# The potential for variable speed control to improve safety on urban freeways

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## Abstract

Variable speed control systems enable transportation managers to dynamically change the posted speed limit in response to prevailing traffic and/or weather conditions. Variable speed control systems have been implemented in a number of jurisdictions throughout the world. Many of these systems have been deployed to address specific safety issues, such as steep grades or frequent occurrences of adverse weather such as fog, high winds, or blowing snow. A smaller number of systems have been deployed as a more general traffic management tool and even for these systems, there is currently limited documentation describing the quantitative safety and operational impacts. Furthermore, the impacts that are reported are primarily from systems in Europe, and may not be directly transferable to North America.

This paper describes a methodology developed to evaluate the safety impacts of variable speed control systems and presents the results obtained using this methodology to evaluate a candidate variable speed control 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.

The keys findings from the study show that the candidate variable speed control has the potential to provide relatively large safety benefits (i.e. up to a 40% reduction in potential for crashes). Furthermore, unlike speed management techniques that rely on in-vehicle devices, variable speed control systems can be implemented with existing technologies and with the existing vehicle fleet.

The study also found, however, that the safety impacts vary depending on traffic conditions; the variable speed control system logic, and the parameters within the system algorithms. Furthermore, the results are based on several important assumptions about drivers' reaction to variable speed limits. In particular, the analysis assumed a high degree of compliance – a level likely to be achieved only through the use of automated speed enforcement. The degree to which this and other assumptions are valid, and the impact that violation of these assumptions may have on the level of safety improvements, requires additional investigation.

## Introduction

Variable speed control systems[1]consist of dynamic message signs (DMS) deployed along a roadway and connected via a communication system to a traffic management centre. The VSCS are used to display a regulatory or advisory speed limit. Unlike typical static speed signs, the VSC system enables transportation system managers to dynamically post a speed limit that is appropriate for current traffic, weather, or other conditions. VSC SYSTEMS are thought to improve safety and reduce driver stress while improving traffic flow and travel times (Shi and Ziliaskopoulos, 2002).

VSC systems consist of one or more electronic dynamic message signs (DMS) mounted on roadside structures or overhead gantries and traffic sensors all of which are connected via a communication system to a traffic control centre. The system may also include automated speed enforcement equipment.

When the system consists of multiple DMS, the signs are typically installed with a spacing of approximately 600-800 metres. This spacing provides drivers with sufficient distance to react to a speed change, but is short enough that drivers are given sufficiently frequent updates of the current speed limit.

VSC systems can be grouped into four application categories:

- Speed control in response to adverse weather and road surface conditions.
- Heavy vehicle speed control (especially preceding steep downgrades).
- Work zone speed control.
- General purpose congestion control.

A number of VSC systems have been successfully implemented. Table 1 identifies several VSC systems, their location, year of deployment, and application category.

[1] In North America, these systems are also referred to as Variable Speed Limit Sign (VSLS) systems. In this paper we will use the term variable speed control system (VSCS).

**TABLE 1: VARIABLE SPEED LIMIT DEPLOYMENTS**

| VSCS Location (Year Deployed) | Application Category | Extent of Roadway Covered |
|---|---|---|
| *E18* Finland (1994) | Weather Response | 36 signs/direction over 12 km |
| *I-90* Washington, USA (1997) | Weather Response | 13 signs over 17 km |
| *Confederation Bridge* New Brunswick, Canada | Weather Response | 17 signs/direction over 13 km |
| *F6 Tollway* Sydney, Australia (1993) | Weather Response (Fog) | 12 signs/direction over 11 km |
| *A16* The Netherlands (1991) | Weather Response (Fog) | 15 signs over 12 km |
| *I-80* Nevada, USA | Weather Response (Visibility) | 2 signs/direction |
| *I-96* Michigan, USA (2002) | Work Zone Response | 4 deployments of up to 7 signs, within 18 miles |
| *Deep Bay Link & Route 8* Hong Kong (2005) | Congestion and Incident Management | 12 signs over 12 km per section |
| *A3, A5, A8, & A9 Autobahns* Germany (1974) | Congestion and Weather Response | Up to 30 km/motorway Signs spaced 1.5 km - 2 km |
| *M25 Controlled Motorways* London, UK (1995) | Congestion Response | Signs every 1 km over 20+ km |
| *A2 Motorway* The Netherlands (1992) | Congestion Response | 40 signs over 20 km |
| *Western Ring Road* Melbourne, Australia (2002) | Congestion Response | 37 signs/direction over 26 km |
| *Ayalon Highway* Israel (late 1990s) | Congestion Response | 32 signs over 15 km |
| *New Jersey Turnpike* New Jersey, USA (1968) | Hazard Response (includes incidents, weather, congestion) | 141 signs over 215 km |
| *Lodge Freeway* Michigan, USA (1960) | Congestion Response | 21 signs over a 5 km length |

