Design and Evaluation of a Probe-based Variable Speed Limit Algorithm in PARAMICS

by

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ABSTRACT

In this thesis, a novel adaptive Variable Speed Limits (VSL) algorithm is presented. The algorithm takes as its only input real-time SMS measurements derived from vehicles equipped with GPS enabled devices acting as probes. The developed algorithm optimizes the VSL input over a short-term future horizon. However, only the VSL outputs corresponding to the first estimation steps are considered final, and implemented. The developed algorithm is tested using a PARAMICS microsimulation model on a section of Highway 2 (also known as the Deerfoot Trail) in Calgary, Alberta. The performance of the algorithms is examined and compared, in terms of delays, densities, flows, travel times and speeds in the cases of existing scenarios (i.e. no VSL) and with VSL scenarios. Several scenarios are created and examined: moderately congested, congested, severely congested and “lane closure due to a car collision”. In addition, a sensitivity analysis is also conducted to compare the performance of the developed probe-based approach for different percentages of penetration rate of probe data (i.e. number of vehicles acting as probes) as well as the composition of probe vehicles (i.e. commercial vehicles versus passenger vehicles). The presented probe-based algorithm is also compared with a conventional VSL algorithm taking traffic information from point detectors. The results of the analysis are promising, and show the effectiveness of developing VSL algorithms taking speed data from vehicle probes on the motorway as the main input parameters. The developed algorithm is as shown to be effective in reducing the variance of the vehicles’ speeds, which is an important indicator of a likely improvement in the road safety level. The probe-based data used as input to the presented
algorithm is shown to be a low cost alternative to commonly used data that are collected based on point detectors
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Chapter 1  INTRODUCTION

Due to a rapidly growing demand for mobility, the number of vehicles on the roads grows drastically every year. According to information published on the Statistics Canada website (Turcotte, n.d.), the proportion of people of aged 18 and older who used their vehicles to drive anywhere within a city reached 74% in 2005, as opposed to 70% in 1998 and 68% in 1992. This tendency leads to pronounced traffic congestion in highly populated urban areas.

Roadway congestion can be divided into two types: recurrent and nonrecurrent (Marino, 1969). Recurrent traffic congestion is created due to a larger number of vehicles using a motorway during certain times of the day (morning and evening rush hour). Nonrecurrent congestions are the result of unexpected traffic situations, i.e. car accident, weather conditions, etc. In 2005, the U.S. Federal Highway Administration conducted research on the causes of congestion:

1. Bottlenecks 40%
2. Traffic incidents 25%
3. Bad weather 15%
4. Work zones 10%
5. Poor signal timing 5%
6. Special events/other 5%

Thus, recurrent congestion accounts for 45% of congestion while non-recurrent congestion accounts for 55%. Due to fiscal, land and environmental constraints, building
more roads is often not a viable solution to address congestion problems. Improving the operational efficiency of urban transportation networks by using existing unused capacity is the sustainable solution. Intelligent Transportation Systems (ITS) rely on real-time control, management and information dissemination to reduce network congestion. Real-time traffic control and management systems optimise the efficiency of traffic networks by responding to the dynamic and the random nature of traffic almost instantaneously, and can therefore be used effectively to mitigate traffic congestion. ITS capitalises on emerging computer and communication technologies to almost instantaneously respond to the dynamic and random nature of traffic. Recent advancements in ITS have shown that ITS strategies are able to effectively reduce congestion, incidents and emissions in urban areas, with no need for additional infrastructure expansion. The Variable Speed Limit (VSL) is an example of an effective ITS strategy that can be used to mitigate congestion. VSL enables dynamic changes in the posted speed limit in response to prevailing traffic and/or weather conditions in order to smooth traffic flow and reduce accidents. Under VSL, electronic devices buried under the pavement monitor traffic flow; and speed limits are indicated by displays on overhead or roadside signs.

1.1 OVERVIEW OF VARIABLE SPEED LIMIT

Why do we need a speed limit on the roads? For high-speed highways a safe speed limit is determined for traffic conditions based on geometric design elements, such as horizontal alignment, vertical alignment, shoulders, etc. (Alberta Transportation, 1999). However, an implemented fixed speed limit is unable to respond to adverse weather conditions, or in the case of lane blockage caused by collisions or construction work operations on a highway. Such events creates traffic shockwaves which might cause drivers
to suddenly decrease their speed to avoid a collision with another car. That decreases the initially established level of safety of the road. Unlike fixed speed limits, the VSL algorithm is able to adjust the variable message signs in accordance with the changing road conditions.

VSL strategies are increasingly gaining the attention of transportation engineers as innovative and effective tools to reduce highway congestion and improve safety. VSL was first implemented in Germany more than three decades ago. Today, VSL is widely used in European countries, USA, Korea and Australia. For instance, Autobahn 9 between Munich and Nurnberg, Germany, contains a VSL system implemented on 18 km segments.

The majority of VSL studies examined the VSL benefits in terms of improved traffic conditions and reduced number of collisions. The improved safety benefits associated with VSL are related to their capability to decrease speed variance and to suppress shockwaves on congested motorways (Hegyi et al., 2003). Such shockwaves can be created either by lane changing behaviour on a congested motorway segment, or incidents occurring (e.g. collisions, vehicle breakdowns, adverse roadway conditions, traffic discharged from on-ramps, presence of a slow moving vehicle, etc.).

The effectiveness of a VSL system varies from one location to another depending on the number of variable message signs and the properties of the network (i.e. demand, OD matrix, geometrical description, etc.). For instance, the VSL system implemented on the A2 in the Netherlands was unable to improve road conditions, whereas the VSL algorithm applied on the M25 in the UK proved to reduce injury-related crashes by 30%, which is a significant contribution in terms of safety (Boice et al., 2006). Bertini et al. (2006) completed a “before VSL” and “after VSL” comparison analysis, which showed the ability of VSL systems to sustain traffic flow, even though it was unable to suppress the
back propagating shockwave. Field tests performed on highway I-495 in Minnesota showed a 25%–35% reduction in average speed, and a 7% increase in traffic throughput of cars passing through the work-zone (Kwon et al., 2007). The VSL implementation also proved to contribute to road safety, providing smoother traffic flow by reducing the average speed of vehicles at a point approaching a problematic zone of the highway (Lin et al., 2004).

1.2 RESEARCH CHALLENGES

The deployment of VSL necessitates the presence of a vehicular detection system transmitting traffic information such as speed, flow and densities in real time. Thus, one of the main challenges of implementing VSL is the high cost associated with the need for such intensive coverage of infrastructure-based vehicle detection systems. Loop detectors are the most commonly used vehicular detection system. However, their installation and maintenance cost and their high frequency of failure are major drawbacks of their use. Other available point detectors are also expensive. Therefore, there is a need for a cost effective way of gathering traffic data.

On the other hand, traffic parameters extracted from point detectors cannot be representative of the whole motorway section. Such readings are not able to adequately indicate the location of shockwave formation, which might occur due to traffic discharged from the on-ramps, lane changing behaviour, or the presence of a slow moving vehicle. This may lead to a sub-optimal solution when using local information to design advanced coordinated traffic control strategies. If traffic information were obtained over the whole motorway section, the traffic control strategies would be able to optimise the traffic on the system from a more network-wide perspective. Thus, intensive detector coverage is needed
to obtain a network-wide monitoring system necessary for the successful deployment of advanced traffic control strategies.

To our knowledge, all VSL algorithms developed take as their input occupancy, speed and flow readings from point vehicular detectors (Hegyi et al., 2003; Lin et al., 2004). With current advancements in positioning and communication technologies, any vehicle that carries a GPS enabled device (e.g. smart phone, navigation device, iPad, and in the future Connected Vehicles, etc.) can act as a mobile sensor (Leduc, 2008). In fact, mobile phone tracking is becoming one of today’s most promising vehicle probe methods for the production of reliable and low-cost network-wide travel time information (Cayford et al., 2006). Data constantly provided from these probes can estimate network wide traffic conditions by constantly providing space mean speed (SMS) information over all motorway sections. Qiu et al. (2007) underlined the promising role that mobile phone detection technology can play for the next generation of traffic data collection. Despite the great deal of controversial debate about the privacy issues surrounding extracting information from these probes, Google Maps Traffic is able to obtain a significant penetration rate for busy highways from drivers carrying a GPS-enabled mobile phone to display traffic updates (Krazit, 2009).

1.3 PROPOSED METHODOLOGY

The main focus of this research is to develop and evaluate the performance of a dynamic VSL algorithm that takes as its only input traffic data from vehicular probes constantly moving on the network. This probe data is capable of detecting shockwave location and intensity and accordingly activates the VSL. The VSL algorithm was formulated to minimise the total time spent (TTS) on the motorway. The presented VSL
methods were then evaluated on a simulated urban motorway segment of 8 km in Calgary, Alberta. Intensive sensitivity analysis was conducted to examine the impact of the following parameters: 1) traffic demand, 2) probe vehicles’ penetration rate, 3) frequency of probe vehicles’ data collection. The performance of the VSL algorithm developed is evaluated for a “normal” traffic condition scenario and “lane closed due to a car accident” scenario. The probe-based algorithm presented was also compared with a conventional VSL algorithm taking traffic information from detectors; however with a much decreased installation and maintenance cost.

1.4 MOTIVATION, GOALS AND CONTRIBUTIONS

Most of the research on probe vehicles is still only focused on traffic state estimation and prediction, with limited effort to exploit this data and use it for traffic control strategies. Pioneering work was initiated by Saidi and Kattan (2010), who extracted data derived from vehicle probes to develop an adaptive ramp metering algorithm. Along the same lines, this research examines the use of data extracted from probes to design an adaptive VSL algorithm. Assuming that the average SMS of vehicles equipped with GPS-enabled mobile phones can be independently obtained during each time step interval on each segment of the motorway; this SMS data is used as input to a proactive VSL.

There has been much research conducted on VSL systems. In the majority of the developed algorithms, point detectors were the most commonly used tools for data collection. Even though detectors are able to provide traffic information, such as occupancy, presence, speed and volume, the information extracted only reflects the traffic conditions in the vicinity of the detector. Thus, intensive detector coverage is needed to provide reliable system-wide monitoring. Since probes acting as mobile sensors are able to
take into account the traffic state on the entire motorway, rather than just localised information; it is expected that advanced traffic motorway control taking input data extracted from probes would be comparable, if not outperform, the point-based detectors.

The main contribution of this research is the development of a proactive VSL algorithm that takes as its only input data collected from probes. The presented VSL constantly monitors the possibility of shockwaves occurring on the motorway from the vehicular probes moving on the network. In the case of significant shockwaves the VSL is activated.

1.5 ORGANISATION OF THESIS

The next chapter of the thesis presents a literature review of previous VSL algorithms. Chapter three presents the probe-based VSL algorithm. The results of the test runs are reported in chapter four, where the evaluation of the VSL algorithm’s performance is conducted and discussed. Conclusions and recommendations for future research are presented in the final chapter.
Chapter 2  LITERATURE REVIEW

2.1 OBJECTIVES OF VSL

The main objective of the installation of VSL is the improvements in safety, which is achieved due to the homogenisation of speeds on a multilane highway, i.e. reduction in speed differences among vehicles in the same lane and reduction in the speed differentiation among adjacent lanes. This reduction in speed variance decreases the probability of collisions. The impact of VSL on traffic safety indicates a reduction in accident numbers by as much as 20–30% after VSL installation (Abdel-Aty et al., 2006). This explains why, in several countries, the selection of motorway segments for VSL installation is solely guided by locations associated with a high incident occurrence.

The other important objective of VSL installation is managing traffic in work zones. Properly managed VSL are shown to reduce the potential of rear-end collision in work zones (Kang, 2003).

Most of the existing literature reviews on VSL focus on the positive impact of VSL on traffic safety. However, the other important objective of VSL installation is managing traffic in work zones. In a recent study, Papageorgiou et al. (2008) analysed real-time information collected during 27 days from a European motorway to examine the VSL impact on aggregate traffic flow behaviour (flow-occupancy diagram).

The main objective was to test the ability of the VSL system to affect the fundamental diagram in accordance with Zackor (1991). Thus, decrease the slope of the flow-occupancy diagram in under critical conditions and enable higher flows at the same occupancy values in overcritical conditions (Figure 2-1).
The results of the analysis of the data showed that the critical occupancy was shifted to higher values due to the application of VSL. The second important conclusion was related to the average speed of traffic flow at undercritical occupancies: the system successfully lowered the average speed, therefore decreasing the traffic flow approaching the area of delay and thus helping delay the activation of bottlenecks. These results indicate that efficient VSL control strategies can improve traffic flow when saturated traffic conditions prevail.

2.2 EXAMPLE OF VSL DEPLOYMENT IN A WORK ZONE

Figure 2-2 gives a schematic example of a motorway segment with 6 VSL sections deployed in the case of a work zone. The VSL systems work based on the following principle: the traffic flow will pass a congestion area in a safe and smooth manner if all the participants slow down to the same speed and maintain it while driving through the area (Hegyi et al., 2005). Therefore, if VSL sensors detect a traffic jam or congestion ahead, a central processing unit dynamically calculates a time-varying optimal speed limit for each VSL sign and displays the information in a timely manner (Lin et al., 2004). By reducing
the speed of the traffic flow, the road users avoid aggressive driving behaviour, which in its turn leads to less number of stops and starts, and a reduction in the number of collisions.

Figure 2-2 Configuration of VSL system for a work-zone scenario (Lin et al., 2004)

2.3 LITERATURE SURVEY

This section reviewed the previous research efforts that have been carried in the literature. Since the first introduction of VSL in 1965, transportation engineers have studied numerous scenarios and applications of these systems in order to evaluate the impact on safety, environment, driving comfort, etc.

Table 2-1 summarises the findings in the literature related to VSL. As the table indicates, most of the studies were conducted in a simulated environment; either microscopic, or macroscopic. The majority of the VSL research is based on simple rule based algorithms. The outcomes from the studies were mostly consistent in showing the safety and mobility benefits in implementing VSL. The sections that follow reviews in more detail the methods that were followed and the outcomes of these studies.
<table>
<thead>
<tr>
<th>Author</th>
<th>Year</th>
<th>Models</th>
<th>Findings</th>
</tr>
</thead>
<tbody>
<tr>
<td>Alessandri et al.</td>
<td>1999</td>
<td>Macrosimulation model, optimisation model</td>
<td>VSL systems have a great impact on density and mean speed behaviour in comparison to a “no control” case</td>
</tr>
<tr>
<td>Lavansiri</td>
<td>2003</td>
<td>Field test, data collection “no VSL” and “ with VSL”</td>
<td>Drivers were compliant with the VSL signs, the total travel time through the work zone was slightly decreased by the VSL control system.</td>
</tr>
<tr>
<td>Lyles et al.</td>
<td>2004</td>
<td>Field test traffic data collection, statistical analysis of the data</td>
<td>Safety and traffic flow were improved.</td>
</tr>
<tr>
<td>Hegyi</td>
<td>2004</td>
<td>METANET macrosimulation model, model predictive control</td>
<td>Coordinated control with continuous speed limits is effective against shockwaves.</td>
</tr>
<tr>
<td>Lin et al.</td>
<td>2004</td>
<td>CORSIM simulation model; two algorithms: 1) to minimise queues “in advance of the work zone area; 2) maximise the workzone throughput</td>
<td>Construction zone throughput and level of safety can be increased with VSL systems.</td>
</tr>
<tr>
<td>Hegyi et al.</td>
<td>2005</td>
<td>METANET macrosimulation model, model predictive control</td>
<td>Ramp metering used in conjunction with VSL systems significantly (up to 16.1%) improves the traffic flow</td>
</tr>
<tr>
<td>Abdel-Aty et al.</td>
<td>2006</td>
<td>PARAMICS simulation model, crash likelihood estimation model</td>
<td>Safety conditions for the “moderate-to-high” (over 37.5 mph) speed case was improved, VSL does not affect the safety in the “low-speed” (below 37.5 mph) case</td>
</tr>
<tr>
<td>Lee et al.</td>
<td>2006</td>
<td>PARAMICS microsimulation model, maximum likelihood estimate (MLE) method</td>
<td>VSL can reduce the crash potential by 5–17%.</td>
</tr>
<tr>
<td>Allaby et al.</td>
<td>2007</td>
<td>PARAMICS microsimulation model</td>
<td>Traffic condition with higher congestions would benefit from VSL system, where traffic with low density would not experience any positive effect from VSL in terms of safety.</td>
</tr>
<tr>
<td>Kamel et al.</td>
<td>2008</td>
<td>METANET simulation model, concept of flatness</td>
<td>Developed a system of VSL and ramp metering; proved that VSL reduced the maximum of the queues at the on ramp.</td>
</tr>
<tr>
<td>Papamichail et al.</td>
<td>2008</td>
<td>METANET simulation model, optimisation by selecting the minimum of TTS function</td>
<td>Reviewed the impact of VSL system and ramp metering on the system; showed traffic system can be significantly improved by VSL systems, especially when used in conjunction with ramp metering.</td>
</tr>
<tr>
<td>Piao and McDonald</td>
<td>2008</td>
<td>AIMSUN microscopic simulation model</td>
<td>VSL reduced the speed difference of cars in the flow and decreased the number of small headways.</td>
</tr>
</tbody>
</table>

Table 2-1 Summary of literature review for VSL algorithms
One of the first pieces of research related to VSL was pioneered by Smulders (1990) who considered VSL systems as tools to avoid or, at least, postpone the occurrence of congestion. The author investigated the impact of a VSL system on driver behaviour and traffic stability on the Dutch Motorway Control and Signalling System in the Netherlands. Based on the traffic flow model, and on a filtering algorithm, the author showed the effectiveness of VSL in stabilising traffic.

