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Variable Speed Limits: Conceptual Design for Queensland Practice

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Abstract

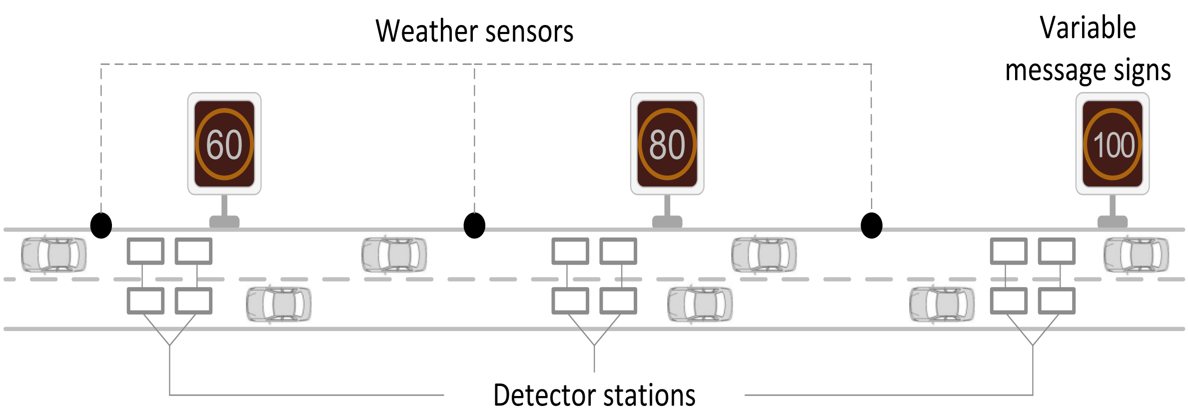
Variable Speed Limits (VSL) is an Intelligent Transportation Systems (ITS) control tool which can enhance traffic safety and which has the potential to contribute to traffic efficiency. Queensland's motorways experience a large volume of commuter traffic in peak periods, leading to heavy recurrent congestion and a high frequency of incidents. Consequently, Queensland's Department of Transport and Main Roads have considered deploying VSL to improve safety and efficiency. This paper identifies three types of VSL and three applicable conditions for activating VSL on for Queensland motorways: high flow, queuing and adverse weather. The design objectives and methodology for each condition are analysed, and micro-simulation results are presented to demonstrate the effectiveness of VSL.

1. Introduction

Variable Speed Limits (VSL) are a type of Intelligent Transportation System (ITS) that can utilise traffic detection, weather information and road surface condition technology to determine appropriate speed limits at which drivers should be travelling, given current roadway and traffic conditions. These regulatory speeds are usually displayed on overhead or portable variable message signs (VMS) (Neudorff, 2003). Trials of VSL have been underway since the 1960s in countries including the US, the UK, Netherlands, Germany, Australia and New Zealand.

A typical VSL system utilises a series of VMS mounted on overhead gantries to display speed limits. It also utilises various types of traffic and weather sensors depending on the type and the primary control objective of the system. Appropriate speed limits are then determined by VSL algorithms based on the traffic data in real time. Figure 1 illustrates a typical configuration of VSL.

Figure 1: A typical VSL configuration (Lee and Chung, 2011)



As shown in Figure 1, the components of a VSL system include:

- Variable message signs for speed limit displays;

- Traffic sensors for traffic state (congestion or incidents) detection;
- Control computer for speed limit decision or control logic processing;
- Weather sensors for detecting rain, wind, temperature, and fog conditions (weather-controlled VSL).

According to the literature (Lee and Chung, 2011), VSL is expected to improve traffic safety significantly, and possibly contribute to mobility. The conceptual design of VSL algorithms differs according to applicable conditions, which means the VSL algorithm has a different focus and expected impact on traffic flow. However, there is no clear statement in the existing literature describing this relationship. In this paper, the principles of conceptual design for three different VSL applicable conditions in Queensland are analysed and discussed.

The structure of this paper is as follows. Three types of VSL are indentified, and three conditions applicable to Queensland are identified. For each condition, the design objective and methodology are discussed. Additionally, micro-simulation results of VSL on a Queensland motorway are presented. Finally, important findings are discussed.

2. Types of Variable Speed Limits

This paper focuses on VSL types based on their impact on traffic flow. Consequently, three different types of VSL are identified: speed harmonisation, speed buffering and speed reduction. Analyses of the impact of these VSL types on traffic flow, and potential benefits from their use, are reported.

2.1 Speed Harmonisation

Speed harmonisation refers to the potential for VSL to reduce speed differentials between vehicles and lanes. With a smaller speed differential, traffic turbulences, such as merging and lane-changing, are reduced, and a more stable traffic flow is achieved. This type of VSL typically applies to dense but still flowing traffic streams, therefore VSL activate at higher speed traffic states compared to the incident or queuing situations. The concept of speed harmonisation was first applied in practice during experiments with the Dutch Motorway Control and Signalling System in 1983 (Smulders, 1990).