The majority of existing VSC systems incorporate a rule-based response logic that operates on real-time traffic and/or environmental data. These data can either be collected and processed by an operator at a traffic management centre, or collected and fed into a central server for automatic response. Weather and road surface data can be collected via Road Weather Information Stations (RWIS) as in Finland (Rämä, 1999) or by visibility sensors, as on the A16 in the Netherlands (Hogema and van der Horst, 1994) and on the F6 in Australia (FHWA, 1995). Traffic performance data can be collected in the form of speed, volume and occupancy data via inductive loop detectors or through closed circuit television (CCTV) cameras. The data are processed and, based on predetermined control logic, the speed limit display is updated to reflect current conditions.

The first variable speed control system in North America was deployed on the Lodge Freeway in Michigan in 1960 (Warren, 2000). The system permitted facility operators to give drivers advance warning of downstream congestion by changing the posted speed limit within a range of 100 – 30 km/h (60 – 20 mph). The system was deployed over a short section of freeway upstream of an area prone to recurrent congestion. It is reported that the system was unsuccessful due to poor motorist compliance (Haboian, 1993).

A few years later, a much longer VSC system was deployed on the New Jersey Turnpike in New Jersey. In this system the posted speed limits are based on average travel speed and are displayed automatically. Speed limits can be manually reduced in response to crashes, congestion, construction, ice, snow, and fog (Robinson, 2000).

In the early 1970s, Germany deployed VSC and now has fully automated VSC on many of the Autobahns including the A8 between Salzburg and Munich, A3 between Sieburg and Cologne, and A5 near Karlsruhe. Though there appears to be little documentation in English describing evaluations of these VSC systems, it has been reported (Robinson, 2000) that the use of the speed limit and speed warning signs has reduced the crash rate by 20 to 30 percent.

Van den Hoogen and Mulders (1994) evaluated a pilot VSCS deployed by the Dutch government on a 20km section of the A2 between Amsterdam and Utrecht. This section experiences significant recurrent congestion caused by very heavy traffic demands at several on-ramps. On the basis of their before and after analysis, Van den Hoogen and Mulder reported that the VSCS reduced mean speeds, reduced speed variation, reduced the number and severity of shock waves, and reduced the fraction of very small time headways (those less than 1 second). The authors concluded that these impacts indicate that the use of variable speed control resulted in a more homogeneous traffic stream and that a more homogenous traffic situation can be expected to increase safety. However, they did not attempt to quantify the safety impacts.

Though the authors found that the majority of approximately 1300 drivers surveyed reported they had benefited from the VSCS, the authors found no evidence that the VSCS improved the capacity or throughput of the roadway.

Ulfarsson et al (2005) conducted a statistical analysis of the impact of the VSC system deployed on I-90 in the Snoqualmie Pass in Washington State. This system reduces the speed limit during adverse weather (primarily snow). They found that the use of VSC had a significant effect in reducing the mean speed but that the impact on speed variability was not consistent. Speed variance decreased for the eastbound traffic but increased for the westbound traffic.

Most recently, Papageorgiou et al (2006) conducted a quantitative evaluation of the VSC system operating on the M42 in the UK. They used flow, occupancy, and speed data measured by loop detectors and assessed the impact of VSC by comparing the traffic data associated with two time periods, namely (1) when VSC was operational but speeds were advisory rather than mandatory, and (2) when VSC was operational and speeds were mandatory and automatically enforced[2].

