Variable Speed Limits: Safety and Operational Impacts of a Candidate Control Strategy for an Urban Freeway

P. Allaby, B. Hellinga, and M. Bullock

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 VSLS have been implemented in a limited number of jurisdictions throughout the world there is currently very limited documentation describing the 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, Canada. The evaluation was conducted using a microscopic simulation model combined with a categorical crash potential model for estimating safety impacts.**

INTRODUCTION

VARIABLE Speed Limit Sign (VSLS) systems consist of dynamic message signs (DMS) deployed along a roadway and connected via a communication system to a traffic management centre. The VSLS 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. VSLS are thought to improve safety and reduce driver stress while improving traffic flow and travel times [1]. Worldwide, VSLS systems have been deployed in a limited number of jurisdictions including the UK, the Netherlands, the USA, Germany, Australia, and New Zealand. Benefits have been reported from empirical studies in terms of safety with reduced collisions [2, 3] and in terms of improved traffic flow perceived by the driver [4]. Although in general, benefits have been recognized, most of the empirical studies to date are limited by one or more of the following:

- Lack of control of important influencing factors such as traffic volumes, degree of enforcement and compliance, etc.
- Empirical benefits reported largely in terms of qualitative evidence.
- Transferability of results to other jurisdictions (ie. Europe to North America).

Also, very few studies have been performed that quantify the expected benefits of implementing comprehensive VSLS control strategies on freeways. In recent studies, Lee et al. [5] and Abdel-Aty et al. [6] used microscopic simulation to test the impacts of VSLS response to real-time traffic safety measures. Lee et al. found that for highly congested locations, VSLS provided a reduction in crash potential of 25%, but increased travel time. In contrast, Abdel-Aty et al. found that VSLS provided a large reduction in crash potential 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 for the low loading conditions using VSLS, although the relative change in travel time from the non-VSLS case to the VSLS case was very small. Considering these results and the limitations from empirical studies, the expected overall benefit of implementing VSLS is still unclear.

The purpose of this study was to quantify the safety and traffic flow impacts of a candidate VSLS control strategy for an urban North American freeway section. Three traffic scenarios were modelled, each under a different condition of recurrent congestion. The effects of the VSLS control strategy on safety and system delay were determined using a microscopic simulation model (PARAMICS) combined with a categorical crash potential model.

I. DESCRIPTION OF STUDY NETWORK

A 10 km section of the eastbound Queen Elizabeth Way (QEW) located near Toronto, Canada was selected as the test 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 segment features a posted speed limit of 100 km/hr, has 3 mainline lanes, contains 4 interchanges, and experiences a directional AADT of about 70 000 vehicles. The section is instrumented with dual loop detector stations in each mainline lane spaced at approximately 600m and single loop stations on entrance and exit ramps (Fig. 1). Every 20 seconds, speed, volume, and occupancy are recorded for all mainline stations, whereas volume is recorded for all ramp stations.

During the morning peak period (6:00 am to 10:00 am) this freeway section experiences high levels of recurrent congestion. This congestion is mainly caused by a

---

P. Allaby is a Transportation Systems Analyst at IBI Group, Toronto, ON, Canada and a MASc candidate at the University of Waterloo, Waterloo ON Canada (e-mail: pallaby@ibigroup.com).

B. Hellinga, PhD, P. Eng, is an Associate Professor in the Dept. of Civil and Environmental Engineering at the University of Waterloo, Waterloo, ON Canada (e-mail: bhellinga@uwaterloo.ca).