Speed harmonisation might contribute to both traffic safety and efficiency. Speed harmonisation control promotes a smoother and more stable flow of traffic by decreasing speed differentials between and within lanes and by creating more uniform and acceptable headways, thus resulting in a reduced risk for primary accidents. At the meantime, fewer accidents indicate less congestion, and this uniform traffic flow could maintain high and stable throughput; therefore speed harmonisation improves motorway's performance during peak periods.

However, this may not be true in some particular situations such as motorway sections with high ramp-density. For these sections, high levels of merging and lane-changing are necessary; the dense and stable flow induced by speed harmonisation always results in short headways, which makes merging and lane-changing very difficult. Consequently, speed harmonisation may have a negative impact on traffic safety and efficiency in these situations.

2.2 Speed Buffering

Speed buffering refers to the potential for VSL to provide gradually reduced speed zones, thereby providing enough space for upstream high speed vehicles to decelerate before they encounter a traffic queue. These VSL systems are primarily designed for congestion queuing and traffic incidents. This type of VSL initially detects the presence of traffic congestion or incidents, which activate upstream VSL to warn upstream drivers and induce speed reductions in approaching vehicles to the congestion or incident location, thereby reduce the risk of rear-end crashes.

Obviously, speed buffering contributes significantly to traffic safety. Research by Hiromi Ikeda and Masahiko Matano (1999) reported a reduction of 3.9% in the total number of accidents using a congestion tail display system.

2.3 Speed Reduction

Speeding is a major contributor to crashes, crash fatalities and severity. Zarean, Robinson and Warren (2000) cited speeding as a contributing factor in 12% of all crashes and 31% of all fatal crashes. A slight reduction in average speed in high risk conditions may contribute to significant decreases in crashes and injury severity (Carlson et al., 2010). VSL can be used to regulate drivers to stay at the most appropriate speed.

Speed reduction VSL are designed to suit changes in environmental conditions such as visibility and slippery surface. These VSL systems adjust the speed limit downwards when events such as adverse weather and/or poor road conditions are detected. A common determinant for installing this VSL type is frequent poor weather conditions. VSL receive weather data from Road Weather Stations (RWS) that operate multiple sensors in the air and also under the road surface to detect rain, temperature, fog and slippery surface conditions. This type of VSL often allows operators to manually modify the speed limit in addition to automated speed control logics embedded in the system computer.

3. Variable Speed Limits Practice in Queensland

Queensland's motorways experience a large volume of commuter traffic in peak periods, leading to heavy recurrent congestion and a high frequency of incidents. Additionally, adverse weather conditions such as thunder storms or cyclones are common in some areas. Accordingly, the local authority - Queensland's Department of Transport and Main Roads - identifies three suitable applicable conditions for VSL to improve traffic safety and motorway efficiency: high flow conditions, queuing conditions and adverse weather conditions. The rest of this section explains the design objectives and methodologies for the three conditions.

3.1 High Flow Conditions

High flow conditions describe the traffic flows which are approaching to or are close to the motorway section capacity. This is the most common condition during recurrent congestion periods.

3.1.1 Objectives

When motorways are running at high flow conditions, the probability of flow breakdown is also very high. Under such conditions, flow breakdown is often triggered by traffic turbulence (for example, one vehicle braking to allow an aggressive driver to merge onto the motorway). The major turbulence includes (Queensland Dept. of Transport and Main Roads, 2008):

- Speed differentials between both vehicles and lanes; and
- Lane-changing and merging.

A speed harmonisation VSL reduces the speed differentials between vehicles, and especially the speed differentials between different lanes, thereby diminishing the advantage of travelling in the fast lane. Consequently, lane utilization is more even and vehicles are less likely to change lanes for the purpose of overtaking. These behaviours were observed in London on the M25 (Highways agency, 2004).

The objective of using VSL under high flow condition is summarised as follows:

> *The application of speed harmonisation VSL is likely result in a more stable traffic flow, creating increased traffic safety and decreased probability of flow breakdown.*

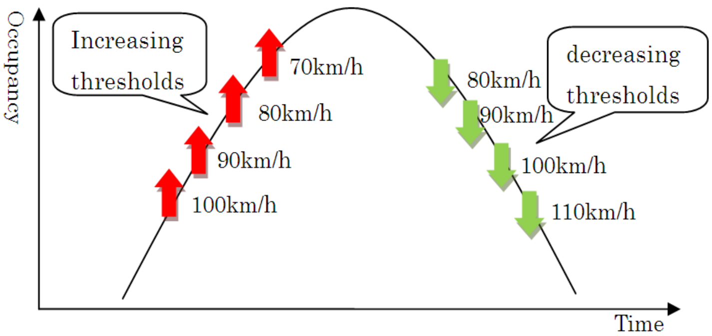
3.1.2 Methodology

Previous analyses and investigation of the Queensland experience identify two steps for incorporating a VSL algorithm under high flow conditions (see Figure 2).