As expected, the authors found that the use of VSC for uncongested traffic conditions reduced the mean speed of the traffic stream (i.e. lowered the slope of the flow-occupancy curve). The authors also looked for evidence that the use of VSC increased the capacity of the roadway. However, the evidence was inconclusive as there were some locations at which a small capacity increase was observed, while at other locations no increase was visible.

According to Hegyi et al (2005) there have been several different methodologies proposed to find a control law for speed control, including multilayer control (Li et al., 1995); sliding-mode control (Lenz et al 1999 and 2001); and optimal control (Alessandri et al., 1999; Di Febbraro et al., 2001). Also, Papageorgiou et al (2006) proposed an improved control strategy after their evaluation of the M42 VSCS.

Hegyi et al (2005) suggests that there are essentially two possible control objectives for *General Purpose Congestion Control*, namely: (a) homogenization of the traffic stream (i.e. reduction of the variance of speed) or (b) optimization of system throughput by preventing flow breakdown. The control logic of existing VSC systems reported in the literature suggests that the majority of existing systems appear to be constructed to achieve the first objective rather than the second objective.

To-date there have been no general purpose VSC systems deployed in Canada. Steel et al (2005) explored the use of VSC on the Trans-Canada Highway within Banff National Park. Their paper provided a review of existing VSC systems and investigated the legislative constraints associated with deploying VSC within Banff National Park. Interestingly, they also concluded that “variable speed limits generally produce a reduction in the operating speed of vehicles; however, an increase in the speed variance may occur.”

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[2] The control logic employed by the VSCS also changed between the two periods, further confounding the analysis.

The review of the literature suggests that VSC can reduce average speeds, reduce speed variation, improve lane utilization and create a calmer driving experience – all of which may contribute to measured reductions in crash frequency and severity. However, there does not appear to be a way to directly assess the impact of different VSC control strategies (or the impact of different parameter values for a given strategy) on safety or traffic flow.

Furthermore, empirical before and after studies tend to be hindered by confounding effects (Ben-Akiva et al., 1997), such as temporal changes in crash risk, changes in traffic demands (Van den Hoogen and Smulders, 1994) and effects of changes in enforcement policies during speed limit changes (TRB, 1998; Lee et al., 2004).

The purpose of the current study was to develop and apply a methodology for quantifying the safety and traffic flow impacts of candidate VSC SYSTEMS control strategies for an urban North American freeway section.

This study differed from those described in the literature in that the VSCS control strategies evaluated were designed (a) for practical implementation by providing dynamic response directly to loop detector data on 20-second intervals and by adhering to typical design standards with respect to maximum speed limit reductions, etc.; and (b) to be similar in structure to those already in use in the UK (UK Highways Agency, 2004) and Netherlands (Van de Hoogen and Smulders, 1994).

Three traffic scenarios were modelled, each under a different condition of recurrent congestion. An initial VSCS control strategy was designed and its impacts on safety and system delay were evaluated using a microscopic simulation model (PARAMICS) combined with a categorical crash potential model. A sensitivity analysis was then conducted to investigate the effects of modifying parameters within the VSCS control algorithm. Descriptions of each aspect of the study and the results of the system evaluations are presented in the following sections. More detailed descriptions of the study are available in the literature (Allaby, 2006)

## Description of Study Network

An 8 km section of the eastbound Queen Elizabeth Way (QEW) located near Toronto, 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/hr, has three mainline lanes, contains four interchanges, and experiences a directional AADT of about 70,000 vehicles. The freeway is instrumented with dual loop detector stations in each mainline lane spaced at approximately 600 m and single loop stations on entrance and exit ramps (Figure 1). Speed, volume, and occupancy are recorded every 20 seconds 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. The congestion is mainly caused by a 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 an upstream moving shockwave that penetrates much of the section. Freeway speeds through the bottleneck during this period typically range from 30 km to 50 km, but at times traffic is observed to be at a standstill.

A VSCS 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.