Similarly, Alessandri et al. (1999) investigated the influence of VSL systems on traffic conditions using a macrosimulation model. To find the optimal VSL values, the following minimisation problem was formulated and solved using Powell's method:

\[
J = \sum_{t=0}^{T} g(x_t, u_t)
\]

(2.1)

Where: \( t=0,1,2,\ldots,T \) is the time step

\( x_t \) - the state vector, reflecting flows and speeds of the sections

\( u_t \) - the measurement vector, which describes densities and queues

\( g(x_t, u_t) \) - the function penalising the arguments given by the state and measurement vectors.

Formula (2.1) represents any criteria that can be assigned according to a main purpose of an experiment. For instance, if the objective is to find VSL values that would maximise total throughput, then formula (2.1) is presented as follows:

\[
J = \sum_{t=0}^{T} \sum_{i=0}^{K} \rho_i(t)v_i(t)
\]
Where: \( \rho_i(t) \) and \( \upsilon_i(t) \) are traffic density and speed, respectively, on section \( i \) at time step \( t \).

The experiments were conducted through macrosimulation modelling of a stretch of the motorway with five sections and no ramps. The results of the study clearly showed that VSL systems had a great positive impact on smoothing the traffic parameters such as speeds and densities compared to the “no VSL” control case.

Rama (1999) investigated the effect of weather-controlled VSL signs on drivers' compliance behaviour by examining average speed. The results showed that drivers reduce their speed according to the VSL sign information. Previous studies also supported that finding, by showing that drivers tend to comply with VSL signs more often than with fixed signs (Luoma and Rama, 1998). Even though Rama’s study confirmed that VSL systems affected the drivers’ behaviour in a positive way, speed reductions were not sufficient to claim the VMS systems as a “socioeconomically profitable” tool.

Hegyi et al. (2005) considered VSL systems as a method to eliminate or reduce shockwaves in the metastable state traffic condition. Shockwaves occur when the conditions of the vehicle stream suddenly varies. For instance, one car is changing lane, forcing the driver behind to slow down (or even stop) to give right of way. A virtual shockwave will send the “slow down” wave to the drivers behind, affecting one car at a time. Similar shockwaves may occur when traffic flow approaches a car accident area (backward shockwave) or when the flow exits bottleneck into a motorway (forward shockwave). Kerner and Rehborn (1996) devoted one of their research works to the classification of traffic flow states:

- **Stable**: existing traffic demand allows any disturbance to vanish without any additional traffic control actions.
- **Metastable**: traffic demand in which small disturbances will dissolve, large disturbances will lead to shockwaves.

- **Unstable**: traffic demand is such that any disturbance will create a shockwave.

The main concept that was used in Hegyi's work was to compensate or decrease the shockwave that was created by uncontrollable external conditions, such as an accident or construction, by creating an artificial shockwave that would be generated by reducing the speed of the approaching traffic flow. In this research, Hegyi et al. (2005) simulated the model by using “the destination-independent version of the macroscopic traffic-flow model METANET” (Figure 2-3). The problem of optimal coordination was solved by applying the model predictive control (MPC) scheme.

![Figure 2-3 METANET model of a motorway link (Hegyi et al., 2005)](image)

MPC is a method to predict the future behaviour of the system based on the set of inputs, representing the current state of the system, and a cost function that is also called an optimisation criterion (Bellemans, 2002). Most commonly, an objective function is defined as a desired future state of the traffic condition, for instance, the traffic system with maximum throughput possible. The next step of the process is to optimise the desired objective function over the prediction horizon $N_p$ at each time step $k$, considering that the variable message sign value can only change during horizon control $N_c$ ($N_c < N_p$). This
approach helps minimise computational complexity by reducing the number of variables in the system. After the minimisation calculations are completed, the corresponding traffic control values are applied to a dynamic traffic system, and the system shifts one control step forward to start the same optimisation process from the beginning.

The average traffic speed prediction model includes (Hegyi et al., 2003):

1. Mean speed at the previous time step
2. A relaxation term (drivers try to achieve the desired speed $V(k_i(t))$)
3. A convection term (drivers adapt their speed to the average speed of the next section)
4. An anticipation term (anticipation of traffic conditions ahead):

$$v_i(t + 1) = v_i(t) + \frac{T}{\tau} \left( V(k_i(t)) - v_i(t) \right) +$$
$$\frac{T}{L_m} v_i(t) \left( v_{i-1}(t) - v_i(t) \right) - \frac{\eta T}{\tau L} \frac{k_{i+1}(t) - k_i(t)}{k_i(t) + \kappa}$$

Where $V(k_i(t))$:

$$V(k_i(t)) = \min \left( (1 + \alpha)v_{ctrl,i}(t), v_{free} \exp \left[ -\frac{1}{\alpha} \left( \frac{k_i(t)}{k_{crit}} \right)^a \right] \right)$$

The signal values that minimised the following objective function were called “optimal solutions”: 

15
\[ J(k_c) \]
\[
= T \sum_{k=Mk_c}^{M(k_c+N_p)-1} \sum_{(m,i) \in I_{\text{links}}} \rho_{m,i}(k)L_m\lambda_m + \sum_{o \in I_{\text{orig}}} \omega_o(k) \\
+ \alpha_{\text{speed}} \sum_{l=K_c}^{k_c+N_c-1} \sum_{(m,i) \in I_{\text{ctrl}}} \left( \frac{v_{\text{ctrl},m,i}(l) - v_{\text{ctrl},m,i}(1-1)}{v_{\text{free},m}} \right)^2
\]

Where:
- \( \rho_{m,i}(k) \) - traffic density of segment \( i \) (link \( m \)) at time step \( k \)
- \( L_m \) - length of link \( m \)
- \( \lambda_m \) - number of lanes on link \( m \)
- \( \omega_o(k) \) - the queue length at time step \( k \)
- \( \alpha_{\text{speed}} \) - nonnegative weight parameter
- \( v_{\text{ctrl},m,i}(l) \) - speed limit imposed on segment \( i \) (link \( m \)) at time step \( l \)
- \( v_{\text{free},m} \) - free flow speed on link \( m \)
- \( I_{\text{ctrl}} \) - set of \( (m,i) \) where speed control is applied
- \( I_{\text{orig}} \) - number of on-ramps
- \( N_p \) - prediction horizon.

Thus one of the major contributions of Hegyi’s work is the introduction of the MPC approach to control the dynamism of traffic in a proactive fashion. In the MPC approach, the traffic optimisation is repeated after a specified time, with a new data collection set to update the demand prediction based on the prevailing new traffic state. As shown in figure 2-2, the MPC approaches have the advantage of reducing the discrepancy between demand prediction and real demand. Later, many motorway
control algorithms such as ramp metering and other VSL strategies followed this MPC approach.

The MPC developed by Hegyi consists of four main components (Hegyi, 2004):

1. **Prediction**: where the future traffic situation is predicted based on current state, expected disturbances and planned control signal of the system. The prediction is valid for particularly defined time horizon ($N_p$).

2. **Performance evaluation**: where the outputs of the algorithm are evaluated.

3. **Optimisation**: the controller values that would satisfy the optimisation criterion over a certain time horizon (typically, objective function).

4. **Control action**: where at each control step only the first sample of the optimal control is applied to the system. The following samples are calculated in the rolling horizon scheme (Figure 2-4).

![Figure 2-4 Prediction and control horizon (Zegeye et al., 2009)]
The simulation model was run several times for “no-control” and for “MPC based VSL control” scenarios. The results showed that “coordinated control with continuous speed limits is effective against the shockwaves”. To be precise, in the controlled case the shockwave was dissolved in 90 minutes within the research area, whereas in the “no-control” case it stayed throughout the whole link and, therefore, affected the upstream traffic flow.

Another important study, conducted by Hegyi (2004), was the consideration of a complex model that includes the integrated control of both ramp metering and VSL systems. The main objective of this research was to prove that ramp metering used in conjunction with VSL systems could significantly improve traffic flow. Similar to the work described earlier, the MPC scheme was coded in METANET software. To solve the optimisation problem, Hegyi (2004) built an objective function that included a total time spent in the network term for the main stream as well as for on-ramp queues, and terms restricting the abrupt variations for ramp metering and VSL. The values of the ramp meters and VSL that would minimise the objective function would be considered “optimal solutions”. The result of the research confirmed the correctness of the assumption, and was presented by a comparison of two cases: “ramp metering only” and “ramp metering and VSL”. It was proved that the combination of VSL and ramp metering creates a network of the TTS of which is significantly lower (improved by up to 16.1%) than TTS of “ramp metering only”.

Kamel et al. (2008) developed an algorithm to coordinate the operation of ramp metering and VSL systems. A simulation model of a motorway segment that consisted of ten segments was coded in METANET. Discretisation of a LWR traffic model (Lighthill
and Whitham, 1955) was used to build the following system of equations to describe the relationship between variables of flow and density:

\[
\begin{align*}
\rho_i(k + 1) &= \rho_i(k) + \frac{T}{L_i \lambda_i} \times [q_{i-1}(k) - q_i(k)], i \neq 7 \\
\rho_7(k + 1) &= \rho_7(k) + \frac{T}{L_7 \lambda_7} \times [q_{6}(k) - q_7(k) + q_r(k)], i = 7
\end{align*}
\]

Where:  
- \( q_i \) - the flow that leaves segment \( i \) and enters segment \( (i+1) \)  
- \( q_r \) - the flow that leaves the ramp and enters the main  
- \( \rho_i \) - density of segment \( i \)  
- \( L_i \) - length of segment \( i \)  
- \( \lambda_i \) - number of lanes in segment \( i \).

The concept of flatness, introduced by Fliess et al. (1995), was also used in the research. The main property of flat systems is that the state variables and the input of a non-linear system can be presented through “flat outputs” and a finite number of its derivatives (Kamel et al., 2008):

\[
\dot{x}(t) = f(x, u), \quad x \in R^n, u \in R^m
\]

The system is differentially flat if three applications exist: \( h: R^n \times (R^m)^{r+1} \rightarrow R^m \), \( \phi: (R^m)^r \rightarrow R^n \), \( \psi: (R^m)^{r+1} \rightarrow R^m \) such as:

\[
\begin{align*}
y &= h(x, u, \ldots, u^r), \\
x &= \phi(y, \dot{y}, \ldots, \dot{y}^r), \\
u(t) &= \psi(y, \dot{y}, \ldots, \dot{y}^{r+1})
\end{align*}
\]

Where \( r \) is a positive integer. Based on the definition above, flat output \( y(t) \) represents the behaviour of the system \( (x(t), u(t)) \).
Two scenarios were examined: “ramp metering only” and “ramp metering and VSL system”. The result of the test showed that the VSL scenario decreased the number of vehicles entering segment 7, which in turn reduced the maximum length of the queue at the on-ramp.

Papamichail et al. (2008) used the METANET model to code an Advanced Motorway Optimal Control tool, which examines the combination of ramp metering and VSL systems. Figure 2-5 presents the 4.5 km road segment with two on-ramps that was calibrated in METANET and used for the experiments. The whole segment was divided into four links (L₁, L₂, L₃ and L₄):

![Discretised motorway link](Image)

Figure 2-5 Discretised motorway link (Papamichail et al., 2008)

Papamichail et al. (2008) developed a proactive VSL algorithm. The following nonlinear macroscopic discrete-time state-space model was used for the whole network to describe the state of the traffic as a function of disturbances and control inputs affecting it at:

\[
x(k + 1) = f(x(k), u(k), d(k)), x(0) = x₀
\]  

(2.8)
Where: $x$ - state vector (includes $\rho_{m,i}$ – density of segment $i$ of link $m$; $v_{m,i}$ – speed of segment $i$ of link $m$, $w_0$ – queue of origin $o$);

$u$ - control vector (contains $b_m$ – VSL rate of link $m$; $r_0$ – ramp metering rate for origin $o$)

$d$ - disturbance vector (includes $d_0$ – demand at origin $o$; $\beta^m_n$ – turning rate at bifurcation node $n$).

As a criterion for VSL control system optimisation, Papamichail et al. (2008) considered an objective function that describes the total time spent (TTS) by the vehicles in the network as follows:

$$J = T \sum_{k=1}^{K_p-1} \sum_{m} \sum_{i} \rho_{m,i}(k)L_m \lambda_m + T \sum_{k=1}^{K_p-1} \sum_{o} w_o(k)$$

$$+ T \sum_{k=1}^{K_p-1} \sum_{o} \alpha_f [r_o(k) - r_o(k - 1)]^2$$

$$+ T \sum_{k=1}^{K_p-1} \sum_{m} \alpha_b [b_m(k) - b_m(k - 1)]^2$$

$$+ T \sum_{k=1}^{K_p-1} \sum_{o} \alpha_w \left[ \max \{0, w_o(k) - w_{max,o}\} \right]^2$$

Where $\rho_{m,i}(k)$ - density in segment $i$ of link $m$ at a time step $k$

$T$ - time step

$L_m$ - length of link $m$

$\lambda_m$ - number of lanes on link $m$
\( w_o(k) \) - queue at the origin \( o \)

\( w_{max,o} \) - maximum admissible queue for origin \( o \)

\( b_m(k) \) - VSL rate on link \( m \) at time step \( k \)

\( r_o(k) \) - ramp metering rate of origin \( o \)

\( \alpha_f, \alpha_b, \alpha_w \) - weighting factors for the penalty terms.

Therefore, the values of the VSL message signs and ramp metering rates that would result in a minimum value of the objective function were used in the simulation model. To evaluate the benefit of the coordinated VSL and ramp metering control, Papamichail et al. (2008) investigated four different scenarios: no control, coordinated ramp metering only, VSL system only, and ramp metering in conjunction with VSL systems. The study showed that the coordination of VSL and ramp metering control decreased TTS by 44.1% in comparison with the “no control” scenario. The “ramp metering only” case did not provide a significant improvement in the flow (2.7%), whereas the “VSL control only” solution showed a 38.5% improvement.

Lin et al. (2004) presented two algorithms to show the effectiveness of VSL systems in controlling the traffic during construction projects on highways. The first algorithm aimed to reduce the length of a traffic queue “in advance of the work-zone area” by reducing the speed limit. The second one aimed to maximise the total number of vehicles going through the entire construction zone, depending on: drivers’ behaviour (whether or not they complied with the VSL signs), traffic demand and spatial distribution of vehicle speeds. Both algorithms were tested in the CORSIM simulation model. It was shown that under normal traffic conditions, the total number of vehicles going through the
whole construction zone could be increased. Furthermore, lower speed variance between the vehicles in the case of VSL system application was also demonstrated compared to the non-control scenario, which is an indicator of a higher level of safety in the construction area. Therefore, it was concluded that the application of VSL systems to road construction areas provided a promising alternative to existing work-zone traffic operation procedures.

Lavansiri (2003) evaluated the safety benefits of VSL around construction zones by analysing field data on roadwork zones in Michigan. The author used the following measures of effectiveness: average speed, travel time through the work zone, speed variance, and the percentage of higher speed vehicles. The study revealed that the VSL systems worked well in areas where there were no special geometric features that could limit the speed choice of the drivers. The road users were found to be compliant with the VSL signs and to adjust their speeds accordingly. Due to proper speed adjustments the total travel time through work zones was decreased, the reduction ranged from 2.8 to 12.9 seconds. Although the speed adjustments due to VSL system implementation took place, no consistency in the impact on speed variance was observed.

Lyles et al. (2004) implemented a VSL system on a highway in Virginia to control work zones. They used both average speed and occupancy as the control thresholds for displaying the set of speed limits. The VSL control algorithm was rule-based and solely depended on the detected average speed, with no control objective to improve safety or traffic flow. They evaluated the extent to which speed limit compliance is affected and found that the speed limit compliance rate to variable message signs was higher in comparison to compliance rates to fixed signs, safety was improved, and traffic flow was increased.
2.4 FINDINGS OF THE LITERATURE RELATED TO SAFETY IMPROVEMENTS

Does VSL improve the safety on highways? To answer this question, Lee et al. (2006) modeled VSL in a microsimulation model that was integrated with a real-time crash prediction model. The real-time crash model was developed by Lee (2006) “to investigate the nature of the relationship between the selected precursors and frequency of crashes adjusted by the appropriate level of exposure”. This model was developed based on a simple regression model calibrated using real crash and traffic data for a 10km stretch of the Gardiner Expressway in Toronto, Canada. The crash potential model has the following formula:

\[
SCP_i = \frac{1}{n} \sum_{j=1}^{n} CP_{ij}
\]  

(2.10)

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

The PARAMICS model was used to examine the performance of VSL in conjunction with the real-time crash model. The results of the study showed that the real-time VSL systems could reduce the overall crash potential by 5–17%.

Abdel-Aty et al. (2006) also examined the safety benefits of a VSL system on Interstate-4 in Orlando. They used PARAMICS microsimulation model and coded several
scenarios corresponding to “moderate-to-high” speed (above 37.5 mph) and “low-speed” (below 37.5 mph) conditions. Abdel-Aty (2006) evaluated the impact of VSL systems on the crash potential for both scenarios by lowering and raising the value of the speed of the control device. This study suggested that in order to improve safety, VSL systems should not only be used during the congestion period but also during off-peak time. The study also showed an improved travel time during off-peak hours when VSL is in operation.

Piao and McDonald (2008) used AIMSUN microscopic simulation to assess the influence of VSL systems on road safety. The real traffic data was collected via sensors and cameras. Piao and McDonald (2008) observed penetration rates, ranges of speed limits and enforcement levels. They showed that VSL systems resulted in a reduction in the speed difference among the cars in the flow and in a decrease in the number of small headways. These two findings illustrated the safety benefits of implementing VSL.

