Variable Speed Limit Systems: Safety and Operational Impacts for Freeways Applications

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ABSTRACT

A candidate Variable Speed Limits Sign (VSLS) control algorithm was applied to an urban freeway in Toronto, Canada using microsimulation. The microsimulation model was combined with a categorical crash model to quantify the impacts of VSLS implementation on safety and traffic performance. The VSLS control strategy was developed as a practical algorithm that responded to real-time measures of traffic conditions. Evaluation of the VSLS impacts revealed that the control strategy could produce desirable impacts (i.e. reduced crash potential associated with a small travel time penalty) but only for a limited range of traffic conditions. Modifications to the algorithm parameters revealed that considerable improvements to the original results could be achieved. The travel time penalty was significantly reduced while a high reduction in crash potential was maintained.

KEYWORDS

Variable Speed Limit Signs, Microsimulation, Freeway Safety

INTRODUCTION

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. In general VSLS systems aim to homogenize traffic flow, improve safety, and reduce driver stress. The use of more sophisticated VSLS systems for real-time congestion management is gradually becoming more widespread with a growing number of applications throughout Europe, the Middle East and Australia; however, despite this increase in use, reported impacts in quantitative terms still remains limited. To date, the only well-documented impact analyses for congestion management systems have been for the M25 Controlled Motorway in the UK [1] and for the A2 Motorway in the Netherlands [2]. 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 impacts reported from empirical deployments, these studies are limited in achieving the following:

- Developing an understanding of the interaction between traffic flow changes and VSLS activity;
- Proposing evidence of relationships between VSLS activity and resulting safety improvements; and
- Studying the impacts on performance of varying the parameters within the VSLS control strategies.

It is suspected that these limitations are in part due to the risk, expense and effort involved in deploying live systems. In addition, before and after studies are difficult to control and can be hindered by confounding effects [3], such as temporal changes in crash risk, changes in traffic demands [2] and effects of enforcement policies during speed limit changes [4, 5].

VSLS microsimulation studies have been undertaken in order to address these limitations. Studies by Lee et al. [5] and Abdel-Aty et al. [6] evaluated comprehensive VSLS control strategies that respond to real-time measures of crash potential; however, from a practical point of view, transportation authorities may be averse to adopting such control strategies based on theoretical measures of crash potential. More recently, a study by Allaby et al. [7] quantified the safety and operational impacts of a VSLS implementation under varying levels of traffic congestion. This microsimulation study differed in that the VSLS control strategy provided dynamic response to loop detector data on 20-second intervals. The results indicated that the VSLS control strategy was successful in producing large safety benefits with little travel time penalty, but was not sufficiently robust to provide consistent benefits for a large range of traffic conditions.

The algorithm evaluated by Allaby et al. [7] was developed only as a preliminary design for practical application. It was unknown whether the selected parameter values would produce the most favourable results. This study addresses this issue by examining the sensitivity of the VSLS impacts to modifications in the control algorithm. The original methodology is summarized in the following sections, followed by the results of the sensitivity analysis.

DESCRIPTION OF TEST NETWORK

An 8 km section of the eastbound Queen Elizabeth Way (QEW) located near Toronto, Canada was selected as the test network (**Figure 1**). 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. Speed, volume, and occupancy are recorded for all mainline stations every 20 seconds.