M. Bullock, P. Eng, is an Associate Director at IBI Group, Toronto, ON Canada (email: mbullock@ibigroup.com)

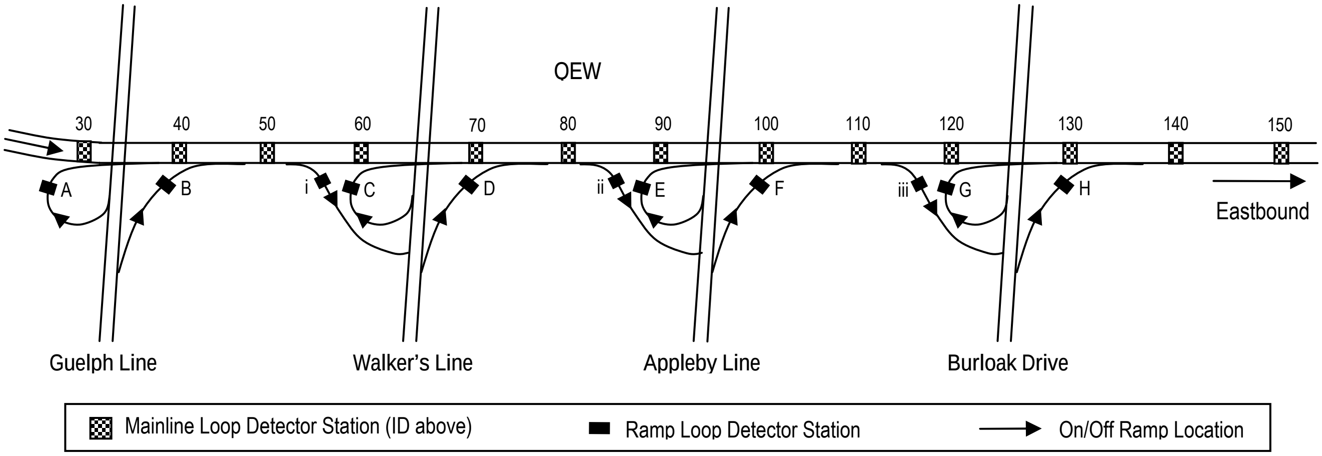

Fig. 1. Layout of QEW Study Section

bottleneck created at the most downstream interchange. At this location, a high volume of traffic (~1000 veh/hr) entering the already congested mainline results in reduced freeway speeds, queues, and a shockwave that travels upstream almost to the Guelph Line interchange. Freeway speeds through the bottleneck during this period typically range from 30 km/h to 50 km/h, 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 a) providing safer deceleration for vehicles encountering the tail of the queue; and b) increasing the mean bottleneck speed by reducing stop-start conditions.

II. SIMULATION DEVELOPMENT: BASE MODEL

The microscopic traffic simulator PARAMICS [7] was selected to perform the modelling work. PARAMICS was chosen primarily 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 modelled segment was coded using actual geometry and traffic volume data. An origin-destination (O-D) matrix was estimated from morning peak-period (6 am to 10 am) loop detector data averaged over 15 non-incident weekdays. Also, temporal variations in volume were examined to estimate the temporal release profile for each O-D pair. Dual loop detectors were placed in the modelled network at approximately the same locations as those in the field and were programmed to report 20-second 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 (within confidence limits of +/- 2σ) matched the observed profiles. The parameter values which produced the best results were 1.2 seconds for mean target headway and 1.0 second for driver reaction time. The mean target headway was increased from the default value to promote the smooth, prolonged shockwave evident from observed data. Driver aggressiveness was not changed from the default value, but driver awareness was increased to reflect the familiarity of commuters. Calibration parameters found in other PARAMICS calibration research [8, 9] were also tested, but these values produced model results that were not representative of the observed traffic conditions.

III. VSLS SYSTEM INTEGRATION

The VSLS system infrastructure was represented within PARAMICS by thirteen variable speed limit signs placed throughout the network. Each VSLS was placed next to a loop detector, spaced at approximately 500m to 600m. Since PARAMICS assigns speed limits by link, the mainline was coded as a series of links corresponding to each detector-VSLS pair. Each link/detector/VSLS set acts as its own entity – the detector gathers information about traffic conditions, the appropriate "condition based" speed is assigned to the link, and the VSLS displays the current speed limit for the benefit of the user/observer. Figure 2 illustrates this layout. Based on traffic data received every 20 seconds from loop detector A, a control algorithm determines the appropriate speed limit to be displayed at