Allaby et al. (2007) considered the installation of thirteen VSL signs on a 10 km section of the eastbound Queen Elizabeth Way located near Toronto, Canada. The PARAMICS simulation model was used to evaluate the safety and travel time impacts due to the influence of the VSL system. Information about traffic conditions was received every twenty seconds from loop detectors, as shown in Figure 2-6.
The PARAMICS was coded to update the VSL signs with the rule-based scheme as presented in Figure 2-7:

For instance, if the loop detectors indicated that the traffic volume was over 1600 vphpl, depending on the average speed of the vehicles, the VSL sign would show 80 km/h.
or 60 km/h values, or would not be activated at all (in the case of an average speed > 80 km/h). They used the same crash potential model developed by Lee et al. (2006) to evaluate the impact of VSL.

They performed a two-tailed t-test (95% level of confidence) to evaluate the significance of changes in the crash potential parameter (SCP) (comparing non-VSL and VSL cases). In the case of a significant difference, the relative safety benefit (RSF) is calculated according to the following formula (Allaby et al. 2007):

\[
RSB_i = \left( \frac{ASCP_i(non-VSL) - ASCP_i(VSL)}{ASCP_i(non-VSL)} \right) \times 100 \tag{2.11}
\]

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).

In that research, the inputs for the VSL control algorithm were extracted using loop detectors, and the traffic volume threshold was established in order to identify the VSL speed for the future time interval. Using the PARAMICS microsimulation model, Allaby et al. (2007) considered the impact of the VSL system under the following traffic conditions: peak (100%), near peak (90%) and off-peak (75%). It was proven that while the average network travel time during off-peak time was the least affected by the VSL algorithm, the average network travel time during near-peak and peak hours was increased by 25% and 11% respectively. It is important to note that Allaby et al. (2007) researched VSL as an apparatus that would improve traffic safety. Therefore, the average travel time increase is a positive outcome, as slower moving traffic would maintain a higher level of safety. Another
important result was the fact that the VSL system has little influence on the average travel time during off-peak hours.

The result of that study could not provide clear evidence whether the VSL system would consistently improve overall safety; although improved safety resulted under certain traffic scenarios. In other words, traffic condition with higher congestion will benefit from the VSL system. However, low congested traffic with low density will not experience any safety benefits from VSL.

2.5 MOTORWAY FLOW DETECTION TECHNIQUES

The reviewed literature show that the implementation of VSL systems necessitates the real-time collection of traffic data. This section describes two families of data collection methods: point detection and probe-based detection techniques.

2.5.1 Measurements at a point

The majority of commonly used traffic surveillance technologies are pneumatic road tubes, inductive loops, piezoelectric cables, and magnetic sensors (Leduc, 2008). These detectors represent a class of inductive (installed in the pavement) sensors and provide the users with real-time traffic information. Although the cost of the devices is relatively low, their high installation cost and their frequent failure forces traffic engineers to seek alternative data collection methods.

Video image processing represents a class of non-intrusive traffic data collection technology. The device is usually installed on the intersection to capture traffic information for long durations, and to transfer the data to a transportation lab for further analysis. It provides broad detailed traffic information for all the lanes on the road. The main
disadvantage of camera detection is its sensitivity to weather conditions and day-to-night transition (Mimbela and Klein, 2000).

Figure 2-7 Point traffic data detectors: a) Inductive Loop Detectors; b) Video Image Processing Detectors

2.5.2 Probe Vehicle Detection Technology

ITS probe vehicle systems attract constantly growing attention from transportation engineers as a tool for traffic information collection. Probe vehicles are able to provide information about vehicle speed, location and therefore the route the vehicle follows. There are five main types of probe vehicles data collection systems (Travel Time Data Collection Handbook, 1998):

- **Signpost-Based Automatic Vehicle Location (AVL)** where probe vehicles communicate with transmitters mounted on existing signpost structures.
- **Automatic Vehicle Identification (AVI)** where an electronic tag, which is attached to a probe vehicle, communicates with roadside transceivers.
• **Ground-Based Radio Navigation** where probe vehicles communicate with radio tower infrastructure.

• **Cellular Geo-location** where the data is collected by tracking mobile phone call transmission.

• **Global Positioning System (GPS)** where probe vehicles are equipped with GPS receivers. The positional information about probe vehicles is transmitted to a control centre.

Global Positioning Systems (GPS) is a space-based radio positioning system that provides the coordinates and time of any object located on or near the surface of the earth. Therefore, knowing the location and point-to-point travel time, the space mean speed of traffic flow can be easily estimated. D'Este et al. (1999) proved that GPS systems were able to provide reliable data that are good indicators of traffic congestion and can thus derive other traffic parameters. However, satellite orbit errors, atmospheric delays, satellite and receiver clock biases and drifts, etc. can cause stochastic errors in GPS data collection (Yi, 2007). In order to account for such errors, complex mathematical models can be used for error estimation. To keep the complexity of the algorithm presented in this research at a moderate level, the error of a GPS technology was not accounted for. However, it can be a logical extension of this work.

Hellinga et al. (2008) proposed travel time evaluation algorithms where traffic data was received from probe vehicles. As described, probe technology is able to report the location of a vehicle at each time step. Therefore a point of location $\bar{m}_k(t_{k,i}) = (x(t_{k,i}), y(t_{k,i}))$ of a sampled mobile probe is available at time $(t_{k,i})$, where $i=
0,1,… For the research, Hellinga et al. (2008) also completed a map matching process (determining the most likely positions of the vehicles, taking into consideration errors occurring due to the data collection method), which resulted in $m_k(t_{k,i})$ for each $\bar{m}_k(t_{k,i})$. Knowing the approximated location nodes, and therefore the ability to determine the length of the segments between the nodes, Hellinga et al. (2008) proposed the following method to estimate route travel time between two reported locations:

$$t_{k,i+1} - t_{k,i} = \sum_{j=0}^{f(k,i)} \{\tau_f(l_{k,ij}) + \tau_s(l_{k,ij}) + \tau_c(l_{k,ij})\}$$

Where:

$\tau_f(l_{k,ij})$ - free flow travel time for a complete or partial link $(l_{k,ij})$;

$\tau_s(l_{k,ij})$ - stopping time for a complete or partial link $(l_{k,ij})$;

$\tau_c(l_{k,ij})$ - time associated with congestion for $(l_{k,ij})$.

The results of the experiment demonstrated the ability of the algorithm to improve the accuracy of the estimated link travel times in comparison to a benchmark while using data from a simulation model, however it overestimated the travel time parameter for links that were not controlled by any traffic control device.

The cellular geo-location data collection method can potentially become the most common source of reliable real-time data for transportation planning since in 2010 78% of Canadian households had a mobile phone (Toronto Sun, 2011), and this number keeps growing.

The main disadvantage of using probe vehicle detection technology is the privacy issue, as travellers might feel uncomfortable with their vehicle being tracked.

Whereas the main advantages are:
• Low data collection cost
• Electronic data collection (data is automatically transferred to a control centre)
• Data can be collected over large areas
• The data collection process does not affect traffic patterns.

In addition, probe data has a network wide coverage, whereas measurement with point technology only provides information about the vehicles that pass a certain point in the network (location where a point detector is installed). Therefore, probe data provides Space Mean Speed (SMS) traffic parameters, whereas detector-based data collection method records Time Mean Speed (TMS) information. TMS is defined as the arithmetic average of all speeds of all vehicles that passed the same point in the network, whereas SMS identifies an average speed based on the average travel time of the vehicles passing through a segment of a road. It is to be noted that SMS is used in the fundamental traffic flow relationship.

In order to obtain a correct estimation of the traffic situation, it is important to obtain an appropriate sample of data from probe vehicles. If the vehicles in the network all act as probe, the estimation result will be the most accurate (Jiang et al., 2006), which is impossible in real life. The Institute of Transportation Engineers (ITE) used a quality-control theory to build a formula for the minimal probe sample size (Hong et al. 2007):

\[
N = \left(\frac{K}{\sigma e}\right)^2 \tag{1.12}
\]

Where: \( N \) - min number of sample size
\( \sigma \) - estimated sample standard deviation

\( K \) - constant corresponding to a confidence level

\( e \) - permitted error in the average speed estimate.

Hong et al. (2007) ran a simulation model and concluded that 2\% of all the vehicles were required to be probe vehicles in order to obtain “good traffic information integrality” for the system.

2.6 TRAFFIC SIMULATION MODELS OVERVIEW

Based on the level of detail needed, traffic simulation models can be divided into the following categories (Hegyi, 2004):

- **Microscopic**: each vehicle is described individually according to car-following or lane-changing models. The main parameters of the vehicles are “distance to” or “speeds of” the surrounding cars. One of the benefits of microscopic simulation is the possibility of assigning specific characteristics (such as vehicle type, driver’s behaviour) to each of the participants in the network. VISSIM, PARAMICS, AIMSUN2 are examples of microscopic simulation software.

- **Mesoscopic**: the model contains time-varying origin-destination information as well as data about link capacities and queuing models. DynaMIT and DYNASMART are examples of mesoscopic simulation software.

- **Macroscopic**: traffic is described as average flow, average density and average speed. CORSIM is an example of macroscopic simulation software.
Macroscopic and mesoscopic models explain traffic as a fluid. Thus they are not able to describe the capacity drop as it occurs in real networks experiencing traffic breakdown.

2.7 DISCUSSION AND MOTIVATION

As reviewed in the literature, all previous VSL algorithms were based on data collected from point detectors. These point detectors can be expensive to maintain, as they are not economically sustainable. In addition, data collected from point detectors is not able to properly reflect the traffic conditions over the whole motorway section unless a high number of point detectors are installed. The following chapter describes a VSL framework that uses data collected from probe vehicles as the only input parameters to develop a dynamic VSL control strategy.
Chapter 3 FRAMEWORK FOR THE PROBE-BASED VARIABLE SPEED LIMIT APPROACH

This chapter describes the algorithm developed for the Variable Speed Limit (VSL) systems implementation on the main stream of a motorway. The ability to predict future traffic conditions, based on the current one, allows the proactive VSL system to effectively improve traffic conditions by anticipating the possible occurrence of congestion and reacting to it before it occurs. The main input is from probe vehicles that are assumed to continuously provide the algorithm with their space mean speed (SMS) information. SMS data is then fed to the VSL algorithm, which consists of a multi-objective formulation that attempts to minimise over a certain horizon:

- The total time spent in the network (TTS) (including motorway mainline and on-ramps queue); and

- The difference in the VSL value between two consecutive time steps

A rolling horizon approach is adopted. Thus, traffic state is predicted and the objective function is minimised over the future horizon. However, only VSL values corresponding to the earliest time step are considered final and implemented. The PARAMICS microsimulation model was chosen for this research as it allows building of a precise and detailed traffic network, and reflects the realistic traffic situation.

3.1 OVERVIEW OF THE FRAMEWORK AND PROBLEM FORMULATION

Figure 3-1 illustrates a scheme of a motorway section that contains the main stream with several on-ramps. Information on traffic condition on the motorway is collected solely through probe vehicles. It is therefore important to emphasise that no point detectors were
placed on the motorway; the traffic information for the main stream was obtained through 
probe vehicles alone. The average speed of probe vehicles over 60 seconds on each section, 
i, of the motorway is obtained as an estimate of SMS. As the figure shows, traffic detectors 
are installed on the on-ramps to capture the queue length and the flow entering the 
motorway. Thus, each on-ramp had two detectors in place: one check in and one check out 
detector.

Figure 3-1 Example of a schematic motorway section with VSL

Figure 3-2 illustrates the general MPC framework followed for the developed 
proactive probe-based VSL approach. The framework consists of four major interrelated 
components: 1) data input, 2) traffic state estimation and prediction model, 3) an 
optimisation component based on a rolling and prediction horizon and ramp metering 
control and 4) a control action that implements the first step of the optimisation results.

As indicated in the figure, traffic conditions on the motorway are affected by:

1) Existing traffic demand

2) Possible disturbances resulting from random events (e.g. incidents, shock waves, 
slow moving vehicles, etc.) and

3) VSL displays that are obtained from the control.
Assuming that speed data can be obtained during each time step interval and on each segment of the motorway separately, any changes in motorway conditions will be reflected in changes in the speed of vehicles, including vehicle probes, travelling on the motorway.

The VSL control presented is an extension of Hegyi's (2004) algorithm. The presented VSL takes SMS data directly extracted from vehicle probes as input, as opposed to the point detectors data as in Hegyi's (2004) analysis, a macroscopic traffic flow model is used to convert SMS data to density readings as required for the traffic prediction steps,
and the VSL is triggered based on the detection of a significant back propagation of shockwaves as indicated from the SMS of the probe vehicles travelling over the whole motorway and constantly checking of shockwave occurrence.

The following sections illustrate the step-by-step details adopted in the MPC approach as related to traffic input parameters, traffic state prediction, system-wide optimisation and control input.

3.1.1 Traffic input

As shown in figure 3-2, an effective VSL control strategy has to capture the dynamics of the transportation system (i.e. demand fluctuation and occurrence of incidents, weather conditions (i.e. disturbances, etc.)) and be able to be responsive in real time. The PARAMICS microsimulator is used to monitor the demand and to extract traffic data from the simulated probe vehicles. The speed information from the probe vehicles travelling on the motorway is input to a traffic prediction model to predict the demand over a short-term horizon T (i.e. 5 min). Furthermore, the on-ramp detectors determine the vehicle demand on the on-ramps. In other words, the difference between the number of vehicles allowed to enter the motorway during the next time step and the demand arriving at the on-ramp, plus a possible residual queue on the ramp from previous time steps (if not yet served), would determine the length of the queue on the on-ramps.

3.1.2 Traffic state prediction

After the SMS data is received from the simulation, the future traffic states need to be predicted. The predicted traffic state is based on the location of shockwaves, which needs flow and density information as its input. Thus, the algorithm converts the SMS
readings into densities and flows for each section of the motorway based on Van Aerde’s (1995) traffic flow model:

\[ k = \frac{1}{C_1 + \frac{C_2}{U_f - U} + C_3 * U} \quad (3.1) \]

\[ q = \frac{U}{C_1 + \frac{C_2}{U_f - U} + C_3 * U} \quad (3.2) \]

Where:

\[ C_1 = m C_2 \quad (3.3) \]

\[ m = \frac{2 U_c - U_f}{(U_f - U_c)^2} \quad (3.4) \]

\[ C_2 = \frac{1}{k_f \left( m + \frac{1}{U_f} \right)} \quad (3.5) \]

\[ C_3 = \frac{-C_1 + \frac{U_c}{q_c} - \frac{C_2}{U_f - U_c}}{U_c} \quad (3.6) \]

Where:  

- \( U \) - average SMS speed  
- \( C_1 \) - fixed distance headway constant (km)  
- \( C_2 \) - first variable distance headway constant (km^2/h)  
- \( C_3 \) - second variable distance headway constant (h)
The standard flow-density relationship at each time step \( t \) for every section \( i \) is described as follows:

\[
q_i(t) = k_i(t) \cdot v_i(t) \cdot \lambda
\]  
(3.7)

Where:
- \( q_i(t) \) - flow of the segment \( i \) at time step \( t \)
- \( k_i(t) \) - density of the segment \( i \) at time step \( t \)
- \( v_i(t) \) - the predicted mean speed of traffic on segment \( i \) at time step \( t \)
- \( \lambda \) - number of lanes.

The next step determines whether a shockwave has occurred between any two sections of the road. For this purpose the system calculates the speed of the shockwave between sections \( i+1 \) and \( i \): \( W_{i,i+1} \), starting with the downstream sections and working towards the upstream ones:

\[
W_{i,i+1} = \frac{q_{i+1} - q_i}{k_{i+1} - k_i}
\]  
(3.8)

If the algorithm identifies the occurrence of a back propagating shockwave of high intensity, the VSL is triggered. Thus, the system updates the VSL signs in the following conditions:
If $W_{i,i+1} \geq -10$, VSL are not activated. In this case, the displayed speed limits are equal to the current fixed speed limit sign (commonly 100 km/h is used for motorways) or the previously implemented VSL sign.

If $W_{i,i+1} < -10$, then $v_{ctr,i}(t) \in (60, 70, 80, 90, 100)$ a system-wide objective function is optimised (described in section 3.13) over a future horizon.

The threshold of 10 km/h for the shockwave speed was chosen based on trial experiments performed prior to thorough VSL algorithm analysis. The test runs were performed for 0 km/h, 10 km/h and 20 km/h shockwave speed values. The 20 km/h showed insignificant improvements in the traffic system, as the VSL algorithm would be initiated at a late stage where the application of the developed system alone is not enough to positively affect the delay. Alternatively, the VSL algorithm activated at a 0 km/h shockwave speed, creates additional delays at low demands by reducing the values of the variable message signs, when even just a small shockwave (i.e. 0.005 km/h) is sensed by the algorithm.

Next, the traffic state is estimated for the future time step in a rolling horizon fashion. The traffic prediction is conducted based on the principle of traffic conservation, which states that the density of the next time step $(t+1)$ is equal to density of the current time step $t$ plus the inflow minus the outflow (Hegyi et al., 2003):

$$k_i(t + 1) = k_i(t) + \frac{T}{L\lambda}(q_{i-1}(t) - q_i(t))$$

(3.9)

The mean predicted speed for the next time step $(t+1)$ depends on the observed speed at the current time step $t$, which is directly extracted from probe vehicles plus a relaxation term, a convection term, and an anticipation term accordingly (Hegyi et al., 2003). The section's density and throughput are obtained by diverting the observed SMS data using Van Aerde's model (1995).
Formula (3.10) represents the dynamic behaviour of the vehicles in the network based on a simple car following model introduced by Payne in 1971 and modified by Papageorgiou et al. in 1990, according to which the speed in section \( i \) at time step \( (t+1) \) equals the speed at time step \( t \) plus the following components (Bellemans et al., 2002):

- **Relaxation** – term that considers the difference between the desired average speed and the actual speed of a vehicle. For instance, if a driver passes a traffic slowdown area, he will try to accelerate to the speed of the flow after he overpasses the problematic area.