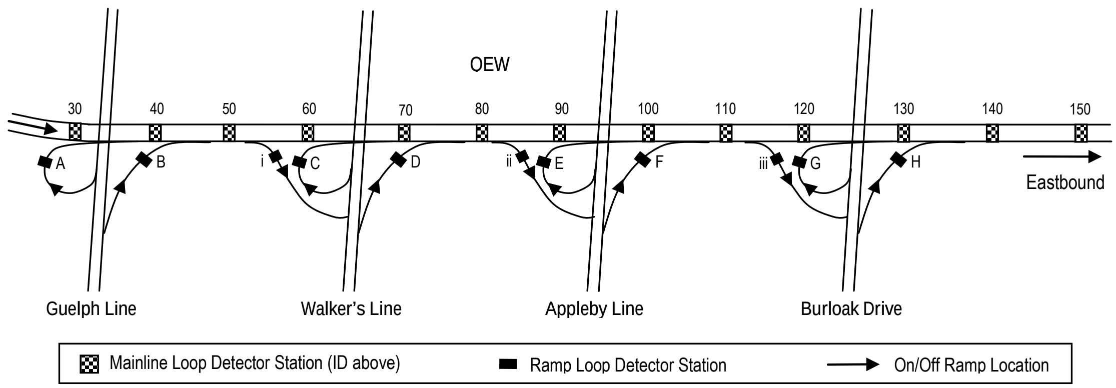


**Figure 1: Study Network**

## Simulation development: Base model

The microscopic traffic simulator PARAMICS (Quadstone, 2005) 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 VSCS 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. The days were chosen from November 2004 and April 2005 under the conditions that (a) the day was a weekday but not a Friday; (b) no incidents were recorded during that day; (c) the speed profile of the peak period exhibited congested conditions and a prolonged shockwave; and (d) 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-minute period so that the growth and dissipation of congestion could be adequately modelled.

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-VSCS) 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 +/- $2\sigma$). The simulation parameter values that 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 (Gardes et al., 2002; Lee et al., 2001) were also tested, but these values produced model results that were not representative of the observed traffic conditions. Note also that behavioural parameters were not modified during active VSCS conditions due to limited documentation on driver response to VSCS.

## VSCS Integration

The VSCS infrastructure was represented within PARAMICS by thirteen variable speed limit signs, each placed next to a loop detector, spaced at approximately 500 m to 600 m. Since PARAMICS assigns speed limits by link, the mainline was coded as a series of links corresponding to each detector-variable speed limit sign pair. Each link/detector/variable speed limit sign 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 variable speed limit sign (VSLS) displayed 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 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."

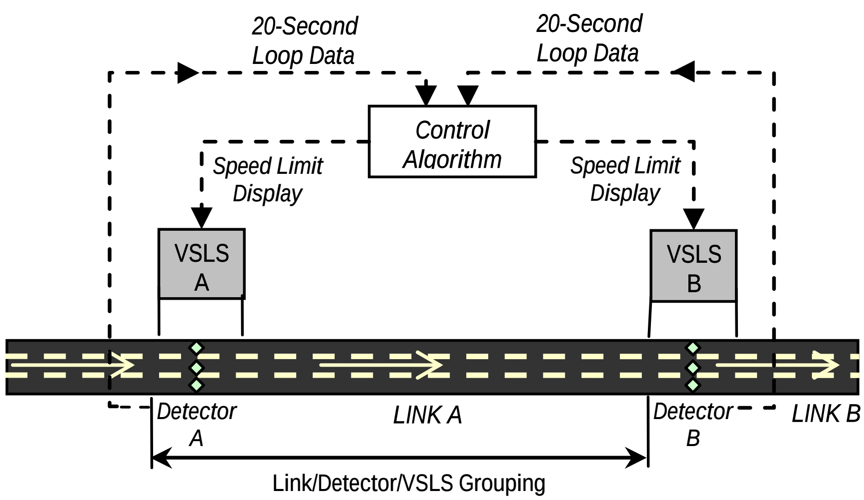


**Figure 2: Basic Layout of Link / Detector / VSLS Groupings**

The original VSCS 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 VSC systems. For example, the VSC system deployed on the M25 Controlled Motorways in the UK is triggered by volume thresholds (e.g. when loop detector station volumes reach 1650 vehicles per hour per lane (vphpl), the speed limits reduce from a default of 70 mph to 60 mph). On the A2 motorway in the Netherlands, the VSC system reduces speeds to either 90 km/h or 70 km/h based on 1-minute 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 revealed that this threshold approximates the critical occupancy at which traffic flow breakdown occurs for this section of road; and the response patterns of VSLS 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-second 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.