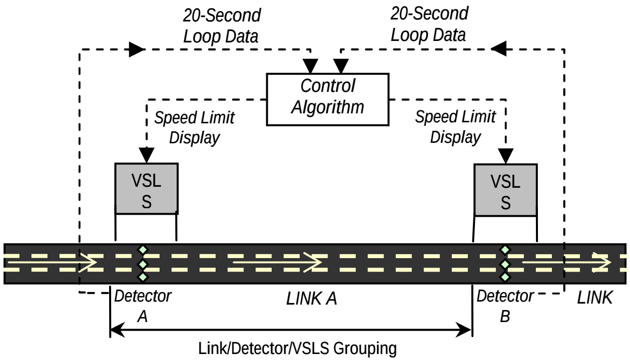

Fig. 2. Layout of Link/Detector/VSLS Groupings

VSLS A. This displayed speed limit governs until the end of Link A, at which point a new displayed speed limit at VSLS B is determined by traffic data from loop detector B.

The VSLS control algorithm employed in this study is an initial concept for a candidate control algorithm that could be implemented in practice. To preserve the potential for practical application, the algorithm was designed to determine an appropriate speed limit using tree logic based on 20-second speed, volume, and occupancy loop detector data (Fig. 3). Based on the selected parameter values, each combination of volume, occupancy, and speed data falls within a particular traffic condition. Note that since this algorithm is only an initial concept, the algorithm structure and parameter values only represent starting points for evaluation and not necessarily an optimal strategy. However, it is suspected that by using the evaluation methods outlined in this study, modifications to this initial algorithm can be tested to explore potential improvements to the strategy.

Figure 3 shows the seven decision tree outcomes – four of which result in a VSLS speed limit reduction. These four were termed *trigger conditions*. Upon detection of a trigger condition at detector *i*, the speed limit displayed at $VSLS_i$ (the *trigger VSLS*) was decremented to the appropriate speed. Only speed decrements of 20 km/h and 40 km/h were tested in this study. Figure 4 shows the dynamic response of a VSLS displayed speed limit to changing traffic conditions.

Once the speed limit was determined for the trigger VSLS, the speeds displayed at upstream speed signs were determined based on a *response zone*, a *transition zone*, and a *temporal countdown* as described below:

Response Zone – Includes the two nearest upstream speed signs. These signs display the same speed limit as the trigger VSLS.

Transition Zone – If VSLS are decremented by 40 km/h, the 3rd upstream sign (1 upstream of the response zone) displays 80 km/h to provide a gradual transition for drivers required to slow from 100 km/h.

Temporal Countdown – If VSLS are decremented by 40 km/h, signs display 80 km/h for 10 seconds prior to displaying 60 km/h.