- **Convection** – term that accounts for the speed adjustment of the drivers exiting section \( (i-1) \) and entering section \( i \).

- **Anticipation** – term that accounts for ability of drivers to see traffic condition ahead and adjust their speed accordingly.

\[
v_i(t + 1) = v_i(t) + \frac{T}{\tau} \left( V(k_i(t)) - v_i(t) \right) + \\
\frac{T}{L} v_i(t)(v_{i-1}(t) - v_i(t)) - \\
\eta \frac{T}{\tau L} k_{i+1}(t) - k_i(t) \\
\frac{\tau L}{k_i(t) + \kappa}
\]

Where:  
\( T = 30 \) (sec) - estimation time step size used in this work  
\( L = 8 \) (km) - total length of the highway stretch  
\( \tau = 0.005 \) (h) - constant that indicates the drivers’ swiftness (large \( \tau \) indicates slower reaction)  
\( \kappa = 40 \) (veh/km/lane) - speed anticipation term parameter
\( \eta \) - speed anticipation term parameter (km\(^2\)/h).

To account for the dynamics of drivers' anticipation, parameter \( \eta \) is developed as follows (Hegyi, 2004):

\[
\eta_i(t) = \begin{cases} 
65, & \text{if } k_{i+1}(t) \geq k_i(t) \\
30, & \text{else}
\end{cases}
\]

\( V(k_i(t)) \) is presented as:

\[
V(k_i(t)) = \min \left( (1 + \alpha) v_{ctrl,i}(t), v_{free} \exp \left[ -\frac{1}{\alpha} \left( \frac{k_i(t)}{k_{crit}} \right)^\alpha \right] \right) \quad (3.11)
\]

Where:
- \( v_{ctrl,i}(t) \) - VSL value implemented on segment \( i \) at time step \( t \)
- \( v_{free} \) - free-flow speed of traffic
- \( k_{crit} \) - critical density;
- \( \alpha \) - parameter of the fundamental diagram, taken to be 1.867 (Hegyi, 2004)
- \( (1 + \alpha) \) - non-compliance factor, where \( \alpha \) is taken to be 0.05

The compliance factor is an important parameter to consider in the system, as it is one of uncertainties in the control process. Prediction of human behaviour is a challenging aspect that requires separate thorough investigation. In formula (3.11) a non-compliance factor is introduced to reflect the drivers' target speed (Hegyi, 2004):

- If \( (1 + \alpha) < 1 \), the target speed is lower than the control speed, therefore drivers are compliant with the VSL
- If \( (1 + \alpha) > 1 \), the target speed is higher than the control speed, therefore drivers exceed the VSL.
In addition, for the network sections that include on-ramps, it is important to consider the possible queues forming in the areas of the merge. The length of queue for the next time step $\omega_r(t + 1)$ is the current queue $\omega_r(t)$ plus the demand $d_r(t)$ minus the outflow $q_r(t)$:

$$\omega_r(t + 1) = \omega_r(t) + T(d_r(t) - q_r(t))$$

(3.12)

Where demand $d_r(t)$ and outflow $q_r(t)$ can be extracted from the simulation model by placing two detectors on each on-ramp. It is important to note that $q_r(t)$ is indirectly a function of the control value of VSL at time step $t$ as the number of vehicles that are discharged from the on-ramps to the motorway depends on the capacity of the motorway at time $t$, which in turn is dependent on the posted speed limit at time $t$.

### 3.1.3 System-wide optimisation

In this step, the objective function is formulated and solved. A system-wide optimisation function is then formulated to obtain the VSL control parameters that would minimise the system delays over the short-term horizon $T$ in a rolling horizon fashion of 5 min. As explained previously, VSL is only triggered if the backward propagating shockwave exceeds the value of 10 Kph. In addition, one of the main challenges encountered during the algorithm’s implementation process is to make sure that the speed reduction on a main stream of a highway, occurring due to the VSL system, does not lead to a queue backing up to the on-ramps. If a severe delay on the ramps is created, it causes a major blocking of an upstream traffic. Thus, on-ramp queues should be considered in the
The following objective function as developed by Hegyi et al. (2005) is adopted:

\[
J(t) = T \sum_{i=1}^{\text{Number of sections}} k_i(t)L\lambda + T \sum_{r=1}^{\text{Number of on-ramps}} \omega_r(t) + \alpha_{\text{speed}} \sum_{i=1}^{\text{Number of activated VSL}} \left( \frac{v_{ctrl,i}(t) - v_{ctrl,i}(t-1)}{v_{\text{free}}} \right)
\]  

(3.13)

Where:

- \( k_i(t) \) - density on segment \( i \) at time \( t \)
- \( L \) - length of the segment
- \( \lambda \) - number of lanes on the highway
- \( w_r(t) \) - queue on the ramp \( r \)
- \( v_{ctrl,i}(t) \) - control variable to be determined related to the value of the VMS indicating the speed limit on section \( i \) at time \( t \)
- \( v_{\text{free}} \) - free flow speed of traffic, taken to be 100 (km/h)
- \( \alpha_{\text{speed}} = 2 \) - non-negative parameter, expressing the importance of each term (Hegyi et al., 2005).

The objective function is subject to:

\[
|v_{ctrl,i}(t + 1) - v_{ctrl,i}(t)| \leq 10;
\]

\[
|v_{ctrl,i}(t) - v_{ctrl,i+1}(t)| \leq 10;.
\]

This function attempts to minimise two objective functions:
1. The total time spent in the network

2. The variation of VSL signs for each segment where VSL is implemented, to assure a smooth transition between one displayed VSL and the previous one.

Therefore, the combination of variable message signs that would minimise $J(t)$, will be the optimal solution for the system.

Two following constraints associated with the control speed variations implemented in the algorithm were also maintained:

1. The difference between speed limits displayed on the same variable message sign in two consecutive time steps cannot exceed 10 km/h: $|v_{ctrl,i}(t + 1) - v_{ctrl,i}(t)| \leq 10$;

2. The difference between speed limits displayed on two consecutive variable message signs at time step $t$ cannot exceed 10 km/h:

$$|v_{ctrl,i}(t) - v_{ctrl,i+1}(t)| \leq 10.$$ 

These conditions protect road users from experiencing large changes between speed limits that could be potentially dangerous as it might confuse the drivers and create further shockwaves.

The algorithm computes the total predictive delay over a prediction horizon $N_p$, of 5 min using Brute Force. In other words, it considers all VSL values ($v_{ctrl,i}(t) \in (60, 70, 80, 90, 100)$ in km/h) and chooses the values that would optimise the objective function over which is chosen to be 5 minutes long. To minimise the computational complexity, the control horizon $N_c$ is chosen to be 3 minutes. In other words, all possible combinations of different speed values variations are tested, considering that the values for the 4th and 5th minutes are taken to be the same as the 3rd minute. It is
important to note that the VSL system is able to adjust the variable message sign value every minute if required.

### 3.1.4 Implemented control action

As mentioned previously, in this step only VSL displays corresponding to the earlier time step $t+1$ are considered final and implemented. The remaining steps are re-estimated in the succeeding estimation steps in a rolling horizon fashion. Thus, at each new time instant $t'$ a new optimisation is performed over the prediction horizon $t', \ldots, t'+T$.

### 3.2 CONCLUSION AND SUMMARY

This chapter describes the development of a VSL probe-based algorithm. The algorithm computes the optimal VSL values for the system based on the minimisation of total travel time and the variations in the variable message signs. The combination of these parameters is presented by means of the objective function that is described in step four of the algorithm.

Chapter 4 examines the implementation of the algorithm in the PARAMICS microsimulation model, where the SMS of the vehicles is received from probe vehicles, and used as input.
In this chapter, the VSL algorithm, presented in chapter 3, is tested using the QUADSTONE PARAMICS microsimulation model. The probe-based VSL algorithm is tested on a simulated real urban network in Calgary, Alberta. This motorway section contains various on-ramps and off-ramps.

The PARAMICS Analyser is used to calculate all the following Measures of Effectiveness (MOE):

- Motorway link delay (sec/veh)
- Motorway link travel time (sec/veh)
- Motorway link speed variance (km/h)
- Motorway flow (veh/h)
- Motorway average speed (km/h)
- Density (veh/ln/km)

Intensive sensitivity analysis is conducted to examine the performance of the algorithm developed as affected by several factors: three different levels of congestion, two different incidence occurrence conditions, several percentages of vehicle probe penetration rate and different frequencies of disseminating SMS information. Thus, the first part of this chapter describes the simulation test for “no control” and “VSL algorithm control” scenarios under “normal” conditions. Normal condition, in this case, means that no “artificial” accident or “bad weather” situation takes place. In the second part an “artificial”
accident traffic situation with a lane closure is created for the algorithm performance evaluation. The sensitivity analysis is conducted for the simulation to evaluate the algorithm’s performance based on the following parameters:

- Probe penetration rate (number of vehicles that are probe vehicles in the network 10%, 20%, 40%)
- Traffic demand (80%, 100%, 120%)
- Probe data collection frequency (1 sec, 5 sec, 10 sec).

Table 4-1 below presents the summary of the sensitivity analyses completed in this work:

<table>
<thead>
<tr>
<th>Scenario</th>
<th>Probe-based VSL</th>
<th>Detector-based VSL</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Probe penetration rate (%)</td>
<td>Probe dissemination rate (sec)</td>
</tr>
<tr>
<td>Normal conditions</td>
<td>10, 20, 40</td>
<td>1, 5, 10</td>
</tr>
<tr>
<td>Minor accident (1-lane closure)</td>
<td>10, 20, 40</td>
<td>1</td>
</tr>
<tr>
<td>Major accident (2-lane closure)</td>
<td>40</td>
<td>1</td>
</tr>
<tr>
<td>Probe data from trucks only</td>
<td>1.4, 2.1, 2.8</td>
<td>1</td>
</tr>
<tr>
<td>Probe data from trucks+pas. veh.</td>
<td>10, 20, 40</td>
<td>1</td>
</tr>
</tbody>
</table>

Table 4-1 Summary of sensitivity analyses described in Chapter 4
4.1 NETWORK DESCRIPTION

The north section of Highway 2 (also known as the Deerfoot Trail) in Calgary, Alberta, has always been an area that has experienced large traffic volume and higher than average traffic collisions. It also provides major access to Calgary Downtown, Calgary International Airport and Cross Iron Mills Mall, one of the largest shopping centres in Alberta. According to the City of Calgary’s forecast, the northeast quadrant of the City will be the fastest growing area over the next sixty years, providing housing facilities to almost 125,000 residents (Office of the Mayor, The City of Calgary, 2011). Thus, the high incidence occurrence and the growing congestion on this motorway make it a good candidate for the deployment of VSL.

For the purpose of the research, an 8 km section of the northern segment of the Deerfoot Trail located between McKnight Boulevard and Memorial Drive NE was considered (Figure 4-1). This section has four major on-ramps and off-ramps. The network was simulated in PARAMICS microsimulation software. The data used to calibrate the model was based on existing speed limits, number of lanes and highway geometry, and traffic and travel time data provided by the City of Calgary. An origin-destination matrix was also calibrated using the PARAMICS calibrator to update an out-dated a priori matrix provided by the City, in order to reflect the traffic counts performed by Alberta Transportation in 2009. The calibration of the model is the process of adjusting the model parameters to reduce the difference between observed data and that simulated. Calibration is usually based on a complex gradient approach in conjunction with trial-and-error (Chu et
The completion of the calibration process ensures that the output of the microsimulation model closely reproduces the observed data.

Figure 4-1 The study area (Google Maps)

The stretch of the highway has on average three lanes in each direction, increasing to four lanes downstream of the on-ramps. Currently, there is a fixed speed limit restriction of 100 km/h along the highway. The speed limit is sometimes manually adjusted to 50–80 km/h for a certain period of time by a construction team or a safety crew in the case of an accident. So far, there have been no adaptive traffic control systems introduced that would be able to collect real-time data, evaluate it and adjust the variable message signs in order to improve the current traffic conditions.
In order to apply the presented adaptive VSL system to the study area, an Application Programming Interface (API) was developed for the PARAMICS software (version 6.8.0), as the standard package only includes a pre-timed VSL. The Deerfoot Trail link was divided into six sections, where the first section starts about 100 metres before the on-ramp exiting McKnight Boulevard NE. The sections have the following attributes (Table 4-2):

<table>
<thead>
<tr>
<th>Section number</th>
<th>1</th>
<th>2</th>
<th>3</th>
<th>4</th>
<th>5</th>
<th>6</th>
</tr>
</thead>
<tbody>
<tr>
<td>Length (m)</td>
<td>305.53</td>
<td>742.89</td>
<td>1291.96</td>
<td>2362.18</td>
<td>2086.00</td>
<td>731.67</td>
</tr>
<tr>
<td>Number of lanes</td>
<td>3</td>
<td>3</td>
<td>4</td>
<td>4</td>
<td>3</td>
<td>3</td>
</tr>
</tbody>
</table>

Table 4-2 Description of sections

Sections 2 to 5 contain one on-ramp each. Sections 1 and 6 allow the collection of traffic data at the point of approach and exit of the link accordingly. To collect information on on-ramp queues, two detectors are placed at the entrance and exit of each of the ramps.

The Beacon tool is used in the PARAMICS microsimulation model to simulate the variable message signs. Beacon in PARAMICS is an object that delivers information to the drivers. To avoid long queues forming on the on-ramps, the VSL signs should be placed well in advance (400–700 metres) of each on-ramp, and the best locations out of several test runs were chosen. This forces the traffic that approaches an on-ramp to slow down, and allows the cars exiting to successfully merge into the highway. Thus, variable speed message signs are placed on sections 1, 3, 4 and 5, primarily located before each of the on-
ramps, in order to ease the traffic delay that would occur due to high volume of vehicles entering the highway.

The real-time individual SMS data is collected from the probe vehicles and then converted to SMS for each section and input into the MPC based VSL approach. The percentage of probe data can be easily changed in PARAMICS API through vehicle type. It is important to note that in all runs except in the sensitivity analyses to vehicle compositions, the probe readings are assumed to be extracted from small vehicles only, i.e. passenger cars. Based on the VSL optimisation algorithm evaluation results, API changes the variable speed message sign value if needed. All the VSL algorithms examined correspond to an updated time step of 30 seconds.

All examined runs are conducted for 1 hour and 15 minutes (AM peak for southbound traffic). The first fifteen minutes is a warm up period and is disregarded from the MOE. Thus actual data was collected during the remaining full one-hour peak period. Each of the examined scenarios corresponds to the average of 10 PARAMICS runs with different random seeds. These random numbers are utilised by PARAMICS to calculate different traffic assignment parameters, such as car following, lane changing, route choice, release of demand, etc. Thus, PARAMICS created a dynamic traffic model for each seed number and varying traffic demand on the motorway section. The same set of random seeds was used for the simulation of different scenarios.

4.2 COORDINATED VSL ALGORITHM FOR “NORMAL CONDITIONS” SCENARIO

These runs examine the performance of the presented VSL algorithm under “normal traffic conditions”. In this research, the term “normal condition” is used to indicate
recurrent traffic congestion with no external cause for traffic delays due to non-recurrent congestion (such as lane closure, car accident, etc.). The simulation was run ten times with random seed values for each of three different levels of traffic congestion representing 80%, 100% and 120% of the demand. All scenarios are compared in two cases: a “probe-based VSL” scenario and “no VSL” scenario.

4.2.1 Results for the various congestion levels

The series of runs evaluated the impact of the VSL system on the network considering three different levels of congestion. All the VSL scenarios examined in this section correspond to a penetration rate of the probe vehicles as 40%; in other words only 40% of the vehicles in the network are able to provide the system with speed data. Furthermore, the probe information is collected every second from the probe vehicles.

Table 4-3 contains the average results for the ten runs of the PARAMICS simulation with different seed values and the demand value of 80%. The table shows no significant difference in the resulting delays and travel time in the case of VSL versus the “no VSL” scenario. However, small reductions of traffic flow and speed values (0.23% and 1.2% respectively) resulted with the application of VSL. Only the speed reduction was shown to be statistically significant with a 5% level of confidence. These results indicated that, at moderate congestion, VSL has no significant effect on improving traffic flow, travel time and density, which is expected. Nevertheless, VSL was able to decrease the average speed of the traffic.
Table 4-3 Results for the demand level of 80%

Table 4-4 reports the average results for 10 PARAMICS test runs with the demand of 100% for each of the cases: “no VSL”, and “VSL” algorithm. The change is presented by percentage in comparison with the “no VSL” scenario. The results indicate that even though the VSL system caused a slight increase in traffic delay and travel time, of 4.2% and 7.7% respectively, it managed to significantly decrease the average speed limit by 3.5% (statistically significant with a 5% level of confidence) and its variance by 2.1%. These latter findings indicate the efficiency of the probe-based VSL in harmonising speed over the motorway section; which is an indication of improved safety conditions.

Table 4-4 Results for the demand level of 100%

Table 4-5 summarises the results of ten runs with different seed values for the case where the network demand is equal to 120%. A slight decrease in traffic delay (i.e. 1.2%)
and in travel time (0.39%) are shown to result from the probe-based VSL. A statistically significant reduction of 8.1% in the average speed and its corresponding standard deviation (4.4%) also resulted from the application of the probe-based VSL compared to the “no VSL” case (statistically significant at a 5% confidence level).