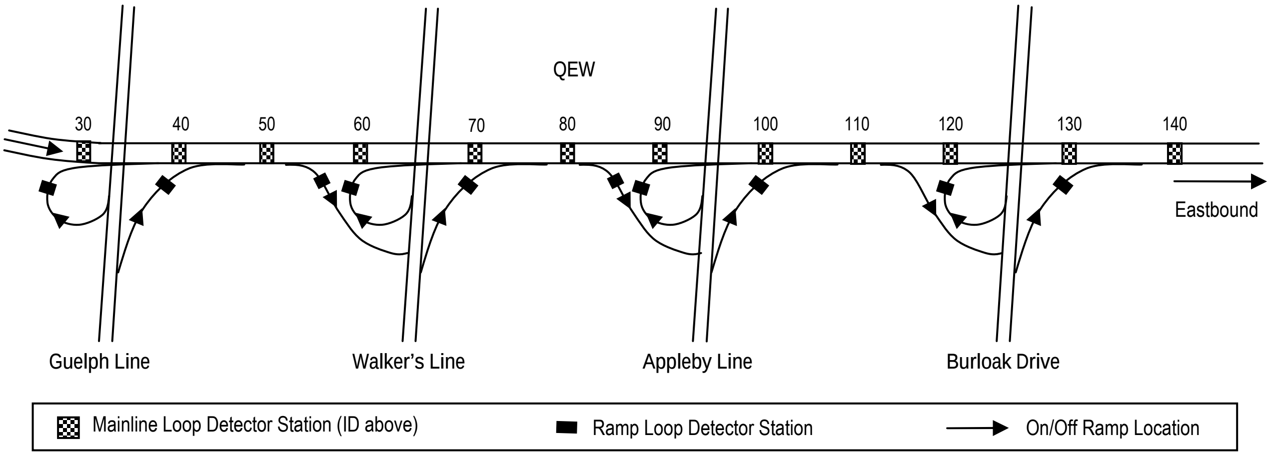

Figure 1 – Schematic of Study Network – QEW, Toronto

CRASH POTENTIAL MODEL

Lee et al. [8] developed a categorical crash model to quantify crash potential from real-time loop detector data. This model was used in Allaby et al. [7] and in this study to measure the relative safety benefit of VSLS implementation. In the model, crash potential is expressed as a log-linear function of three measures of traffic conditions, two control factors (road geometry and time of day), and exposure. The measures of traffic conditions, termed crash precursors, can be calculated directly from loop detector data. They provide an indication of the level of turbulence experienced within a traffic stream by quantifying speed variability, spatial speed difference, and spatial covariance of volume between lanes (surrogate measure of lane changing activity). The higher the crash precursor values, the more instability in the traffic stream and the higher the likelihood of an impending crash condition.

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 (i.e. 20 second loop detector intervals). Also, the model can capture the spatial or temporal changes in crash risk that may exist between adjacent road sections based on the introduction of a traffic control/management system such as VSLS. Therefore, this crash model was an effective tool for capturing the relative impact to safety after the introduction of VSLS.

Within the simulation model, values of crash potential were calculated on 20-second intervals at each detector station. The relative safety impact was determined by comparing the average value of crash potential at each loop detector station for the VSLS and non-VSLS cases, expressed as a percent difference. Since the non-VSLS and VSLS cases differed only by the introduction of the VSLS system, the station crash potential 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 crash potential (or VSLS safety impact) at the 95% level of confidence.

SIMULATION MODEL

The microscopic traffic simulator PARAMICS [9] 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 10 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[1] until the speed profile adequately matched the observed profile (within confidence limits of +/- 2σ).

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[1] Several parameters can be adjusted within PARAMICS that influence car following and merging behaviour, such as mean target headway, mean reaction time, vehicle kinematics and driver aggressiveness.

Three scenarios of traffic congestion were modelled – the peak-scenario, representing the morning peak period volume; b) the near-peak scenario, representing approximately 90% of the peak volume; and c) the off-peak scenario, representing 75% of the peak volume.

VSLS CONTROL STRATEGY

The original VSLS control strategy was implemented within PARAMICS by placing a "message beacon" on each link adjacent to a detector station (13 stations in total). The API was programmed to calculate average station speed, flow, and occupancy on 20-second intervals at each detector station. These traffic performance measures represented the primary input parameters to the VSLS control algorithm. Based on specified parameter threshold values, a speed control algorithm (**Figure 2**) determined the appropriate posted speed limit. When the posted speed limit was reduced for one link, the same reduced speed limit was posted within an upstream threshold distance (i.e. 2 nearest upstream message signs). If the speed limit drop was greater than 20 km/h, a transition speed (spatial countdown) was displayed upstream of the threshold distance. Once a VSLS sign was activated the posted speed limit was not increased until stable flow conditions (occupancy ≤ 15%) were sustained for a predetermined time period.