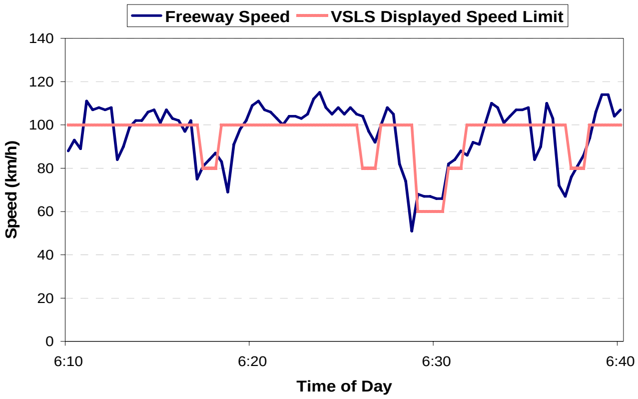

Fig. 4. VSLS response to freeway traffic conditions

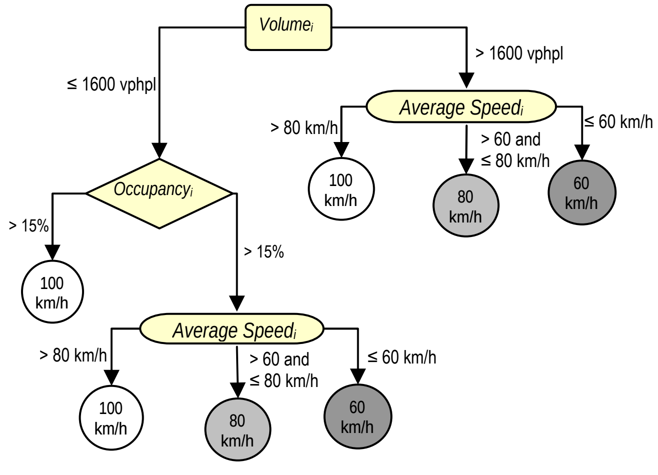

Fig. 3. Decision Path for Determining New Posted Speed of Trigger $VSLS_i$

After a reduction in the displayed speed limit had occurred, the speed limit could not be incremented until three consecutive 20-second intervals of traffic flow improvement were detected. Traffic flow improvement was indicated by detector occupancies less than 15%, the threshold at which flow breakdown appears to occur for the study section. VSLS 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 more than 20 km/h higher than the displayed speed of its next downstream VSLS.

IV. CATEGORICAL CRASH POTENTIAL MODEL

A. *Model Overview*

The crash model structure employed in this study was first introduced by Lee et al. in 2003 [10]. The model uses a calibrated log-linear function to determine a relative crash potential 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 below.

Coefficient of Variation of Speed (CVS) - Measures the average speed variation within each lane at a particular location.

Spatial Variation of Speed (Q) - Measures the difference between the average speeds at upstream and downstream locations.

Covariance of Volume (COVV) – Measures the difference in average covariance of volume (between adjacent lanes) upstream and downstream of 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 non-crash conditions. Traffic data for crash conditions were compiled from loop detector data preceding 299 crashes on the QEW between 1998 and 2003. Non-crash conditions were compiled from loop data from 12 non-incident days.

B. *Application of Crash Potential Model*

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

In this study, the safety impact of VSLS was measured by calculating the relative change in crash potential 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 crash potential (CP) was calculated from crash precursor values on 20-second intervals. Then, average values of station crash potential (SCP) were obtained for each run over the simulation period (1).

$$SCP_i = \frac{1}{n}\sum_{j=1}^{n} CP_{ij} \tag{1}$$

where,

SCP_i : Station Crash Potential for Station *i* (crashes/million veh-km);
CP_{ij} : Crash Potential for Station *i* at 20-second interval *j* (crashes/million veh-km);
n : Number of 20-second intervals in period (720 for 4-hour period)

Since the non-VSLS and VSLS cases differed only by the introduction of the VSLS system, the SCP values could be paired by simulation run. A paired 2-tailed student 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 relative safety benefit represented a decrease in crash potential.

$$RSBi = \left(\frac{ASCP_i\,(non-VSLS) - ASCP_i\,(VSLS)}{ASCP_i\,(non-VSLS)}\right)\times 100 \tag{2}$$

where,

RSB_i : Relative Safety Benefit at Station *i* (%);
$ASCP_i$: Average Station Crash Potential (average of SCP over *10* simulation runs) at Station *i* (crashes/million veh-km).

V. 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 peak traffic scenario was represented by the validated simulation model from the observed peak period conditions. The near-peak 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 reaction of the VSLS system, rather than to replicate real traffic conditions. VSLS impact was quantified in terms of the relative changes in safety (crash potential) and vehicle travel times before and after the implementation of the VSLS control strategy.

