depicting the activity of the VSLS system.

The results of the analysis for the original VSLS control algorithm suggested that the implementation of the VSLS system could provide improvements in safety but that these were obtained at a cost in terms of increased travel times. Furthermore, these impacts were not consistent for all traffic conditions. Safety improvements were achieved for heavily congested (peak period) and moderately congested (near-peak period) traffic conditions, but a new reduction in safety resulted for uncongested conditions (off-peak period). The use of VSLSs increased travel times for all traffic scenarios considered.

Further analyses were performed on modifying the parameters within the VSLS control algorithm, and the resulting impacts were quantified. Although this was only a preliminary analysis, considerable improvements to the original VSLS strategy were identified. It was found that certain modifications were successful in achieving significant additional safety improvements and reductions in the increase of travel times. The ability to preserve high safety benefits while reducing the travel time impacts suggests that the original control algorithm was causing prolonged unnecessary VSLS responses. Unfortunately, a strategy that could provide consistent and positive impacts for both safety and travel time under all degrees of congestion was not identified, but this analysis provided evidence that significant improvements were attainable. It is anticipated that further modifications to the algorithm could result in a VSLS that is able to operate over a wide range of traffic conditions and provide more consistent safety and travel time benefits.

This analysis offered encouraging results and some initial insights into the relationship between the choice of control strategy parameter values and the resulting safety and operational impacts. Furthermore, this study suggests that microscopic simulation offers an effective environment for evaluating candidate VSLS control strategies.

It is necessary to interpret the findings of this study within the context of the assumptions that were made. One of the most important assumption in this study pertain to the driver's behavior with respect to the following: 1) compliance with the posted speed limit and 2) changes in the driving behavior due to the need to read and respond to speed limit signs.

In this study, the driver behavior has been assumed to be the same for the VSLS case as for the non-VSLS case. The extent and type of enforcement is likely to have a significant impact on the driver behavior. The type, size, placement, and spacing of VSLSs may also impact the driver behavior. At the time of this study, no information was available that quantified these changes in the driver behavior, and therefore, these impacts were not considered in this study.

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