Figure 3 shows the four conditions resulting in a speed limit reduction, which 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 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.

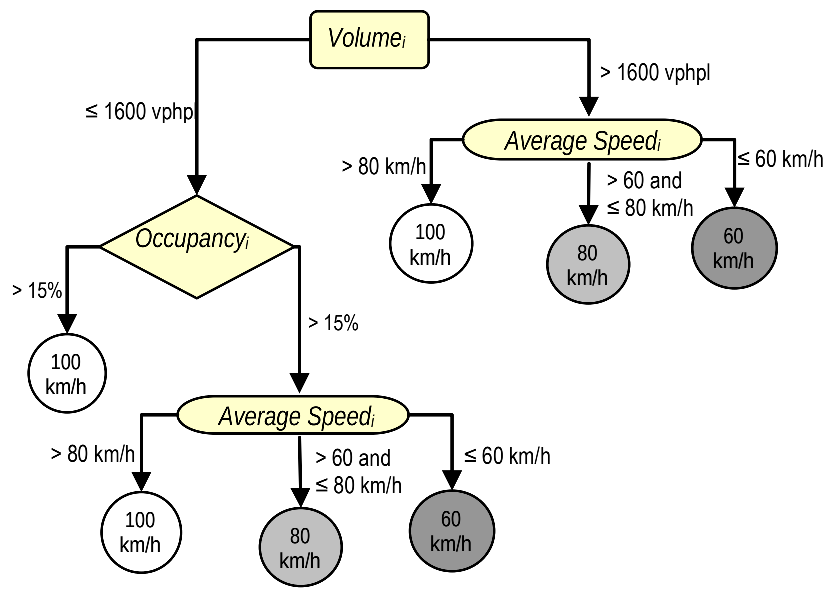


**Figure 3: Decision Path for Determining New Posted Speed of Trigger VSLS$_i$**

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* 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 the posted speed limit was reduced from 100 km/h to 60 km/h at the response zone, then the 3$^{rd}$ 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 posted speed limit was reduced from 100 km/h to 60 km/h then the variable speed limit signs displayed 80 km/h for 10 seconds 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-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 was found to occur for this study section. Speed limits posted on the signs 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.

Figure 4 shows the dynamic response of the VSC displayed speed limit to changing traffic conditions (measured at a detector station).

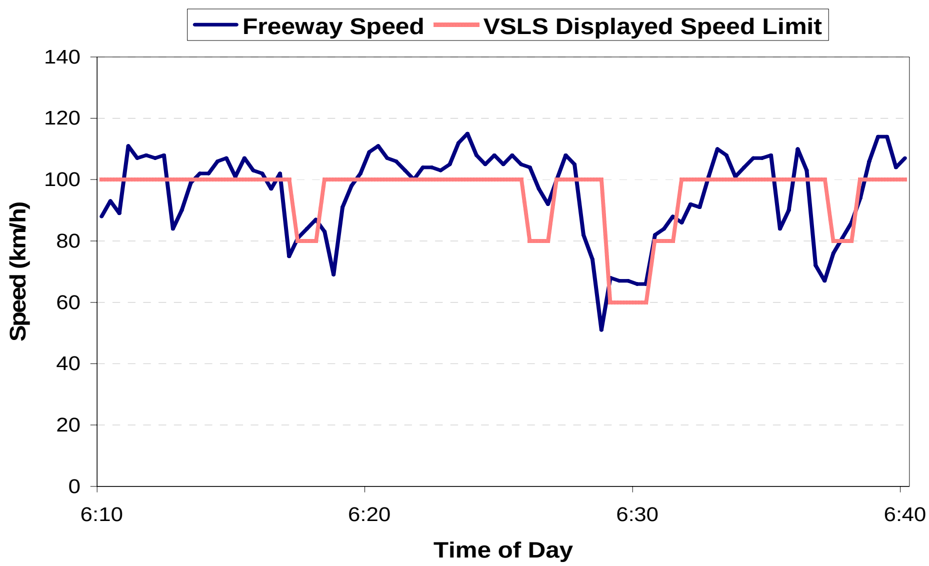


**Figure 4: VSCS response to freeway traffic conditions**

## Categorical Crash Potential Model

### *Model Overview*

The crash model employed in this study was introduced by Lee et al. in 2003 (Lee et al., 2003). 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 of 12 non-incident days.