<table>
<thead>
<tr>
<th></th>
<th>Mainline delay (sec/veh)</th>
<th>Traffic flow (veh/h)</th>
<th>Average speed (km/h)</th>
<th>Variance of speed (km/h)</th>
<th>Travel time (sec/veh)</th>
<th>Density (veh/ln/km)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Average (no VSL)</td>
<td>503</td>
<td>4223</td>
<td>66</td>
<td>29.8</td>
<td>766</td>
<td>44</td>
</tr>
<tr>
<td>Average (VSL)</td>
<td>497</td>
<td>4212</td>
<td>60</td>
<td>28.5</td>
<td>763</td>
<td>44</td>
</tr>
<tr>
<td>Change (%)</td>
<td>-1.2%</td>
<td>-0.26%</td>
<td>-8.1%</td>
<td>-4.4%</td>
<td>-0.39%</td>
<td>-0.88%</td>
</tr>
</tbody>
</table>

Table 4-5 Results for the demand level of 120%

The above runs show that the probe-based VSL strategies result in more pronounced speed limit reductions at higher congestion traffic levels. Therefore, the VSL equipment implemented on a low congested highway would not compensate for the installation cost in terms of traffic quality improvement. In other words, the performance of such a system at the low level of traffic demand would not differ from the “no control” scenario, and might possibly make the traffic situation worse.

These runs confirm the findings that were previously presented by Allaby et al. (2007), who demonstrated an increased average network travel time during near-peak periods. It is important to note that Allaby et al. (2007) researched VSL as an apparatus that would improve traffic safety. Therefore, the average travel time increase was considered a positive outcome, as slower moving traffic would maintain a higher level of safety. Another
supportive finding from Allaby et al. (2007) is that the VSL system has little influence on the average travel time during off-peak hours.

4.2.2 Percentage of probe penetration rate sensitivity analysis

The main objective of this section is to investigate the impact of probe penetration rate on the performance of the algorithm. As discussed previously, advanced positioning and tracking technologies allow identifying the location and speed of vehicles by using GPS technology. For example, Google Maps real time traffic information is based on mobile phone detection as modern mobile phones contain a GPS, and the reliability of Google Map reports depend on a number of GPS vehicles detected in a traffic flow.

The percentage of the probe vehicles that provide their speed and travel time information is changed through the PARAMICS interfaces. Three levels of penetration rates of 10%, 20% and 40% were examined. In the previous runs, the VSL algorithm developed was shown to positively affect the traffic under “normal conditions”, mostly at higher demands. Therefore, the traffic volume corresponding to the demands of 100% and 120% are considered in this section. Similarly to the previous analysis, speed data is collected every second, each scenario is run ten times with random seed values and evaluated according to the same measures of effectiveness (MOEs): traffic flow, density, average speed, speed variance, travel time and delay. Table 4-7 summarises the data analysis performed based on the outputs of the tests for 100% demand:
<table>
<thead>
<tr>
<th>Probe penetration rate</th>
<th>Mainline delay (sec/veh)</th>
<th>Average speed (km/h)</th>
<th>Traffic flow (veh/h)</th>
<th>Variance of speed (km/h)</th>
<th>Travel time (sec/veh)</th>
<th>Density (veh/ln/km)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Average (no VSL)</td>
<td>335</td>
<td>75</td>
<td>4315</td>
<td>24.2</td>
<td>570</td>
<td>39</td>
</tr>
<tr>
<td>Average (10%)</td>
<td>349</td>
<td>73</td>
<td>4288</td>
<td>23.9</td>
<td>614</td>
<td>39</td>
</tr>
<tr>
<td>Average (20%)</td>
<td>317</td>
<td>73</td>
<td>4320</td>
<td>23.9</td>
<td>581</td>
<td>39</td>
</tr>
<tr>
<td>Average (40%)</td>
<td>349</td>
<td>73</td>
<td>4299</td>
<td>23.7</td>
<td>614</td>
<td>39</td>
</tr>
</tbody>
</table>

Table 4-6 Results for the probe penetration rate sensitivity analysis for 100% demand

In the previous part of this chapter, it was demonstrated that the VSL algorithm was able to significantly reduce the average speed of traffic flow under “normal conditions”, and therefore improve the level of drivers’ safety. The results, presented in Table 4-6, confirmed the previous observations by showing statistically significant (with a 5% level of confidence) average speed reduction of 3.4%, 3.6% and 3.5% in the cases of 10%, 20% and 40% probe penetration rates, respectively, in comparison to the “no control” scenario. Furthermore, the VSL system was observed to substantially reduce the speed variances by 1.4%, 1.6% and 2.2% for 10%, 20% and 40% probe penetration rates, accordingly, in respect to “no VSL”.

In terms of traffic flow and average delay on the motorway, only the VSL system receiving the data from 20% of probe vehicles showed improvements of 5.4% and 0.1% for average delay and traffic flow, respectively, whereas the VSL with 10% and 40% probe vehicles increased the delay by 4.2% in each case, and decreased traffic flow by 0.6% and 0.4% for 10% and 40% probes, respectively, in comparison to the “no control” case. It is important to note that the difference in results for the delay and traffic flow parameters for the 100% demand did not show statistical significance in comparison to the “no VSL”
scenario as well as among themselves. Thus, a 10% probe penetration rate is sufficient to design these VSL systems.

The next step is to evaluate the sensitivity of the developed VSL algorithm to probe information penetration rates in the case of “normal condition” and at 120% demand. The results are summarised in Table 4-7:

<table>
<thead>
<tr>
<th>Probe penetration rate</th>
<th>Mainline delay (sec/veh)</th>
<th>Average speed (km/h)</th>
<th>Traffic flow (veh/h)</th>
<th>Variance of speed (km/h)</th>
<th>Travel time (sec/veh)</th>
<th>Density (veh/ln/km)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Average (no VSL)</td>
<td>503</td>
<td>67</td>
<td>4223</td>
<td>29.8</td>
<td>766</td>
<td>44</td>
</tr>
<tr>
<td>Average (10%)</td>
<td>497</td>
<td>63</td>
<td>4218</td>
<td>29.2</td>
<td>763</td>
<td>44</td>
</tr>
<tr>
<td>Average (20%)</td>
<td>492</td>
<td>63</td>
<td>4245</td>
<td>30.6</td>
<td>758</td>
<td>44</td>
</tr>
<tr>
<td>Average (40%)</td>
<td>497</td>
<td>60</td>
<td>4212</td>
<td>28.5</td>
<td>764</td>
<td>44</td>
</tr>
</tbody>
</table>

Table 4-7 Results for the probe penetration rate sensitivity analysis for 120% demand

Compared to the “no VSL” scenario, the results show a slight reduction in traffic delay of 1.2%, 2.2% and 1.2% in the cases of 10%, 20% and 40% probe penetration rates respectively. Similarly, the main motorway travel time is improved by 0.4%, 1.04% and 0.3% for 10%, 20% and 40% probe penetration rate cases, respectively.

The average traffic delay obtained for the case of the 20% probe penetration rate turned out to be slightly lower than the other probe penetration rate conditions. In other words, 1.0% reduction in delays was identified compared to the 10% and 40% probe penetration rates.

In the case of the 20% probe penetration rate, the travel time parameter showed an improvement of 0.7% and 0.8% in comparison to 10% and 40% probe penetration rate
scenarios accordingly. None of the improvements in traffic delay and travel time described above showed statistical significance at the 5% level of confidence.

In terms of the average speed of the traffic, it appeared to be significantly decreased (5% level of confidence) by 4.3%, 4.6% and 8.1% in the cases of the 10%, 20% and 40% probe penetration rates, respectively, due to the VSL algorithm application.

In summary, these runs indicate a slight sensitivity of the algorithm to the penetration rate. However, it is important to note that even with only 10% penetration rate the probe-based VSL is shown to result in significant improvement compared to the “no VSL” case.

4.2.3 Sensitivity analysis of frequency of disseminating speed information

In the previous experiments, the probe vehicles were assumed to transmit their positioning and speed information at a frequency of 1 second. In this section, the performance of the probe-based VSL was examined at three different frequencies of information dissemination of 1 sec, 5 sec and 10 sec. For the purpose of this test, the runs were conducted at 100% and 120% demand with a 40% probe vehicle penetration rate. The simulation was tested ten times for each case with different seed values. Table 4-8 and Table 4-9 report the outcome of the simulation runs, the results for the “no VSL” are shown for comparison.

<table>
<thead>
<tr>
<th>Dissemination rate</th>
<th>Mainline delay (sec)</th>
<th>Traffic flow (veh/h)</th>
<th>Average speed (km/h)</th>
<th>Variance of speed (km/h)</th>
<th>Travel time (sec/veh)</th>
<th>Density (veh/ln/km)</th>
</tr>
</thead>
<tbody>
<tr>
<td>No VSL</td>
<td>335</td>
<td>4315</td>
<td>75</td>
<td>24.2</td>
<td>570</td>
<td>39</td>
</tr>
<tr>
<td>Average (1 sec)</td>
<td>349</td>
<td>4299</td>
<td>73</td>
<td>23.7</td>
<td>614</td>
<td>39</td>
</tr>
<tr>
<td>Average (5 sec)</td>
<td>319</td>
<td>4353</td>
<td>73</td>
<td>23.7</td>
<td>583</td>
<td>39</td>
</tr>
<tr>
<td>Average (10 sec)</td>
<td>325</td>
<td>4339</td>
<td>72</td>
<td>25.0</td>
<td>589</td>
<td>39</td>
</tr>
</tbody>
</table>

Table 4-8 Results for the probe data extraction frequency rate analysis for 100% demand
From Table 4-8, the motorway delay was the most affected when the VSL system received the traffic updates every 5 seconds. It reduced the average delay by 4.8%, whereas the VSL with updates every 10 sec decreased the delay by 3.0%. The VSL with updates every 1 sec, in fact, increased the average delay by 4.2% in comparison to the “no control” scenario. However, none of these changes in traffic delay due to the VSL system application showed a statistically significant difference (with a 5% level of confidence) in comparison to the “no VSL” case and among themselves. Similar observations were registered for the travel time on the motorway, average throughput and traffic density: even though the VSL that collected data every 5 sec seemed to provide better output than the case of 1 sec and 10 sec, the differences in results are not significant.

The VSL system developed showed an enhancement in the safety level of the highway by significantly reducing the average speed limit by 3.5%, 3.7% and 3.8% in the cases of 1 sec, 5 sec and 10 sec data collection frequencies, respectively, in comparison to the “no VSL” scenario. It is important to note that no significant change in average speed limit values was observed among the reviewed frequencies (with a 5% level of confidence).

Table 4-9 presents the results of the similar experiments for the 120% traffic demand in the network:

<table>
<thead>
<tr>
<th>Dissemination rate</th>
<th>Mainline delay (sec)</th>
<th>Traffic flow (veh/h)</th>
<th>Average speed (km/h)</th>
<th>Variance of speed (km/h)</th>
<th>Travel time (sec/veh)</th>
<th>Density (veh/km)</th>
</tr>
</thead>
<tbody>
<tr>
<td>No VSL</td>
<td>503</td>
<td>4223</td>
<td>66</td>
<td>29.8</td>
<td>766</td>
<td>44</td>
</tr>
<tr>
<td>Average (1 sec)</td>
<td>497</td>
<td>4212</td>
<td>60</td>
<td>28.5</td>
<td>763</td>
<td>44</td>
</tr>
<tr>
<td>Average (5 sec)</td>
<td>477</td>
<td>4262</td>
<td>64</td>
<td>29.1</td>
<td>743</td>
<td>44</td>
</tr>
<tr>
<td>Average (10 sec)</td>
<td>462</td>
<td>4264</td>
<td>63</td>
<td>28.7</td>
<td>728</td>
<td>44</td>
</tr>
</tbody>
</table>

Table 4-9 Results for the probe data extraction frequency rate analysis for 120% demand
From Table 4-9 it can be seen that the most improved traffic condition occurred when the probe information was received every ten seconds, as opposed to every one and every five seconds. In case of 10 sec frequency, the average delay was reduced by 3.1% and 7.0% compared to 5 sec and 1 sec frequencies, respectively. However, only delay difference between 10 sec and 1 sec data collection method showed statistical significance with a 5% level of confidence.

The following results related to changes in traffic flow conditions are obtained for the test runs. In the case of 10 sec probe-speed update frequency, traffic flow is shown to increase by 0.05% and 1.2% only, in comparison to the 5 and 1 sec updates, respectively; that is not statistically significant at a 5% level of confidence. However, 1.2% traffic flow improvement in the case of the 5 sec update in comparison to the 1 sec update is proven to be significant with the same level of confidence.

Although, the average speed values for all three cases show similar values, the value of average speed and its variance is more reduced for the case of every 1 sec speed information update, which is statistically significant at a 5% level of confidence, in comparison to the “no VSL” scenario. Therefore, higher safety benefits are expected to result in the case of the most frequent probe information collection rate for the 120% demand scenario.

In summary, the results show a significant decrease in average speed for all three data collection frequencies. Furthermore, the variance of speed is also shown to drop significantly for all update rates tested. These runs indicate the sensitivity of the algorithm to the frequency of information dissemination. However, it is important to note that the probe-based VSL is shown to result in significant improvement for 1 sec, 5 sec and 10 sec data dissemination rates compared to the “no VSL” case.
4.3 COORDINATED VSL ALGORITHM FOR A “MINOR ACCIDENT” SCENARIO

The second part of this chapter is devoted to the performance evaluation of the probe-based VSL algorithm in the case on non-recurrent congestion occurring on the motorway. Car collisions or road construction can be examples of such conditions. Such an event would result in temporary lane closures and, depending on the severity of the incident, one or in some cases two lane closures might take place. To model such a traffic situation, a lane at the end of the Deerfoot Trail stretch is blocked through the PARAMICS simulation model interface. The lane is located on the left-hand side of the three-lane highway and is approximately 138 meters long. For each scenario, statistics are calculated and averaged over ten runs to estimate performance results. Based on the important conclusion about the efficiency of receiving probe data on an every second basis in part 4.2.3, the sensitivity analyses in this part are completed assuming the probe penetration rate to be one second. To complete the sensitivity analyses, the same performance measures are extracted and analysed.

It is important to note that the PARAMICS simulation model, presented in this work, reflects AM traffic observations performed in 2009 by Alberta Transportation. Therefore, in addition to a lane closure, delays occurring on the off-ramps by vehicles exiting the highway contribute to the overall traffic congestion conditions. For instance, exits to Memorial Drive and 16 Avenue carry a large volume of traffic in the mornings as these streets allow the drivers to access the downtown area of Calgary.
4.3.1 Traffic demand sensitivity analysis for a 10% probe penetration rate

This part of the research reports the results for numerous simulation runs where the probe penetration rate is assumed to be 10%. The demand parameter varies and is taken to be 80%, 100% and 120% in order to review the impact that the algorithm has on the system under different traffic conditions. Table 4-10 presents the summary of the tests:

<table>
<thead>
<tr>
<th></th>
<th>Mainline delay (sec/veh)</th>
<th>Traffic flow (veh/h)</th>
<th>Average speed (km/h)</th>
<th>Variance of speed (km/h)</th>
<th>Travel time (sec/veh)</th>
<th>Density (veh/ln/km)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Average (no VSL)</td>
<td>689</td>
<td>3241</td>
<td>68</td>
<td>29.8</td>
<td>950</td>
<td>36</td>
</tr>
<tr>
<td>Average (VSL)</td>
<td>532</td>
<td>3460</td>
<td>66</td>
<td>27.5</td>
<td>796</td>
<td>36</td>
</tr>
<tr>
<td>Change (%)</td>
<td>-22.8%</td>
<td>+6.8%</td>
<td>-2.9%</td>
<td>-7.7%</td>
<td>-16.2%</td>
<td>+0.8%</td>
</tr>
</tbody>
</table>

Table 4-10 Test runs for 80% traffic demand condition and one lane closure (10% probe penetration rate)

Table 4-10 shows a significant improvement in road conditions in the case of an activate VSL system in comparison to the “no VSL” scenario. The developed system manages to slightly decrease the average speed limit of the traffic, which resulted in a significant improvement in traffic throughput (i.e. 6.8%), decreased delays (22.8%) and decreased the average travel time on the main motorway (16.2%). These outcomes indicate the promising results of the VSL system’s capability in managing traffic delays due to construction or accidents, when the total traffic demand is less than 100%. Therefore, it can be successfully used to control non-recurrent congestion due to an incident that occurs at moderate congestion. For instance, most of the road repair operations are scheduled for the daytime or nighttime, when the traffic is expected to run at the lowest volume possible.

For the next step of the analysis the total demand is increased to 100%, and the results are summarised in Table 4-11:
Table 4-11 Test runs for 100% traffic demand condition (10% probe penetration rate)

In these runs, the probe-based VSL is shown to result in significant reductions in delays on the main stream by 15.3%, a substantial decrease in travel time by 11.7% and an increase in traffic throughput by 7.8%. The overall average traffic speed is slightly (4.5%) lowered by the VSL system. However, the variance of speed is reduced which shows the likely safety benefits associated with VSL implementation. Thus, the VSL algorithm is effective in improving traffic conditions; however the percentage improvements are slightly lowered than in the case of lower traffic demand conditions.

Table 4-12 represents the summary for test runs corresponding to severely high congestion levels of 120%:

Table 4-12 Test runs for 120% traffic demand condition (10% probe penetration rate)
The results show that the VSL algorithm slightly decreases the traffic delay and travel time on the main stream. However that was not statistically significant (with a 5% confidence level), whereas a 5.1% increase in traffic flow, 8.1% increase in density and 11.3% reduction in average speed of the vehicles are significant at the same level of confidence.

In summary, it can be concluded that the VSL algorithm, developed for the Deerfoot Trail NE area, performs better during off-peak time in comparison to the AM peak period in the case of a lane closure. These findings are expected since little can be done at severe congestion levels resulting from both high congestion and lane closure. In such situations, other traffic management solutions such as adaptive ramp metering and ATIS can work in conjunction with VSL to effectively alleviate congestion. However, that is out of the scope of this research.