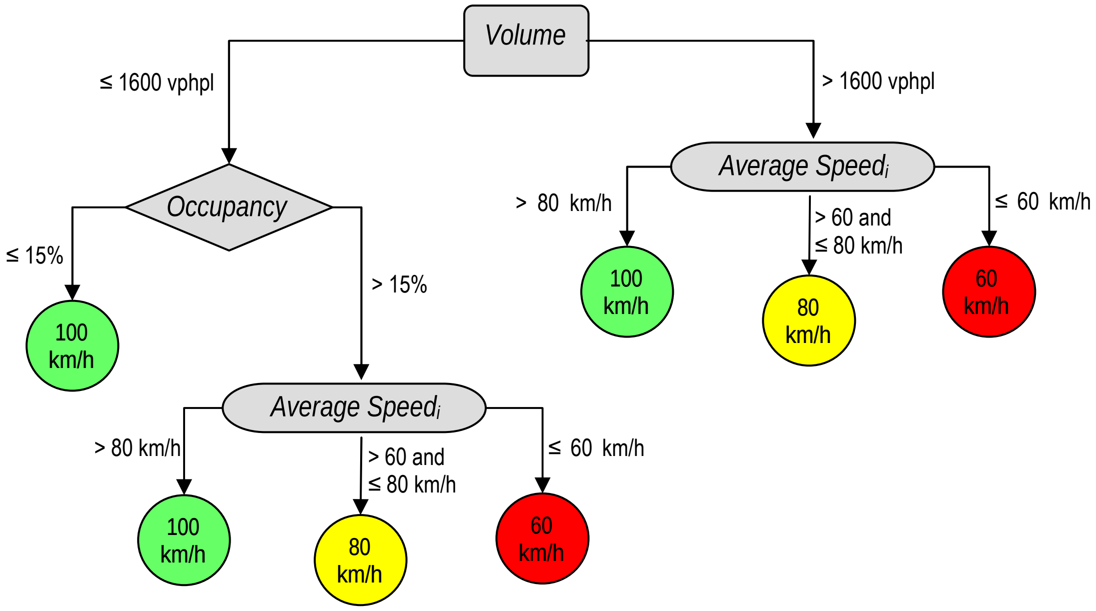

Figure 2 - Original Structure of VSLS Control Strategy

Figure 2 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 level. Only speed decrements of 20 km/h and 40 km/h were tested in this study. Once a speed was determined for the current, or trigger VSLS, the speed limits displayed for its upstream speed signs were determined based on a response zone, a transition zone, and a temporal countdown as described below:

- *Response Zone* – Included the two nearest upstream speed signs. These displayed the same speed limit as the trigger VSLS;

- *Transition Zone* – If VSLS were decremented by 40 km/h, the 3rd upstream sign (1 upstream of response zone) displayed 80 km/h to provide a gradual transition for drivers required to slow from 100 km/h; and
- *Temporal Countdown* – If the VSLS were decremented by 40 km/h, signs displayed 80 km/h for 10 seconds prior to displaying 60 km/h.

EVALUATION

Original Algorithm

Ten simulations were performed for each scenario – with VSLS and without VSLS, and the relative safety and travel time impacts were computed. Similarly to the crash potential analysis, network travel time data was collected for each of 10 simulation runs, paired by the non-VSLS and VSLS cases, and the difference tested for significance using a paired 2-tailed student t-test. The most desirable outcomes for a VSLS impact were a large decrease in crash potential associated with a decrease in travel time. Overall the results 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. The peak scenario experienced the best results on average, but the near-peak and off-peak scenarios exhibited diminishing safety benefits from the VSLS as well as fewer stations that achieved positive results with statistical significance.

The average network safety and travel time impacts for each scenario are included in **Table 2**. Note that the network safety impacts differ from those presented in Allaby et al. [7] due to the removal of Station 40 (most upstream station) from the analysis. Station 40 was removed based on evidence of irregular turbulence that caused very high values of crash potential for both the VSLS and non-VSLS cases. It is suspected that this turbulence was mostly due to the close proximity of Station 40 to the mainline vehicle release zone. Upon the removal of Station 40 results, the statistical significance of the network safety impact showed noticeable improvement.

Modifications to Algorithm Parameters

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

- Occupancy threshold for triggering a speed limit reduction;
- Occupancy threshold for allowing reduced speeds limits to increase;
- Volume threshold for triggering a speed limit reduction; and
- Number of VSLS included in response to a speed limit reduction.

The original parameter values were selected on the basis of engineering judgment. A volume of 1600 vphpl was selected as it represents a freeway level of service C[2]; an occupancy threshold of 15% was selected as evidence revealed it represented the approximate level of traffic flow breakdown; and the response patterns of VSLS were selected to reduce traffic speeds well in advance of a congested location. Five modifications were tested, each varying one or more of the parameter values (**Table 1**) to analyse the sensitivity to both individual and combined modifications. Cells that are shaded indicate the parameter that was modified.

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[2] As specified by the Highway Capacity Manual 2000.

Table 1 - 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%

*First row in cell indicates the VSLS response to a speed limit reduction from 100 km/h to 60 km/h speed limit reduction, whereas the second row indicates the VSLS response to a speed limit reduction from 100 km/h to 80 km/h. Signs are listed in sequence from upstream to downstream.

For each of the modifications listed in **Table 1**, ten simulations were performed using the same simulation volumes and seeding values as the original analysis. The overall results for VSLS activity, safety and travel time impacts for each modification were compiled in the same manner as the original analysis and are presented in **Table 2**.