### *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 (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 VSCS.

In this study, the safety impact of VSCS was measured by calculating the relative change in crash potential from the non-VSCS case to the VSCS case. Ten simulation runs were performed for the non-VSCS case and ten for the VSCS case. The same set of ten seed values was used for the VSCS and non-VSCS 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-VSCS and VSCS cases differed only by the introduction of the VSCS, 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 VSCS 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.

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

where,

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

## VSCS Impact Results

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

### *VSCS Activity*

During the peak scenario, the degree of congestion was severe enough that all VSCS signs displayed 60 km/h for the majority of the period, whereas the off-peak scenario experienced very little VSCS activity. The near-peak scenario provided the most dynamic VSCS 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 depicts the speed limits implemented by the VSCS for a single simulation run over the 4-hour simulated period for the near-peak scenario. Table 2 shows the average network VSCS coverage for each of the three scenarios in terms of the percent time a speed limit was displayed.

**TABLE 2: VSCS 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 |

### *VSCS Safety Impact*

Examination of the safety impact results revealed that the relative safety benefit achieved by the VSCS 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 VSCS (Table 3). 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 crash precursor Q, and to in-lane speed variation measured by reductions in crash precursor CVS.

**TABLE 3: VSCS SAFETY IMPACT SUMMARY**

| Station ID | Relative Safety Benefit (RSB) of VSCS | | |
|---|---|---|---|
| | *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.

The near-peak and off-peak scenarios experienced diminishing safety benefits from the VSCS as well as fewer stations that achieved significant results. Although the near-peak scenario experienced a positive network RSB of 27%, the results varied largely between simulation runs. Over the 10 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.

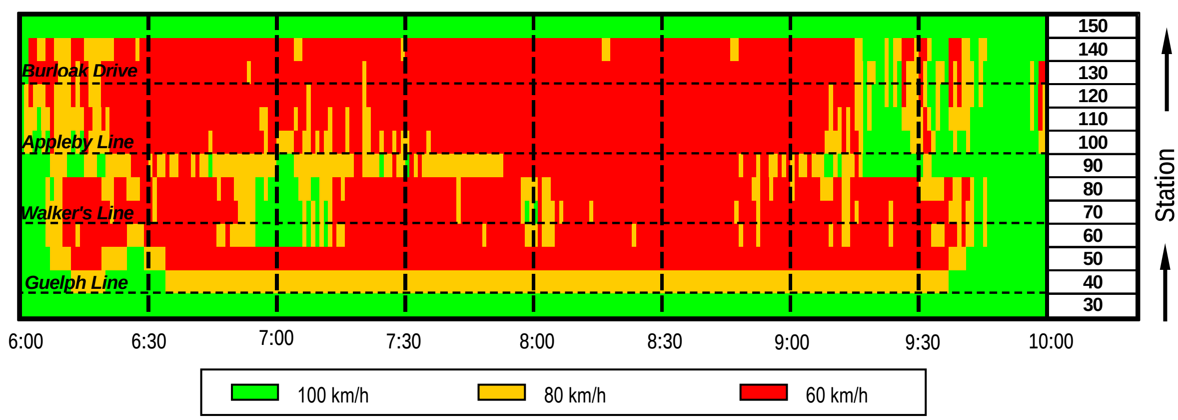


**Figure 5: Mapping of VSCS Displayed Speeds for the Near-Peak scenario**

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 VSCS and the safety benefit achieved after VSCS implementation. This relationship indicates a diminishing safety benefit as VSCS 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 VSCS 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.

### *VSCS Travel Time Impact*

The travel time impacts of VSCS implementation were measured by the relative change in average network travel time per vehicle from the non-VSCS case. For all three scenarios, the implementation of VSCS resulted in an increase in average travel time (Table 4), 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 minutes per vehicle) 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 very little travel time impact largely because the low activity of the VSCS.