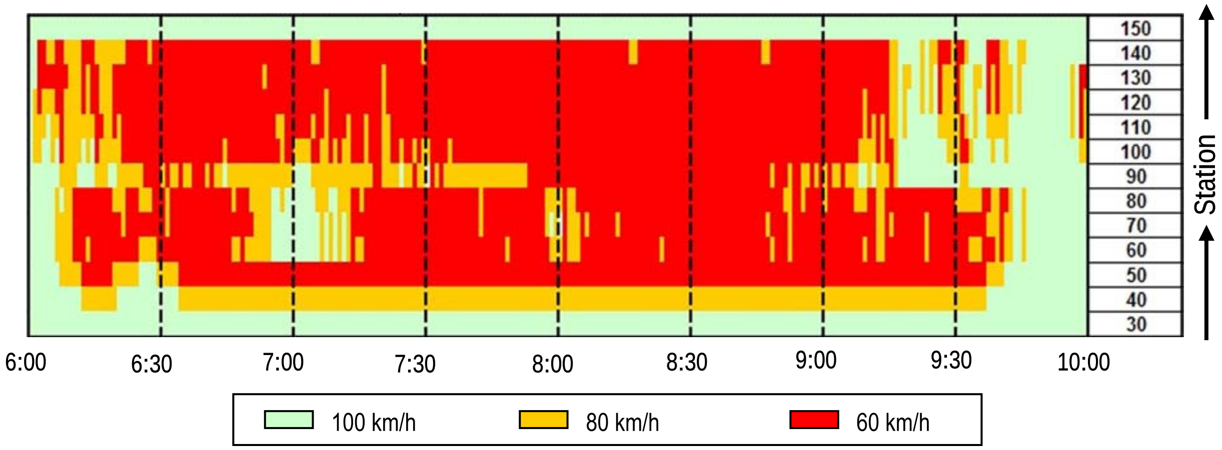

Fig. 5 Mapping of VSLS Displayed Speeds for the Near-Peak scenario

A. *VSLS Activity*

During the peak scenario, the degree of congestion was severe enough that all VSLS 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. Figure 5 provides the mapping of VSLS displays for a single simulation run over the 4-hour 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 time a speed limit was displayed.

TABLE I
VSLS COVERAGE

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

B. *VSLS Safety Impact*

Examination of the safety impact results revealed that the relative safety benefit achieved by VSLS varied widely by the amount of congestion experienced within the network. For the peak scenario, a network average relative safety benefit of 40% was achieved with the implementation of VSLS (Table II). Also, all stations but one experienced a significant reduction in crash potential. 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 to spatial speed differential measured by reductions in precursor Q, and to in-lane speed variation measured by reductions in precursor CVS.

TABLE II
VSLS SAFETY IMPACT SUMMARY

	Relative Safety Benefit (RSB) of VSLS		
Station ID	*Peak*	*Near-Peak*	*Off-Peak*
40	*N.S.*	-75%	*N.S.*
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.*
Average RSB	**+40%**	**+20%**	**-11%**

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

The near-peak and off-peak scenarios experienced diminishing safety benefits from the VSLS as well as fewer stations which achieved significant results. Although the near-peak scenario experienced an overall positive RSB of 20%, the results varied largely between simulation runs. Over the 10 runs, the individual network RSBs ranged from -27% to +39%. 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-hour period (a surrogate measure of congestion) without VSLS and the safety benefit achieved after VSLS implementation. This relationship indicates a diminishing safety benefit as VSLS responds to periods of lower congestion (higher mean speeds). This result raises concern regarding the current control strategy and its ability to provide desirable response to temporal variations in traffic conditions.

The negative safety benefit (increase in crash potential) result for the off-peak scenario may provide some explanation for the 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, occurred between Stations 140 and 130. Spatial speed differentials arising between the resulting response zones and the upstream stations, 100 and 110, caused an increase in crash potential. Note, however, that the absolute values of crash potential for this scenario were much lower than those for the peak and near-peak scenarios, meaning the relative changes represent smaller changes in absolute value.

VI. TRAVEL TIME IMPACT

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

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%**

For the peak period the travel time data was further examined to include O-D trip specific travel times. It was found that the network average was biased towards the heavy volume of vehicles originating at the upstream end of the mainline. Vehicles traveling through the entire study network incurred significant delay while vehicles making shorter trips experienced very little travel time impact. This suggests that most of the travel time increases occur on the upstream portion of the network when the speed limit is reduced even though no evidence of congestion exists.

These results are somewhat troubling as they imply that the use of VSLS (at least with the specified control algorithm) can create sustained congestion for some locations when no sustained congestion would have occurred if VSLS had not been implemented. An investigation of the data revealed the cause of these results. Early in the simulation, congestion occurs sporadically in very short time periods. In the absence of VSLS control, this congestion clears very quickly. However, when VSLS is implemented, the control algorithm responds to the detected congestion and reduces the speed limit. Due to response zone requirements, the reduced speed limit cascades upstream.