It is interesting to note that the results of these runs were not consistent with the previous runs discussed in section 4.2, where the cases of “no accident” or “normal traffic condition” were reviewed. This paradox can be explained by the following. In both cases scenarios a large volume of vehicles exiting the motorway through Memorial Drive was observed. As was mentioned previously, Memorial Drive allows drivers to reach downtown destinations, which explains the high volume during the AM period. When the vehicles queue at the off-ramp, it creates a delay for vehicles merging into the main stream from the previous on-ramp. According to the coded VSL logic, VSL is triggered once the SMS from vehicle probes sense the presence of a shockwave (Chapter 3). In the case of “normal traffic conditions” such shockwave occurrence would activate the algorithm, but it does not necessarily need it, especially at low demand levels, as traffic is still in a stable condition. In the case of the “car accident” scenario, in addition to a naturally created traffic delay,
artificially simulated lane closure takes place at the end of the highway stretch. Therefore, traffic evolves into unstable condition at a higher level of demand (120%), where the effect of the VSL system becomes minimal.

In terms of the variation of parameters, it can be noticed that the higher the level of demand, the larger the value of standard deviation. This trend can be justified by the following. The vehicles enter the study area at free flow speed (approximately 100 km/h) and encounter a serious delay caused by off-ramp and on-ramp queues, and a closed lane, which would result in more pronounced shockwaves. The higher the demand (i.e. 120%), the larger the number of vehicles on the motorway, therefore the higher the speed variance expected.

4.3.2 Probe penetration rate sensitivity analysis

The next important aspect considered in this work is the behaviour of the VSL system in response to different rates of probe vehicles penetration rates. The same concept is used for the VSL probe-based approach, where the performance of the algorithm is tested with various congestion levels and various penetration rates for the case of one lane closure.

4.3.2.1. Sensitivity analysis for 80% traffic demand

Table 4-13 contains the results for 80% traffic demand condition, taking three different values of probe penetration rate (10%, 20% and 40%):
Table 4-13 Probe penetration rate sensitivity analysis results for 80% demand (with one lane closure)

<table>
<thead>
<tr>
<th>Probe penetration rate</th>
<th>Mainline delay (sec/veh)</th>
<th>Traffic flow (veh/h)</th>
<th>Average speed (km/h)</th>
<th>Variance of speed (km/h)</th>
<th>Travel time (sec/veh)</th>
<th>Density (veh/ln/km)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Average (no VSL)</td>
<td>689</td>
<td>3241</td>
<td>68</td>
<td>29.8</td>
<td>950</td>
<td>36</td>
</tr>
<tr>
<td>Average (10%)</td>
<td>532</td>
<td>3460</td>
<td>66</td>
<td>27.5</td>
<td>796</td>
<td>36</td>
</tr>
<tr>
<td>Average (20%)</td>
<td>491</td>
<td>3502</td>
<td>68</td>
<td>27.2</td>
<td>754</td>
<td>35</td>
</tr>
<tr>
<td>Average (40%)</td>
<td>577</td>
<td>3358</td>
<td>67</td>
<td>29.03</td>
<td>841</td>
<td>36</td>
</tr>
</tbody>
</table>

For the 80% level of demand in the network, the VSL algorithm shows significant traffic condition improvements on the main stream at all three probe vehicle penetration rate values, in comparison to the “no control” scenario. In terms of traffic delay, the VSL is able to decrease the value by 22.8%, 28.7% and 16.3% in the cases of 10%, 20% and 40% amount of vehicles that are able to distribute speed information respectively in comparison to the “no VSL” output. The application of the algorithm also shows substantial improvement in traffic flow on the main stream: 6.8%, 8.1% and 3.6%, respectively, for the 10%, 20% and 40% probe frequency rates. The travel time parameter reaches the highest number in the case when no VSL algorithm is implemented, whereas the average travel time is decreased by 16.2%, 20.6% and 11.5% when the probe vehicles penetration rate is 10%, 20% and 40% respectively. As observed, the average speed and speed variations stay in the same range for all three parameter scenarios. Although the result of the two-tailed T-test showed no significant difference in average speeds and densities, the average speed was observed to be 77–80 km/h with variations of 27.2–29.8 km/h thus, it can be concluded that at 80% demand the traffic condition is overall safe in these test runs.
It is important to emphasise that, as expected, different results of the VSL system are produced based on the different number of available probe readings. This shows that the probe-based VSL strategy is sensitive to the penetration rate. However, for all penetration rate scenarios examined, the resulting MOEs were consistently improved compared to the “no VSL” scenario. In addition, the results of the runs were not shown to be significantly different when comparing the 40% probe penetration rate (with a 5% level of confidence) to the 10% value of penetration rate. For instance, in terms of traffic flow, VSL improves the level of stability by decreasing the variation of the parameter’s value. Figure 4-2, Figure 4-3, Figure 4-4 and Figure 4-5 present the traffic flow diagrams for the “no VSL”; and “VSL” with 10%, 20% and 40% probe penetration rate tests respectively:

Figure 4-2 Traffic flow distribution under “no control” condition at 80% demand
Figure 4-3 Traffic flow distribution for VSL algorithm with 10% probe penetration rate and 80% demand.

Figure 4-4 Traffic flow distribution for VSL algorithm with 20% probe penetration rate and 80% demand.
Figure 4-5 Traffic flow distribution for VSL algorithm with 40% probe penetration rate and 80% demand

From the figures it can be observed that the VSL algorithm substantially suppressed the variation in the traffic flow value at 10% and 20% probe data availability. The delay that can be clearly seen from Figure 4-2 is caused by a lane closure in the area of the Memorial Drive off-ramp and by traffic merging into the highway from 16 Avenue NE as discussed previously. The VSL system was able to stabilise the traffic flow in the problematic area and allowed a larger number of vehicles to pass through the area in comparison to the ‘no control” scenario. It is important to note that the traffic demand is at 80% for these tests, which also contributes to the ability of the VSL algorithm to recover the road conditions.

4.3.2.2. Sensitivity analysis for 100% traffic demand with one lane closure

These runs examine the performance of the VSL strategies developed during AM peak hours (100% demand) with three different probe penetration rate values (10%, 20%
and 40%). For this purpose, ten runs of the simulation software are performed with random seed values, and the results are reported in Table 4-14:

<table>
<thead>
<tr>
<th>Probe penetration rate</th>
<th>Mainline delay (sec/veh)</th>
<th>Traffic flow (veh/h)</th>
<th>Average speed (km/h)</th>
<th>Variance of speed (km/h)</th>
<th>Travel time (sec/veh)</th>
<th>Density (veh/ln/km)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Average (no VSL)</td>
<td>929</td>
<td>3123</td>
<td>57</td>
<td>35.6</td>
<td>1192</td>
<td>41</td>
</tr>
<tr>
<td>Average (10%)</td>
<td>787</td>
<td>3367</td>
<td>54</td>
<td>33.7</td>
<td>1053</td>
<td>42</td>
</tr>
<tr>
<td>Average (20%)</td>
<td>855</td>
<td>3319</td>
<td>53</td>
<td>33.6</td>
<td>1121</td>
<td>42</td>
</tr>
<tr>
<td>Average (40%)</td>
<td>866</td>
<td>3234</td>
<td>54</td>
<td>34.7</td>
<td>1132</td>
<td>41</td>
</tr>
</tbody>
</table>

Table 4-14 Probe penetration rate sensitivity analysis results for 100% demand

In the case of 100% traffic demand, the VSL system showed a significant improvement in traffic flow, delay and travel time for all probe vehicles penetration rates reviewed in comparison to the “no control” scenario. From Table 4-14, the implementation of the control system affects the average delay of traffic on the motorway the most when the probe speed information was collected through 10% of all road users, and reduced the value by 15.3%, which is a significant improvement with a 5% level of confidence. Even though the VSL system with 20% and 40% probes penetration rate parameters did not show as high an impact, it still decreased the average delay by 8.0% and 6.8%, respectively, which is also significant with the same level of confidence in comparison to the “no control” case. The VSL system also noticeably increased the number of vehicles that was able to pass through the zone of delay by improving the flow of the traffic by 7.8%, 6.3%, and 3.6% in cases of 10%, 20% and 40% probe populations, respectively. It is important to emphasise that even though, the statistical evaluation of traffic flow data showed that the improvement in the case of the 10% probe data in comparison to the 20% probe data is not significant, each of them significantly increased the flow in comparison to the “no control
In addition, the average travel time of the main stream was also positively affected by the control system by demonstrating a substantial reduction of 11.7%, 6.0% and 5.0% for the 10%, 20% and 40% probes penetration rates, respectively. All the test runs revealed a significant (with a 5% level of confidence) improvement in traffic travel time with respect to the “no control” scenario, with the exception of experiments with the 20% penetration rate parameter, which showed a marginally significant difference.

Figures 4-6 to 4-8 present the travel time percentage difference for 10%, 20% and 40% probes penetration rates tests in comparison to the “no VSL” scenario respectively:

Figure 4-6 Travel time percentage difference for “no VSL” scenario in comparison to 10% probes penetration rate scenario (100% demand)
The overall results for the 100% traffic demand proved the efficiency of the VSL system as a tool to reduce traffic disturbances on the Deefoot Trail NE. Even though, the case of 20% probes penetration rate did not present a significant improvement in traffic
travel time, it substantially reduced the average delay and increased the traffic flow rate. In terms of the average speed on the highway, the VSL system that had 40% of probe vehicles available significantly reduced the average speed by 4.9%, whereas a speed reduction of 6.2% occurred due to the VSL with 20% probes is marginally significant. The average speed on the highway was proved to remain around 60 km/h with an approximate variation of 33 km/h. These numbers show that the road condition remained relatively safe.

4.3.2.3. Sensitivity analysis for 120% traffic demand

The next step in the research is to complete the test runs for the case when the traffic demand is 120%. Table 4-15 reports the results of the experiments for this case:

<table>
<thead>
<tr>
<th>Probe penetration rate</th>
<th>Mainline delay (sec/veh)</th>
<th>Traffic flow (veh/h)</th>
<th>Average speed (km/h)</th>
<th>Variance of speed (km/h)</th>
<th>Travel time (sec/veh)</th>
<th>Density (veh/ln/km)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Average (no VSL)</td>
<td>964</td>
<td>3072</td>
<td>57</td>
<td>36.1</td>
<td>1227</td>
<td>40</td>
</tr>
<tr>
<td>Average (10%)</td>
<td>927</td>
<td>3229</td>
<td>50</td>
<td>35.1</td>
<td>1192</td>
<td>44</td>
</tr>
<tr>
<td>Average (20%)</td>
<td>886</td>
<td>3249</td>
<td>52</td>
<td>34.7</td>
<td>1152</td>
<td>42</td>
</tr>
<tr>
<td>Average (40%)</td>
<td>877</td>
<td>3318</td>
<td>51</td>
<td>34.7</td>
<td>1143</td>
<td>44</td>
</tr>
</tbody>
</table>

Table 4-15 Probe penetration rate sensitivity analysis results for 120% demand

Similarly to the previous cases, the VSL positively affected the main stream traffic conditions for the 120% demand scenario. The traffic delay was reduced by 3.8%, 8.1% and 9.0% for the 10%, 20% and 40% probes penetration rates, respectively, out of which only the VSL used in conjunction with the 20% probe participation rate showed statistical significance with a 5% level of confidence. Unlike the case of delay, the VSL system significantly (with the same level of confidence) improved traffic throughput by 5.1%, 5.8% and 8.0% for 10%, 20%, and 40% probes penetration rates, respectively, in
comparison to the “no control” experiments. Even though no significant improvement was observed for the travel time parameter for the 10% probes penetration rate, the VSL significantly decreased the average travel time on the Deerfoot Trail NE by 6.1% and 6.9% for the 20% and 40% probe vehicles participation rate, accordingly. The VSL system also significantly, with a 5% level of confidence, affected the speed of traffic flow, decreased by 6.6%, 4.9% and 4.9% for 10%, 20% and 40% probes penetration rate, respectively, which provides a higher level of safety on the congested area of the highway. In terms of density, VSL application increased the density of traffic flow by 4.9%, 2.4% and 4.6% for 10%, 20% and 40% probes penetration rates, respectively, which is statistically significant with a 5% level of confidence.

From Table 4-13 it can be seen that the VSL system improved traffic conditions the most for the 80% demand value when the speed data was distributed by 20% of all vehicles in the network. A different result was observed for the 100% demand, where the highest positive impact was registered for the case when 10% of vehicles are probes (Table 4-14). And finally, for the 120% demand scenario, the VSL receiving real-time traffic information from 40% of vehicles was able to contribute the most to the traffic conditions on the motorway. It is also important to remember that even though the 20% and 10% probe vehicles penetration rate experiments appeared to improve the road conditions the most for 80% and 100% demand, respectively, the 40% probe vehicles penetration rate case was able to significantly (with a 5% level of confidence) decrease the congestion level. One of the reasons for such results might be the sensitivity of the VSL algorithm to speed readings from the probes, as well as the possibility that all 10% vehicles that the readings are taken from, pass the segment at the same speed. By relying on a small number of probe vehicles, there is a higher chance of error. Wang et al. (2007) proved that the larger the sample of the
probe vehicles, the more accurate “the link average speed based on the mathematical average method’, which was used in this research.

Overall, the VSL algorithm developed showed the ability to improve traffic conditions on the Deerfoot Trail, NE Calgary, by reducing the delays and total travel time, and increasing traffic flow, for all one lane closure case scenarios discussed above. Even though it did not show a significant impact on the motorway when the traffic volume was at the highest level (120% demand), it significantly reduced the effect of the delays on driving condition in the cases of off-peak (80%) and peak (100%) demands.

4.4 COordinated VSL ALGORITHM FOR A “MAJOR ACCIDENT” SCENARIO WITH 2 LANE CLOSURE

In these runs, the performance of VSL with a major “accident” scenario occurring on the Deerfoot Trail is considered. The tested incident location is sited at the end of the research area, and a 40% probe vehicles penetration rate parameter is used in these runs. The effectiveness of the algorithm is tested by the variations in demand (80%, 100% and 120%), and by adopting the same MOEs listed in section 4.1

4.4.1 Major “accident” at the end of the motorway

To simulate the major accident case, 2 lanes of a 3-lane highway segment were closed. The simulation was run ten times with random seed values for each demand variation. The results for each case were averaged over ten possible outcomes. Table 4-16, Table 4-17 and Table 4-18 present the results of the experiments:
<table>
<thead>
<tr>
<th></th>
<th>Mainline delay (sec/veh)</th>
<th>Traffic flow (veh/h)</th>
<th>Average speed (km/h)</th>
<th>Variance of speed (km/h)</th>
<th>Travel time (sec/veh)</th>
<th>Density (veh/ln/km)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Average (no VSL)</td>
<td>1663</td>
<td>1948</td>
<td>55</td>
<td>39.8</td>
<td>1923</td>
<td>37</td>
</tr>
<tr>
<td>Average (VSL)</td>
<td>1621</td>
<td>1958</td>
<td>49</td>
<td>38.2</td>
<td>1886</td>
<td>37</td>
</tr>
<tr>
<td>Change (%)</td>
<td>-2.5%</td>
<td>+0.5%</td>
<td>-10.9%</td>
<td>-4.0%</td>
<td>-1.9%</td>
<td>+0.1%</td>
</tr>
</tbody>
</table>

Table 4-16 Test runs for 80% traffic demand condition

<table>
<thead>
<tr>
<th></th>
<th>Mainline delay (sec/veh)</th>
<th>Traffic flow (veh/h)</th>
<th>Average speed (km/h)</th>
<th>Variance of speed (km/h)</th>
<th>Travel time (sec/veh)</th>
<th>Density (veh/ln/km)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Average (no VSL)</td>
<td>1803</td>
<td>1864</td>
<td>52</td>
<td>39.6</td>
<td>2064</td>
<td>38</td>
</tr>
<tr>
<td>Average (VSL)</td>
<td>1798</td>
<td>1863</td>
<td>47</td>
<td>37.7</td>
<td>2064</td>
<td>37</td>
</tr>
<tr>
<td>Change (%)</td>
<td>-0.28%</td>
<td>-0.05%</td>
<td>-10.4%</td>
<td>-4.8%</td>
<td>-0.02%</td>
<td>-2.1%</td>
</tr>
</tbody>
</table>

Table 4-17 Test runs for 100% traffic demand condition

<table>
<thead>
<tr>
<th></th>
<th>Mainline delay (sec/veh)</th>
<th>Traffic flow (veh/h)</th>
<th>Average speed (km/h)</th>
<th>Variance of speed (km/h)</th>
<th>Travel time (sec/veh)</th>
<th>Density (veh/ln/km)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Average (no VSL)</td>
<td>1911</td>
<td>1824</td>
<td>51</td>
<td>40.5</td>
<td>2172</td>
<td>38</td>
</tr>
<tr>
<td>Average (VSL)</td>
<td>1842</td>
<td>1852</td>
<td>46</td>
<td>38.3</td>
<td>2107</td>
<td>37</td>
</tr>
<tr>
<td>Change (%)</td>
<td>-3.6%</td>
<td>+1.5%</td>
<td>-9.9%</td>
<td>-5.4%</td>
<td>-3.0%</td>
<td>-1.3%</td>
</tr>
</tbody>
</table>

Table 4-18 Test runs for 120% traffic demand condition

It can be clearly seen from the tables that the VSL control system was unable to substantially change the traffic condition in terms of delay, throughput and travel time. The average speed limit decreases of 10.9%, 10.4% and 9.9% in the cases of 80%, 100% and 120% demand, respectively, due to the VSL algorithm application showed significance (at a 5% level of confidence) in comparison to the “no control” scenarios. The main
explanation is attributed to the fact that the average speed of the traffic decreases to an average of 50 km/h, whereas the VSL system is allowed to vary the variable message signs anywhere between 50 km/h to 100 km/h. This restriction does not allow the control system to greatly influence road conditions. However, for all traffic congestion levels examined, the VSL strategies lead to an increase in speed harmonisation over the whole motorway; that is an indicator of effective shockwave suppression; accordingly a likely improvement in safety would result in preventing the occurrence of secondary collisions. Additional motorway traffic management tools such as ramp metering and ATIS should be used in coordination with VSL to alleviate severe traffic congestion.