**TABLE 4: VSCS TRAVEL TIME IMPACT SUMMARY**

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

These results seem to suggest that the evaluated VSCS 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 VSCS control algorithm can create sustained congestion for some locations when no sustained congestion would have occurred if VSCS had not been implemented. An investigation of the data revealed the cause of these results. Early in the simulation, congestion occurred sporadically in very short time periods. In the absence of the VSCS, this congestion cleared very quickly. However, when VSCS 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.

### Conclusions of Preliminary Analysis

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

1. Traffic scenarios experiencing higher congestion were more likely to benefit from the VSCS in terms of higher positive relative safety benefits and less negative travel time impact 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 relative safety benefits with less impact to travel time;
3. For less congested conditions, stations upstream of VSCS response zones were more likely to experience negative relative safety benefits; and
4. Vehicles making longer trips were more likely to experience negative travel time impacts under the current VSCS control algorithm than vehicles making shorter trips.

The most desirable results (both positive safety and positive travel time impacts) were usually observed under moderately congested scenarios during which the VSCS 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 VSCS. This suggests that the tested VSCS 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. It was anticipated that modifications to the algorithm could result in a VSCS 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 analysed using the same methodology as was applied for the original algorithm. A description of the modifications and the impacts to performance are provided in the following section.

### Modification to Control Algorithm Parameters

The original variable speed limit control algorithm was developed only as a preliminary design for practical application. 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 favourable results. The results of the preliminary analysis revealed that the original algorithm does have the potential to operate favourably during some conditions, but produces inconsistent and undesirable results during the near-peak and off-peak scenarios. It was suspected that changes to the original algorithm could result in improvements to the overall VSCS 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 to safety and travel time impacts following different modifications to the parameter values.

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 variable speed limit signs included in response to a speed limit reduction.

Five modifications were tested, each varying one or more of the above parameter values to analyse the sensitivity to both individual and combined modifications. The modifications are displayed in Table 5. 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 VSCS response:

- raising the minimum level of congestion to which VSCS responds, thus reducing the overall degree of VSCS response and eliminating the VSCS response to brief pockets of light turbulence; and
- reducing the number of upstream variable speed limit signs included in a response, thus limiting the distance affected by the VSCS and reducing the undesired cascading effect, previously noted.

Cells in Table 5 that are shaded indicate the parameter that was modified. For each of the modifications listed in Table 5, ten simulations were performed using the same simulation volumes and random number seed values as the original analysis. The overall results for VSCS activity, safety and travel time impacts for each modification were compiled in the same manner as the original analysis and are presented in Table 6 and Table 7.

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 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.

A primary explanation for the improvement in travel time impact for both *Modification 2* and *Modification 5* was the reduction in the number of VSCS responses during the simulation period. It was evident from the original analysis that the VSCS frequently responded to short term pockets of congestion and, due to response zone requirements, speed limit reductions cascaded upstream and the VSCS was 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 VSCS activity, without compromising the safety benefit, indicates that the original control algorithm caused many VSCS responses that were unnecessary. It should also be noted that during the off-peak scenario under *Modification 5*, the VSCS 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 expected to operate full-time in an automatic state.

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

**TABLE 5: MODIFICATIONS OF PARAMETER VALUES FOR SENSITIVITY ANALYSIS**

| Case | Parameters for Speed Limit Reduction | | | Parameters for Speed Limit Increase |
|---|---|---|---|---|
| | Occupancy Threshold | Volume Threshold | # of Responding VSCS* | 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 6: VSCS ACTIVITY RESULTING FROM PARAMETER MODIFICATIONS**

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

**TABLE 7: OVERALL NETWORK SAFETY AND TRAVEL TIME IMPACTS RESULTING FROM 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% |