The travel time impact results for the near-peak scenario show a similar relationship with congestion as the safety impact results. For more congested simulation runs of this scenario, travel time impacts were minimal, whereas for less congested simulation runs, the travel impacts were substantially higher. However, note that the off-peak scenario experienced very little travel time impact, indicating that below a certain level of congestion, travel time may no longer be largely impacted.

VII. CONCLUSION

The most desirable outcomes for a VSLS impact would be a large decrease in crash potential associated with a decrease in travel time. Overall the results provide no clear indication that the implementation of a VSLS system under the current control algorithm would positively impact safety and travel efficiency measures for all traffic scenarios. However, the analyses of the VSLS impacts under this particular control algorithm do provide evidence which suggest the following:

1) Traffic scenarios experiencing higher congestion are more likely to benefit from a VSLS system in terms of higher positive relative safety benefits and less negative travel time impact than traffic scenarios with less congestion. These benefits appear 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 which trigger speed limit decrements are more likely to experience positive relative safety benefits with less impact to travel time.
3) For less congested conditions, stations upstream of VSLS response zones are more likely to experience negative relative safety benefits.
4) Vehicles making longer trips are more likely to experience negative travel time impacts under the current VSLS control algorithm than vehicles making shorter trips.

The most desirable results (both positive safety and positive travel time impacts) were usually observed for moderately congested scenarios during which the VSLS response exhibited frequent speed limit decrements and recoveries. The least desirable results were usually observed under conditions which caused prolonged speed limit reductions and thus lower freeway speeds than would have been observed without 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 operate effectively over a wide range of traffic conditions. However, it is anticipated that modifications to the algorithm can 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.

It is recommended that alternative VSLS control algorithms be explored and it is suggested that the evaluation framework used in this study is an effective tool for optimizing the algorithm structure and parameter values.

REFERENCES

[1] H. Shi and A. Ziliaskopoulos. "Traffic Flow Control Using Variable Speed Limits," Department of Civil Engineering, Northwestern University, Evanston, Illinois, 2002.

[2] UK Highways Agency. "M25 Controlled Motorways: Summary Report," Issue 1, 2004.

[3] M. Robinson, "Examples of Variable speed Limit Applications," Presented at the Speed Management Workshop at the 79th Annual Meeting of Transportation Research Board, Washington, D.C., 2000.

[4] E. Van den Hoogen, S.A. Smulders, "Control by variable speed signs: results of the Dutch experiment," *7th International Conference on Road Traffic Monitoring and Control*, London, 1994.

[5] C. Lee, B. Hellinga and F. Saccomanno. "Assessing safety benefits of variable speed limits," *Transportation Research Record 1897*, TRB, National Research Council, Washington, D.C., 2004, pp. 183-190.

[6] M. Abdel-Aty, J. Dilmore, A. Dhindsa, "Evaluation of variable speed limits for real-time freeway safety improvement," *Accident Analysis and Prevention 38*, 2006, pp. 335-345.

[7] Quadstone. Reference Manual, PARAMICS Modeller Version 5.1. Quadstone Ltd., Edinburgh, U.K., 2005.

[8] Y. Gardes, D. May, J. Dahlgren, A. Skabardonis, "Freeway calibration and application of the PARAMICS model," Presented at the 81st Annual Meeting of Transportation Research Board, Washington, D.C., 2002.

[9] D. Lee, X. Yang, P. Chandrasekar, "Parameter Calibration for PARAMICS using Genetic Algorithm," Presented at the 80st Annual Meeting of Transportation Research Board, Washington, D.C., 2001.

[10] C. Lee, B. Hellinga and F. Saccomanno. "Real-Time Crash Prediction Model for the Application to Crash Prevention in Freeway Traffic," *Transportation Research Record 1840*, TRB, National Research Council, Washington, D.C., 2003, pp. 67-77.