Important common observations were obtained for “minor accident” and “major accident” scenarios: the designed VSL system manages to decrease the average travel time and delay on the motorway, and at the same time it reduced the average speed of the traffic flow. These results can be explained by the ability of the VSL system to restrict the inflow to the congested area, by delaying the arrival of vehicles to the bottleneck by reducing the average speed limit of the vehicles (Hegyi et al., 2003). In other words, the VSL system prevents the breakdown occurring by creating an artificial delay over the controlled part of the motorway. Figure 2-1 represents the pattern in which the VSL system adjusts the density-flow diagram case where the algorithm is activated:
4.5 COLLECTION OF PROBE DATA FROM PASSENGER VEHICLES AND HEAVY VEHICLES

The previous runs assumed that the probe sample is fully derived from passengers' vehicles. One of the important factors when dealing with a sample is the need for the sample to be representative of the vehicles moving in the network. In other words, the composition of vehicle probes (i.e. percentage of passenger versus commercial vehicles) is an important factor that might affect the performance of the algorithm. Most commercial vehicles are already equipped with GPS devices; since extracting information from such vehicles is not subject to privacy issues, some municipalities might already have data from these vehicle types (McCormack, 2011). Thus, the VSL algorithm presented might be applied based on commercial vehicles acting as probes. However, the characteristics of the drivers’ behaviour of commercial vehicles are not similar to drivers' of passenger vehicles. That is explained by drivers of commercial vehicles usually having more driving experience, and exhibiting different driving behaviour such as acceleration, deceleration, lane changing manoeuvres, gap acceptance, etc. These driving behaviours will definitely be
reflected in different speeds and vehicular trajectory profiles. Thus, it is important to examine the performance of the probe-based VSL algorithm depending on the composition of commercial vehicles and passenger's vehicles acting as probes. It is to be noted that this problem is not present with the point detectors since the data is collected from all types of vehicle passing over the detectors.

As mentioned previously, the study area is part of the CANAMEX corridor, which is a trade corridor with a relatively large number of commercial vehicles. Based on the traffic counts provided by Alberta Transportation (2009), the total percentage of such vehicles is 2.8% of total traffic flow during the AM period. The following attributes of a large heavy truck are described in the PARAMICS microsimulation model: length – 11 metres, width – 2.5 metres, height – 4 metres.

This experiment considers the case of 100% of the demand with one lane closed. The presented scenario results correspond to ten runs with different random seed values. All the results are compared with the “no VSL” base case scenario.

4.5.1 Speed data collected by only commercial vehicles

The first test runs evaluated the VSL system performance taking real-time speed data collected only from commercial vehicles. Three possible cases were reviewed: 100%, 75% and 50% of the trucks are assumed to be probe vehicles. Considering that the total number of heavy trucks in the network is 2.8%, the probe penetration rates examined are: 2.8%, 2.1% and 1.4%, corresponding to 100%, 75% and 50% respectively, disseminating real time information. The results of the tests are presented in Table 4-19.
<table>
<thead>
<tr>
<th>Probe penetration rate</th>
<th>Mainline delay (sec/veh)</th>
<th>Traffic flow (veh/h)</th>
<th>Average speed (km/h)</th>
<th>Variance of speed (km/h)</th>
<th>Travel time (sec/veh)</th>
<th>Density (veh/in/km)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Average (no VSL)</td>
<td>929</td>
<td>3123</td>
<td>57</td>
<td>35.6</td>
<td>1192</td>
<td>41</td>
</tr>
<tr>
<td>Average 50% trucks</td>
<td>833</td>
<td>3328</td>
<td>53</td>
<td>33.7</td>
<td>1099</td>
<td>42</td>
</tr>
<tr>
<td>Average 75% trucks</td>
<td>845</td>
<td>3321</td>
<td>53</td>
<td>34.0</td>
<td>1112</td>
<td>43</td>
</tr>
<tr>
<td>Average 100% trucks</td>
<td>824</td>
<td>3375</td>
<td>53</td>
<td>33.8</td>
<td>1090</td>
<td>43</td>
</tr>
</tbody>
</table>

Table 4-19 Results for speed data readings from heavy trucks only

In terms of the total traffic delay on the motorway, significant improvements were observed for all three scenarios in comparison to the “no VSL” case: 11.3%, 9.04% and 10.3% in 100%, 75% and 50% truck participation rate scenarios, respectively. These findings were all statistically significant with a 5% level of confidence. However, the T-test showed no significant difference among the performance of the various percentage of penetration rates of commercial vehicles. Table 4-19 shows that compared to the “no VSL” scenario, significant traffic flow improvement of 8.1%, 6.3% and 6.6% were obtained with the VSL system application, corresponding to 100%, 75% and 50%, respectively of commercial vehicles acting as probes.

In addition, a decrease in the average speed on the motorway of 7.1%, 7.2% and 5.9% and a decrease in average travel time on the motorway of 8.6%, 6.7% and 7.8% resulted with VSL applications corresponding to 100%, 75% and 50% respectively of commercial vehicles acting as probes. These findings were showed to be statistically significant with a 5% level of confidence in comparison to the “no VSL” scenario. It is worth noting that the variance of speed also decreased significantly; which indicates that
the VSL was also able to improve the level of safety on the highway. No significant change was obtained for the traffic density.

Overall, the VSL system proved to be capable of reducing the average traffic speed and delays while collecting the probe speed data from heavy commercial vehicles only. Considering that the total percentage of this type of vehicles was maximum of 2.8%, the experiment also demonstrated the ability of the developed system to improve the traffic condition even if only 50% of the commercial vehicles were acting as probes.

4.5.2 Speed data distribution by passenger vehicles and heavy trucks for a total of 10% probe penetration rate

In this section, three scenarios of probe speeds data collection were considered. The first one represents the case where readings were collected from 75% of all heavy trucks in the network, which is 2.1% out of a 10% total penetration rate. Therefore, the rest of the data was gathered from passenger small cars (7.9%). The second scenario provides the evaluation of the VSL algorithm in the case where the speed information is collected from 50% of the total population of heavy trucks in the network, which is 1.4% out of a 10% penetration rate. Thus, 8.6% of the total penetration rate is passenger cars. And the final variation considers traffic data collection from 100% of trucks on the road (which is 2.8% out of total 10% probe penetration rate) in conjunction with 7.2% of probe data collection from passenger vehicles. Table 4-20 reports the summary of both experiments along with the previously derived results for “no VSL” and “10% probe penetration rate from small vehicles only” scenarios:
From Table 4-20, it can be seen that the VSL algorithm tested for all three scenarios managed to decrease the average delay over the whole study area by 0.8%, 4.4% and 6.0% in the cases of 1.4%, 2.1% and 2.8% trucks participation rate in a 10% probe penetration rate, respectively. These findings were all not statistically significant except for the case of “2.1% of trucks as probes” which was marginally significant in comparison to the “no VSL” case. A significant increase of 3.4% and 6.7% in traffic flow due to the VSL system application was observed for 2.1% and 2.8% of truck participation rates, accordingly. Even though the similar improvement occurred for the 1.4% heavy vehicle probe penetration rate, it did not show significance. It is important to note that the variance of traffic speed was reduced for all three cases in comparison to the “no VSL” scenario, which shows the...
resulting increase in safety with the application of VSL. Furthermore, slight reductions in travel time were observed for all scenarios.

Table 4-20 also shows the results of the VSL experiments, described at the beginning of this chapter, which used the probe data collected from 10% of small cars only. The VSL run that collected the data from passenger cars only outperformed the VSL system that collected the data from both types of vehicles for all combinations considered. That is explained by the fact that these vehicles represent over 95% of the traffic travelling on the network. Nevertheless, even for the case of all data collected from commercial vehicles, the probe-based VSL was able to effectively manage traffic by reducing delays and travel time and improving throughput. These findings play an important role in the presented probe-based VSL system, as any type of vehicle with GPS equipment that can transmit data is shown to be effective in acting as a probe to feed input to the presented VSL algorithm. However, the performance of the algorithm is shown to be quite sensitive to the composition of the vehicle probes.

4.5.3 Speed data distribution by passenger vehicles and heavy trucks for 20% probe penetration rate

The next part of the analysis describes the behaviour of the VSL system in the case of a 20% total probe penetration rate, considering that the data is received from passenger vehicles as well as from heavy trucks in the network. Similarly to the previous analysis, three probe penetration rates for truck and small vehicle combinations were reviewed (1.4%, 2.1% and 2.8% trucks contribution to the total of 20%). The summary of the results is reported in Table 4-21:
Table 4-21 Results for speed data readings from passenger vehicles and heavy trucks for a 20% total probe penetration rate

From Table 4-21, the VSL system, that collected traffic information from 1.4% of trucks and 18.6% of passenger cars was not able to positively affect the traffic conditions, in fact it increased the average delay on the motorway by 4.5%, decreased traffic flow by 0.2% and extended the average travel time by 3.8% in comparison to the “no VSL” scenario. These findings are counterintuitive and more work needs to be conducted in the future to better understand these results. That might be explained by the fact that if only one or two segments of the motorway contain a slow moving probe truck, that it will bring the average speed for the section to a value much lower than its mean, as trucks tend to maintain lower speed limits in comparison to small vehicles. That might cause the VSL algorithm to sense a “false” shockwave and lower the VSL, which will increase the delay and travel time.
However, the VSL algorithm managed to decrease the average speed by 4.9% as well as its variation by 4.5%, which is statistically significant with a 5% level of confidence, in the case of only 1.4% trucks participation rate in the probe data collection.

A traffic delay decrease of 6.6% and 3.6% in comparison to the “no VSL” scenario occurred due to the VSL system application while collecting partial speed data from 75% and 100% heavy vehicles, respectively. Furthermore, a 6.6% reduction proved to be statistically significant with a 5% level of confidence. The significant improvements of 4.5% and 4.2% in the traffic flow, and 6.3% and 5.6% reduction in the average speed, were observed for the VSL tests when 100% and 75% of trucks participated in the data collection, respectively, in comparison to the “no VSL” system. Similarly, average travel time was decreased by 2.5% and 4.8% for 100% and 75%, accordingly. However, only the result for the 75% truck participation rate in probe data collection showed statistical significance with a 5% level of confidence.

Similar to the previous section, the VSL algorithm, that collected the real time traffic from passenger vehicles only proved to outperform the variations considered of trucks percentage in a total of 20% probe vehicles. However, only traffic flow parameter showed significance (with a 5% level of confidence) compared to 75% and 100% truck participation rate scenarios.

In summary, the presented VSL was effective in managing the traffic even in the case of the speed data being only collected from trucks, which represents only 2.8% of the traffic composition. The algorithm was effective for all three scenarios: 50%, 75% and 100% truck probe penetration rates. However, the VSL presented showed better performance when the vehicle probes were all passenger vehicles. That was true in both cases of 10% and 20% penetration rates. Overall, the VSL system proved to be effective in
reducing average traffic delay, travel time and speed limit while collecting the data from trucks and passenger vehicles.

4.6 COMPARISON OF PROBE-BASED ADAPTIVE VSL WITH DETECTOR-BASED ADAPTIVE VSL CONTROL SYSTEM FOR 100% DEMAND

In this part, the VSL taking input data from loop detectors is compared to the performance of the probe-based VSL. Unlike the case of probe data collection, where the speed provided was a SMS, detectors transfer TMS information and traffic flow information. Therefore, TMS readings are directly extracted from detectors, and SMS is calculated according to the following formula (Highway Capacity Manual, 2010):

\[ S_R = 1.026 \times S_T - 3.042 \] (4.1)

Where:  
\( S_R \) - Space Mean Speed (SMS) (km/h),  
\( S_T \) - Time Mean Speed (TMS) (km/h).

The PARAMICS microsimulation model allows users to extract traffic flow information directly from point detectors, and therefore by knowing traffic flow and SMS, the density can be easily calculated based on the fundamental traffic-flow relationship according to Greenshield model:

\[ q_i(t) = k_i(t) \times v_i(t) \] (4.2)

Where:  
\( q_i(t) \) - traffic flow on section i at time t  
\( v_i(t) \) - space mean speed of section i at time t  
\( k_i(t) \) - density at section i at time t.
This means the Van Aerde’s (1995) model is no longer needed, as traffic flow information and density are obtained differently. The estimated values of SMS, density and flow parameters are then plugged into the same optimisation process that was used for the probe-based algorithm.

A total of twelve point detectors were placed along the study area. Table 4-22 reflects the data about number of detectors per section:

<table>
<thead>
<tr>
<th>Section number</th>
<th>1</th>
<th>2</th>
<th>3</th>
<th>4</th>
<th>5</th>
<th>6</th>
</tr>
</thead>
<tbody>
<tr>
<td>Length (m)</td>
<td>305.53</td>
<td>742.89</td>
<td>1291.96</td>
<td>2362.18</td>
<td>2086.00</td>
<td>731.67</td>
</tr>
<tr>
<td>Number of detectors</td>
<td>1</td>
<td>1</td>
<td>2</td>
<td>4</td>
<td>3</td>
<td>1</td>
</tr>
</tbody>
</table>

Table 4-22 Locations of loop detectors

Since loop detectors are able to determine the traffic data at the locations where they are installed, several detectors were placed on longer stretches of the highway, i.e. there were four point detectors implemented in section 4, and the readings were averaged. There were three cases reviewed: “normal” condition scenario, “minor” accident at the end of the motorway and “major” accident at the end of the motorway. The performance of the detector-based VSL was tested for the condition of 100% demand, where each case was run ten times with random seed values. The following tables (Tables 4-23 to 4-25) report the results for the detector-based VSL algorithm for “normal” condition, “minor accident” and “major accident” scenarios, respectively, as well as the previously derived data for the probe-based VSL algorithm for the same scenario with 100% demand:
Table 4-23 Results of the detector-based and probe-based algorithm’s impact on the traffic system for “normal” conditions and 100% demand scenario

<table>
<thead>
<tr>
<th></th>
<th>Mainline delay (sec/veh)</th>
<th>Traffic flow (veh/h)</th>
<th>Average speed (km/h)</th>
<th>Variance of speed (km/h)</th>
<th>Travel time (sec/veh)</th>
<th>Density (veh/km)</th>
</tr>
</thead>
<tbody>
<tr>
<td>No VSL</td>
<td>335</td>
<td>4315</td>
<td>75</td>
<td>24.2</td>
<td>570</td>
<td>39</td>
</tr>
<tr>
<td>Detector-based</td>
<td>337</td>
<td>4283</td>
<td>71</td>
<td>23.2</td>
<td>602</td>
<td>39</td>
</tr>
<tr>
<td>Probe-based (10%)</td>
<td>349</td>
<td>4288</td>
<td>73</td>
<td>23.9</td>
<td>614</td>
<td>39</td>
</tr>
<tr>
<td>Probe-based (20%)</td>
<td>317</td>
<td>4320</td>
<td>73</td>
<td>23.9</td>
<td>581</td>
<td>39</td>
</tr>
<tr>
<td>Probe-based (40%)</td>
<td>349</td>
<td>4299</td>
<td>73</td>
<td>23.7</td>
<td>614</td>
<td>39</td>
</tr>
</tbody>
</table>

For the “normal” condition scenario, the results derived for detector-based VSL in comparison to the 10%, 20% and 40% probes VSL did not show statistically significant difference between each other for all parameters, for the exception of the reduction in speed limit. The statistical T-test with a 5% level of confidence revealed that the detector-based VSL system was able to significantly reduce the average speed limit in comparison to the 10% and 40% probe-based VSL. However, no substantial difference was registered between the speed parameters for the 20% VSL and detector-based VSL. The results for average delay, traffic flow, travel time and density parameters did not show significant variations between the scenarios, therefore the tested data collection methods resulted in similar impacts on the traffic system with 100% demand and “normal” conditions.

The next step was to evaluate the difference for a 100% demand and “minor accident” scenario, where one lane is closed at the end of the motorway:
Table 4-24 Results of the detector-based and probe-based algorithm’s impact on the traffic system for “minor accident” and 100% demand scenario

For a “minor accident” scenario the VSL system that receives the data from probe vehicles showed a higher impact on the traffic condition for all reviewed probe penetration rates in comparison to the detector-based VSL. Furthermore, the average throughput parameter was significantly increased by 6.1%, 4.6% and 1.9% in the cases of 10%, 20% and 40% probe-based VSLs, respectively, in comparison to the detector-based one. In terms of delay, average speed and travel time parameters, the probe-based VSL was proven to have a greater positive impact in comparison to the detector-based VSL, however it was not statistically significant with a 5% level of confidence.

The final step of the detector-based and probe-based VSL comparison for 100% demand is the case of a “major” accident, where two lanes are closed at the end of the highway. The results are reported in Table 4-25:
Table 4-25 Results of the detector-based and probe-based algorithm’s impact on the traffic system for “major accident” and 100% demand scenario

In the case of a “major accident”, the probe-based and detector-based VSL systems showed similar results. Even though the average delay, traffic flow and travel time parameters for the detector-based VSL performance reported better results in comparison to the 10%, 20% and 40% probe-based VSL, the difference was not statistically significant with a 5% level of confidence.