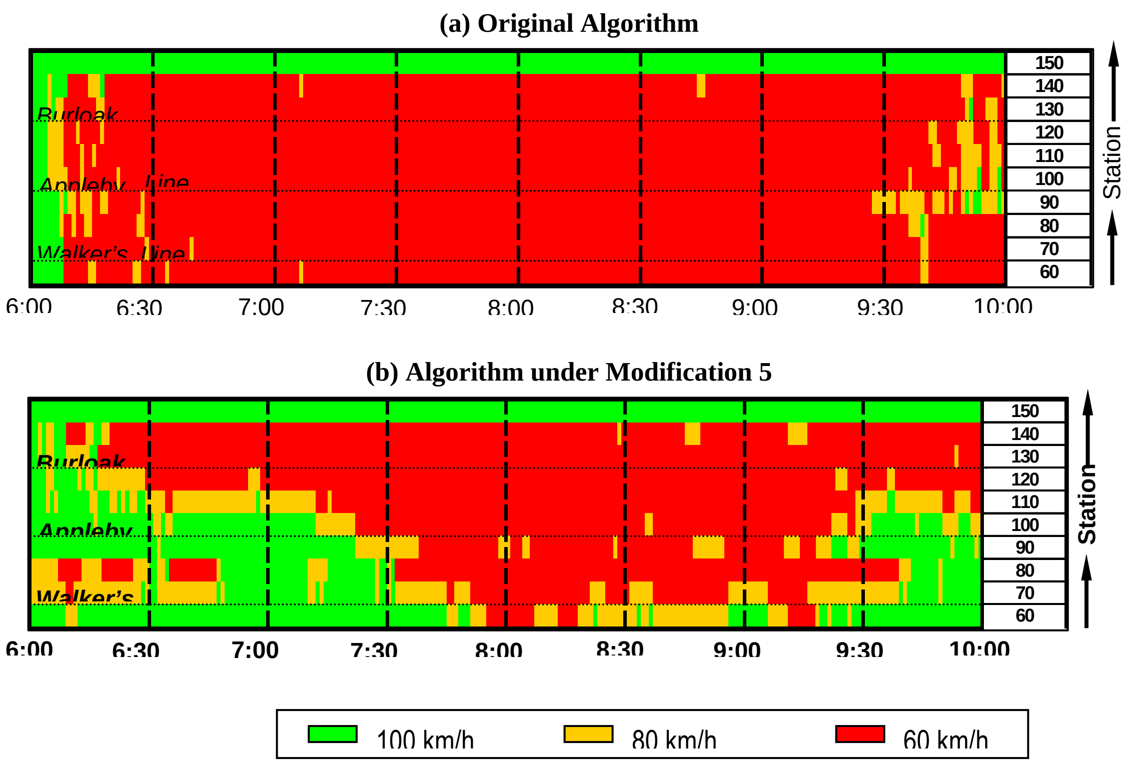


**Figure 6: Mapping of VSCS Displayed Speeds for Peak Scenario**

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 VSCS response triggers showed that volume related responses were reduced, but occupancy related responses increased by approximately the same degree. Consequently, the overall VSCS 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 VSCS 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 increased to 15% in *Modification 2*, the performance results improved considerably.

## Conclusions

Although a number of studies, both empirical and theoretical, have reported impacts of VSCS control strategies aiming to increase safety and reduce congestion, little has been documented that quantifies the expected safety and operational impacts of a practical VSCS control strategy and the sensitivity of these impacts to parameter values in the control logic.

The evaluation framework presented in this paper 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 VSCS. 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 VSCS.

The results of the analysis for the original VSCS control algorithm suggested that the implementation of the VSCS 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. Net reduction in safety resulted for uncongested conditions (off-peak period). Use of VSCS increased travel times for all traffic scenarios considered.

Further analyses were performed on modifying the parameters within the VSCS control algorithm and the resulting impacts were quantified. Although this was only a preliminary analysis, considerable improvements to the original VSCS 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 preservation of high safety benefits associated with considerable reductions in travel time increases suggest that the original control algorithm was causing prolonged VSCS responses that were unnecessary. Unfortunately, a strategy was not identified that could provide consistent and positive impacts for both safety and travel time under all degrees of congestion, but this analysis provided evidence that significant improvements were attainable. It is anticipated that further modifications to the algorithm could result in a VSCS 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 insight into the relationship between the choice of control strategy parameter values and the resulting safety and operational impacts. Furthermore, this study suggests microscopic simulation offers an effective environment for evaluating candidate VSCS control strategies.

It is necessary to interpret the finding 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 behavior with respect to (a) compliance with the posted speed limit; and (b) changes in driving behavior due to the need to read and respond to speed limit signs.

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

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