Table 2 - Network Safety and Travel Time Impacts after Parameter Modifications

Analysis Case	Relative Safety Impact			Relative Travel Time Impact*		
	Peak	Near-Peak	Off-peak	Peak	Near-Peak	Off-peak
Original	39%	27%	-5%	11%	25%	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%

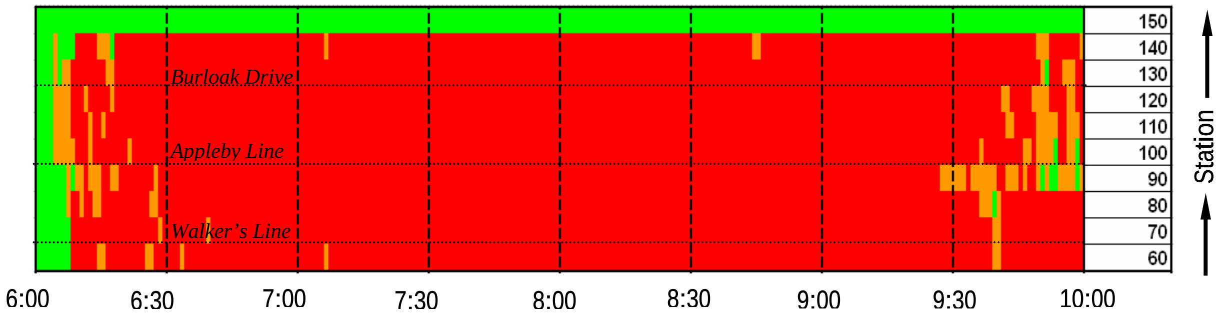
*Positive values of travel time impact indicate an increase in travel time per vehicle.

As shown in **Table 2**, the results of the modification cases vary. The worst performer 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.

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 an adverse impact to the net safety impacts. For the best performer, *Modification* 5, the travel time impact was nearly erased without impacting the net decrease in crash potential 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% relative safety benefit. Furthermore, the negative safety impact for the off-peak scenario was improved from a 5% increase in crash potential to a 1% increase in crash potential. It should be noted that during the off-peak scenario with *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.

A primary explanation for the improvement in travel time impact for both *Modification 2* and *Modification 5* was 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 pockets of congestion and, due to response zone requirements, speed limit reductions cascaded upstream and the VSLS were not able 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. **Figure 3** shows the mapping of the VSLS displayed speed limits during simulation runs before and after the modification (with identical seed values). Note that under the original algorithm (**Figure 3a**), the VSLS responded to congestion early in the period and were unable to recover. In contrast, after *Modification 5* (**Figure 3b**) the VSLS provided a more dynamic response, closely following the development of the peak period shockwave.

(a) Original Algorithm



(b) Algorithm with *Modification 5*

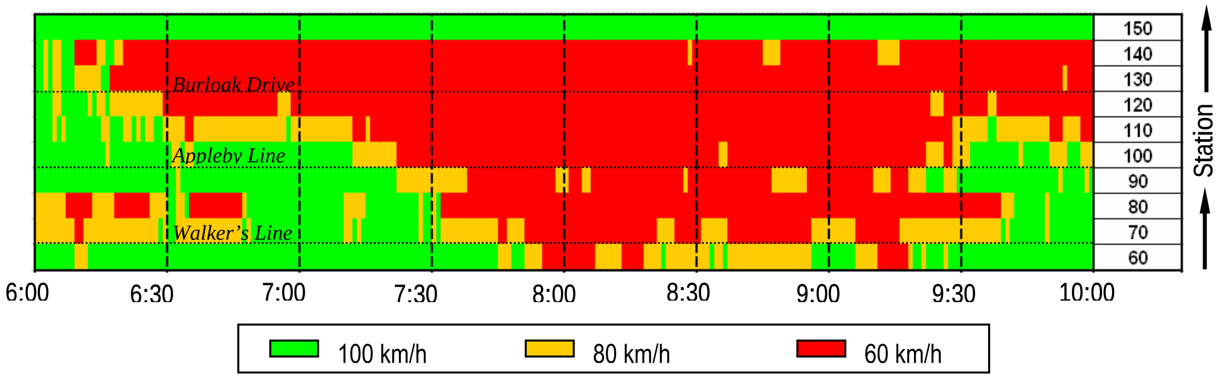


Figure 3 - VSLS Speed Contours Resulting from Original Algorithm for Peak Scenario

CONCLUSION

Although a number of studies, both empirical and theoretical, have reported impacts of VSLS control strategies aiming to increase safety and reduce congestion, little has been documented regarding the evaluation of control strategy modifications. The objective of this study was to perform a preliminary sensitivity analysis of VSLS impacts to changes in control algorithm parameter values by building upon results of previous work. The VSLS strategies were evaluated using a microsimulation model combined with a categorical crash model. The results of this sensitivity analysis provided evidence that significant improvements in VSLS performance were possible by modifying the parameters within the control strategy. The preservation of high safety benefits associated with considerable reductions in travel time impacts suggest that the original control algorithm was causing prolonged VSLS responses that were unnecessary. This analysis offered encouraging results and some initial insight into the relationship between the choice of control strategy parameter values and the resulting safety and operational impacts. Furthermore, this study suggests microsimulation provides an effective environment for evaluating candidate VSLS control strategies.

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