4.7 COMPARISON OF PROBE-BASED ADAPTIVE VSL WITH PROBE-BASED ADAPTIVE VSL CONTROL SYSTEM FOR 120% DEMAND

Similarly to the previous section, the probe-based VSL algorithm is compared to a detector-based VSL algorithm for the case of a highly congested network (i.e. demand of 120%). Table 4-26, Table 4-26 and Table 4-27 report the results of the experiments:
Table 4-26 Results of the detector-based and probe-based algorithm’s impact on the traffic system for “normal” conditions and 120% demand scenario

From table 4-26, the VSL system that collected the data from probe vehicles demonstrated the ability to improve traffic conditions in terms of average delay and travel time in comparison to the detector-based VSL. In fact, the traffic delay was reduced by 0.8%, 1.8% and 0.8% in the case of 10%, 20% and 40% probe penetration rates, respectively, whereas travel time was decreased by 0.5%, 1.2% and 0.5% for the same cases. However, the results for the probe-based VSL did not show significance (with a 5% level of confidence) in comparison to the detector-based VSL.

Table 4-27 reflects the results for the “minor accident” scenario and 120% demand scenario:

Table 4-27 Results of the detector-based and probe-based algorithm’s impact on the traffic system for “minor accident” and 120% demand scenario

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For the case of a “minor accident” and 120% demand, the detector-based VSL showed a higher level of improvement of 9.5%, 5.3% and 4.3% in the average delay in comparison to the 10%, 20% and 40% probes respectively. However, the detector-based VSL was shown to outperform the probe-based approach in the case of the 10% penetration rates of probes. That might be explained by the fact that at severe congestion the VSL was unable to precisely evaluate the data when a low number of vehicles were being tracked. In terms of traffic density, the VSL system working with 10% and 20% probes did not provide a statistically significant difference in the results in comparison to detector-based one. However, the VSL with 40% probes managed to significantly outperform the probe-based VSL by increasing the density by 2.6%. With respect to speed, flow and travel time, no significance was determined in the cases of 20% and 40% VSL in comparison to the detector-based VSL.

<table>
<thead>
<tr>
<th></th>
<th>Mainline delay (sec/veh)</th>
<th>Traffic flow (veh/h)</th>
<th>Average speed (km/h)</th>
<th>Variance of speed (km/h)</th>
<th>Travel time (sec/veh)</th>
<th>Density (veh/ln/km)</th>
</tr>
</thead>
<tbody>
<tr>
<td>No VSL</td>
<td>1911</td>
<td>1824</td>
<td>51</td>
<td>40.5</td>
<td>2172</td>
<td>38</td>
</tr>
<tr>
<td>Detector-based</td>
<td>1787</td>
<td>1859</td>
<td>47</td>
<td>38.1</td>
<td>2053</td>
<td>37</td>
</tr>
<tr>
<td>Probe-based (10%)</td>
<td>1841</td>
<td>1861</td>
<td>46</td>
<td>37.9</td>
<td>2106</td>
<td>37</td>
</tr>
<tr>
<td>Probe-based (20%)</td>
<td>1804</td>
<td>1868</td>
<td>47</td>
<td>38.0</td>
<td>2069</td>
<td>37</td>
</tr>
<tr>
<td>Probe-based (40%)</td>
<td>1842</td>
<td>1852</td>
<td>46</td>
<td>38.3</td>
<td>2107</td>
<td>37</td>
</tr>
</tbody>
</table>

Table 4-28 Results of the detector-based and probe-based algorithm’s impact on the traffic system for a “major accident” and 120% demand scenario

For the case of a “major accident”, Table 4-28 illustrates that the traffic delay was reduced by 2.9%, 0.9% and 3.0% in the case of the detector-based VSL in comparison to the 10%, 20% and 40% probe-based VSL, respectively. However, only delay reduced due to the detector-based algorithm in comparison to the 40% probe VSL, presenting statistical
significance with a 5% level of confidence. Similarly, the average speed on the highway maintained approximately the same value for all cases, with the exception of the 40% probes VSL, where the speed limit was significantly reduced by 1% in comparison to the detector-based VSL. No significance was observed in the results of the difference in traffic flow and density parameters for the 10%, 20% and 40% demand in respect to the probe-based VSL, as well as among themselves.

In summary, in this section, the performance of the probe-based VSL algorithm developed was tested by using probe-based data collection technology and a detector-based data collection concept for 100% and 120% demand. The results showed consistency in similar outcomes for the systems for 10%, 20% and 40% probes VSL in comparison to the detector-based VSL. Furthermore, the implementation of the probe-based VSL developed significantly improved the average throughput for all probe penetration rates considered in comparison to the detector-based VSL. Only in the case of 120% demand and a “minor accident” did the VSL system show a slightly lower performance result for the 10% probe-based data collection.

The above findings illustrate to the robustness of the presented probe-based VSL. Overall, the performance of the VSL algorithm with data extracted from probes is shown to be comparable, and in some cases outperform, the results when data are collected from point detectors. It is important to also note that twelve loop detectors were needed on an 8 km stretch of the highway. Thus, in addition to the similar performance, consideration should be given to the high installation and maintenance costs for detector-based technology, as the equipment needs to be physically installed on the pavement. On the other hand, probe vehicles can give reliable network-wide travel time information at relatively low cost (Cayford et al., 2006). The results of this analysis prove the economic
efficiency of using probe-based technology instead of a detector-based one. Significant reductions in the deployment cost of such advanced motorway control are expected.
Chapter 5  CONCLUSION AND RECOMMENDATIONS

This research presented a proactive VSL algorithm and tested a simulated 8 km segment of an urban motorway in Calgary, Canada. Although, presently there has been no adaptive VSL system implemented in Canada, it is broadly considered as a new way of traffic control on busy highways in Canada. This chapter summarises the results of the research findings, highlights the contribution to the literature, and discusses the potential recommendations for future research.

5.1  CONCLUSIONS

In this research, a proactive VSL algorithm was developed for an 8 km stretch of the Deerfoot Trail located in Calgary, Alberta. The presented algorithm extends the capability of Hegyi's et al. (2005) VSL model to take as its input data SMS information derived from vehicle probes constantly moving on the network. The main stream traffic condition is constantly monitored and estimated by extracting information from probe vehicles alone. On-ramp queue information is monitored by the installation of 2 detectors on each ramp. The location and occurrence of the potential shockwaves are monitored through the probe vehicles constantly moving on the network. If the occurrence of a shockwave is confirmed, the VSL algorithm is activated to estimate the optimum VSL values. The objective function is based on minimising the total time spent (TTS) in the network for a rolling horizon of 5 min. However, only the VSL outputs corresponding to the first estimation steps are considered final and are implemented. The VSL algorithm runs all possible values of the variable message signs for the next six time intervals (control horizon), and the set of VSL values that provides the lowest total time spent on the
motorway is implemented for the next time step. The cycle is repeated each 60s interval with the new set of collected probe data.

The probe-based VSL developed is rigorously evaluated on an 8 km long stretch of Highway 2 (Deerfoot Trail) in Calgary, Alberta. The study area is located between McKnight Boulevard and Memorial Drive NE. This highway passes through fast developing industrial communities and small businesses. It is also a major access to downtown Calgary through the exit onto 32 Avenue NE and Memorial Drive. As a result, traffic congestion reaches high levels during the AM peak hours, when a high share of the commuting trips is destined to the city centre.

To evaluate the performance of the algorithm under various conditions, the algorithm is tested for several traffic condition scenarios:

1. **“No accident” scenario.** The traffic condition is assumed to have no external interruptions, such as lane closures. The sensitivity analysis is conducted by using three traffic demand values (80%, 100% and 120%); three probe vehicles penetration rate values (10%, 20% and 40%) and three probe vehicles penetration rate values (1 sec, 5 sec and 10 sec).

2. **“Minor accident” scenario.** One lane is blocked through the PARAMICS interface to imitate an accident. The sensitivity analysis is conducted by using three traffic demand values (80%, 100% and 120%) and three probe vehicles penetration rate values (10%, 20% and 40%)

3. **“Major accident at the end of the motorway” scenario.** Two lanes are blocked through the PARAMICS interface to imitate an accident. The sensitivity analysis is conducted by using three traffic demand values (80%, 100% and 120%).
The algorithm is also tested for different cases of vehicle probe distribution. Finally, the probe-based algorithm is compared to a conventional VSL algorithm that takes detectors data as the input. It is to be noted that the probe-based and the latter detector-based algorithms examined follow the same control logic with the only difference being the type of input data.

A summary of the results is presented in Figure 5-1:

<table>
<thead>
<tr>
<th>Experiment</th>
<th>Results</th>
</tr>
</thead>
<tbody>
<tr>
<td>No accident</td>
<td>VSL would benefit traffic the most effectively when demand is high; offers an improvement in safety</td>
</tr>
<tr>
<td>Minor accident</td>
<td>VSL demonstrated significant (with a 5% level of confidence) traffic improvements for all cases of sensitivity analyses: demand variations and probe vehicles penetration rate variations</td>
</tr>
<tr>
<td>Major accident</td>
<td>VSL was unable to resolve or significantly improve the congestion level for all three levels of demand tested</td>
</tr>
<tr>
<td>Probe data collection from trucks only, trucks and small vehicles</td>
<td>Network with a larger number of heavy trucks would lead to the highest level of traffic condition improvement. However, the VSL algorithm that collected the speed data from small vehicles only managed to outperform the VSL that accounted for trucks in the network</td>
</tr>
<tr>
<td>Probe-based VSL vs. detector-based VSL</td>
<td>Probe-based data collection proved to be a strong alternative for the classic detector-based method for this particular research</td>
</tr>
</tbody>
</table>

Figure 5-1 Summary of results
5.1.1 Results for a “no accident” scenario

With no external disturbance, the VSL system developed proved to be mostly effective under high congestion condition scenarios. The tests also demonstrated that the larger the sample of probe vehicles in the network, the better the performance in terms of the average speed of the VSL algorithm for high demand: the average speed was decreased by 3.6% and 3.5% in comparison to the “no VSL” case for 20% and 40% probes, respectively, at 100% demand. Whereas, the VSL system reduced the average speed by 4.6% and 8.1% for 20% and 40% probes, respectively, for 120% demand. These improvements were statistically significant with a 5% level of confidence.

The results for the speed information update frequency rate sensitivity analysis showed that the VSL system is generally not significantly affected by the frequency of probe data penetration. Overall, the experiment leads to a conclusion that the developed VSL system would benefit the traffic the most effectively when demand is high. However, despite the likely improvements in safety, it might potentially create induced delays at lower demands. Therefore, it is recommended to only activate the system during the peak periods and to switch it off outside these peaks.

5.1.2 Results for a “minor accident” scenario

One lane at the end of the motorway stretch was closed to simulate a “minor incident” scenario. The VSL system demonstrated significant (with a 5% level of confidence) traffic improvements for all cases of sensitivity analyses: demand variations and probe vehicles penetration rate variations.

For the off-peak period (80% demand) the highest traffic condition improvement was registered for the case of the 20% probe penetration rate and was 28.7% for average
delay, 8.1% for traffic flow and 20.6% for average travel time. However, the improvements occurred due to 10% and 40% probe vehicles penetration rate also highly impacted on the system.

For the AM peak period (100% demand), the collection of speed data from 10% of all traffic participants resulted in the strongest impact on the system: a 15.3% decrease in traffic delay, 7.8% increase in traffic flow and 11.7% reduction in average travel time on the highway in comparison to the “no control” scenario. In the case of 120% level of demand, the greatest positive change was observed for the 40% probe penetration value: a 9.0% reduction in traffic delay, 8.0% increase in traffic flow and 6.9% decrease in average travel time. Overall, the VSL system showed promising results in solving traffic congestion in the case of non-recurrent congestion (collision, maintenance, adverse road weather condition, etc.).

### 5.1.3 Results for a “major accident at the end of the motorway” scenario

Unlike the analysis for a “minor accident” case, the results for the VSL system application to a two-lane closure at the end of the motorway did not show a significant improvement, with the exception of the speed limit parameter. The VSL system was able to significantly reduce the average speed limit of traffic flow by 10.9%, 10.4% and 9.9% for 80%, 100% and 120% traffic demands, respectively. In addition to the closure, traffic was also disturbed by congestion caused by the vehicles merging onto the highway from 16 Avenue NE and exiting onto Memorial Drive. Due to all these disturbances, the traffic changed to an unstable condition (i.e. breakdown condition), where any additional disturbance creates a shockwave. In this case, the average speed limit of the vehicles reduced to about 50 km/h, whereas the VSL control signs can lower the value to a 50 km/h
minimum. Therefore, the proposed VSL algorithm was unable to resolve or substantially improve the congestion level for all three tested levels of demand (80%, 100% and 120%).

5.1.4 Results for the VSL algorithm based on data collection from small vehicles and trucks

The test results revealed that out of all variations of truck participation rate considered, the network with the larger number of heavy trucks lead to the highest level of traffic condition improvement. However, the VSL algorithm that collected the speed data from small vehicles alone managed to outperform the VSL that accounted for trucks in the network.

5.1.5 Results for the probe-based and detector-based VSL comparison

The probe-based data collection proved to be a strong alternative to the classic detector-based one for this particular research. Considering the high installation and maintenance cost of loop detectors, probe-based data can be connected at no cost, as there is no special equipment needed for its implementation. Moreover, the probe data can be collected from any GPS-enabled device (such as mobile phone) that is commonly used in day-to-day life.

5.2 RESEARCH DISCUSSION AND CONTRIBUTIONS

This thesis made the following contributions to the research component of transportation engineering:


Traditional VSL systems receive traffic data from loop detectors that need to be placed underneath the pavement. The cost associated with the installation of the detectors,
delays caused by work operations, and expensive maintenance of the equipment has always been a significant drawback of its usage. Furthermore, point detectors are only capable of disseminating localised information in the vicinity of the loop location. The speed data collected at the location is mainly related to TMS. On the other hand, data collected from probe vehicles does not require specific equipment, as every mobile phone carried in a car is capable of disseminating its location and speed information. Thus, it is an economically efficient method of collecting traffic data. Although, there have been several studies completed on the subject of probe-based data reliability, it has never been implemented in conjunction with a VSL system. The approach presented in this research allows exploring new ways of applying existing technology to solve traffic congestion. That is expected to drastically decrease the cost of deploying such advanced motorway control methods.

2. Development of VSL algorithm that is only triggered if a shockwave is sensed.

The VSL algorithm developed is only activated if a backpropagading shockwave takes place on the highway. The threshold of -10 km/h was established for the tests in this work; that value was based on trial and error test. Thus, if the speed of a shockwave, going in the opposite direction to the traffic flow, is higher than 10 km/h, the VSL algorithm developed is activated to desipate the shockwaves. This approach protects the traffic system from potential delays on the highway created by the VSL system at small demands that can result is small shockwaves that can be easily absorbed.

3. Sensitivity analysis for probe-based data collection approach for the developed VSL algorithm.

Intensive senstivity annalysis is conducted to explore the full potential of the presented VSL and examine its benefits and drawbacks. Most importantly, a sensitivity
analysis for probe-based data collection from passenger and large vehicles for the developed VSL algorithm is also conducted. When the traffic data is collected from GPS carriers, there is no way to distinguish between the types of vehicles that send the signal. The difference in technical description of a small car and a large truck causes different patterns of its behaviour on the roads. Therefore, the sensitivity and performance of the developed VSL system based on various trucks and passenger vehicles probe participation rates was evaluated. These experiments showed the ability of the VSL system to improve the traffic conditions for 75% and 100% of the trucks participation rate.

4. Comparison of probe-based and detector-based VSL algorithm

In addition, the probe-based data collection method is compared to a “traditional” detector-based method by evaluating the performance of the developed VSL algorithm for both cases. Although, the probe-based VSL did not always outperform the detector-based one, it showed similar results to the detector-based VSL, and therefore was shown to be a great alternative, as there is significant decrease in the deployment cost when using probe data collection.

5.3 FUTURE RESEARCH

The following future research aspects can potentially extend and contribute to this work:

- In this research, the VSL impact was evaluated based on main stream traffic conditions only. For future research it can be extended to the roads around the main highway, as the improvement to the main stream does not guarantee the stability of traffic on roads linking to it.
• This research used a rolling horizon concept with 5 minute prediction horizon and 3 minute control horizon. Therefore, in future work several different variations of rolling and control horizons should be reviewed.

• The threshold for speed of the shockwave is assumed to be -10 km/h, which means that the VSL algorithm is only initiated when the speed of a shockwave is less or equal to this value. In the future, sensitivity of the VSL system to different shockwave speed values can be investigated.

• In this work, possible delays of communication and errors that might be due to the inaccuracy of GPS device estimation were not accounted for. Future research can examine the impact of such factors as part of the sensitivity analysis.

• In this research, the VSL algorithm was alone used as a tool to improve traffic conditions. Therefore, in the future, a combination of VSL algorithm with, for example, ramp metering can be evaluated.

• In the developed algorithm, the Brute Force concept was used to find optimal VSL message sign values. In the future, a more complicated algorithm can be developed.

• In the presented algorithm, Van Arde’s macroscopic model is used to convert SMS to flow and density readings. Future research might consider calibrating a traffic flow model for the area and use it instead of a generic model.

• The VSL system contained four variable message signs along the highway in this work. In future research, the number of variable message signs can be extended to evaluate the advantages of the system.
The detector-based VSL algorithm received data from 12 loop detectors placed within the pavement. In the future, tests with a different number of detectors can be conducted to evaluate the threshold for the probe-based and detector-based methods equivalency.
REFERENCES


Marino, R., 1969, "Freeway Inventory of Geometric Bottleneck Congestion," Freeway Operations Department, California, Division of Highways.


Yi, Y., 2007, “On Improving the Accuracy and Reliability of GPS/INS-Based Direct Sensor Georeferencing”, Report No. 484, Geodetic Science and Surveying Graduate Program, Ohio State University, Columbus, Ohio.