Figure 2: Flow chart of VSL under high flow conditions

- Step one: select an appropriate detector measurement as the traffic state indicator. There are four common measurements available from loop detector: volume, occupancy, headway and speed. Among these measurements, occupancy is supposed to be the most stable one (Papageorgiou et al., 1991); therefore, occupancy is recommended as the major indicator. The candidate algorithm for Queensland practice under high flow conditions employs two sets of occupancy thresholds to determine the speed limits (see Figure 3). In the initial simulation test, the existing detector stations on the Pacific Motorway are considered as the real-time measurement source (details in Section 4.1).

Figure 3: Two thresholds for high flow conditions (Queensland Dept. of Transport and Main Roads, 2008)



- Step two: the logic of determining new speed limit can be retrieved from the speed-flow relationship curve (see Figure 4). According to the speed-flow curve, different speed limits have different maximum stable flow rates. Therefore, the logic of speed limit selection is stated as follows:

  > *Gradually lower the speed limit to guarantee that traffic flow remains stable at the current flow rate.*

3.2 Queuing Conditions

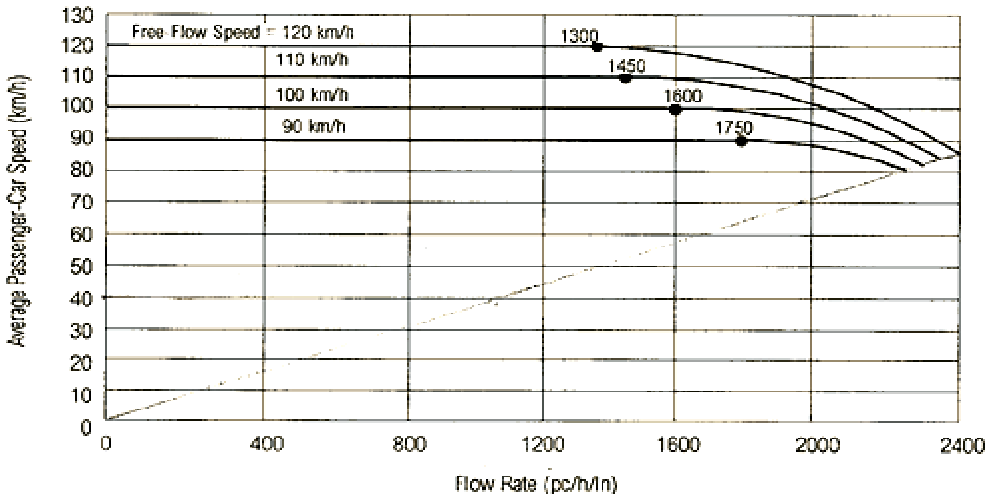
A traffic queue is defined as a vehicle platoon that is stopping or slow moving. Accordingly, queuing conditions describe traffic flow within a queue. Obviously, safety is the major concern under queuing conditions due to the high free flow speed on motorways.

3.2.1 Objectives

The free flow speed on motorways is very high (usually over 100km/h); therefore, stationary or slow moving queues can potentially be dangerous to high speed vehicles approaching from the upstream end of the motorway segment. At the point where high speed vehicles meet the end of the queue, the high speed vehicles have to adopt rapid deceleration, sustainably increasing the probability of rear end crashes. Compared with the initial incidents causing the queue, these crashes are defined as secondary crashes. Consequently, the objective of VSL use under queuing conditions is summarised as follows:

> *The deployment of speed buffering VSL enables the use of upstream VMS to provide advance warning, and induces the upstream high speed vehicles to lower their speed in advance so as to avoid secondary crashes.*

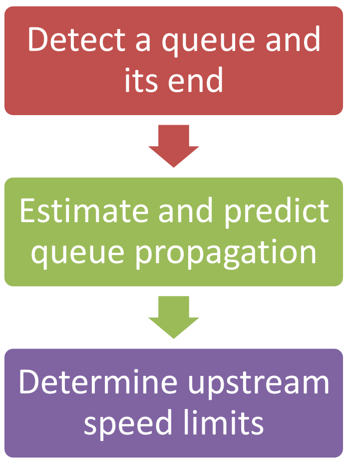
Figure 4: Speed-flow Curve (Queensland Dept. of Transport and Main Roads, 2008)



3.2.2 Methodology

Three steps are identified for designing a VSL algorithm under queuing conditions (see Figure 5).

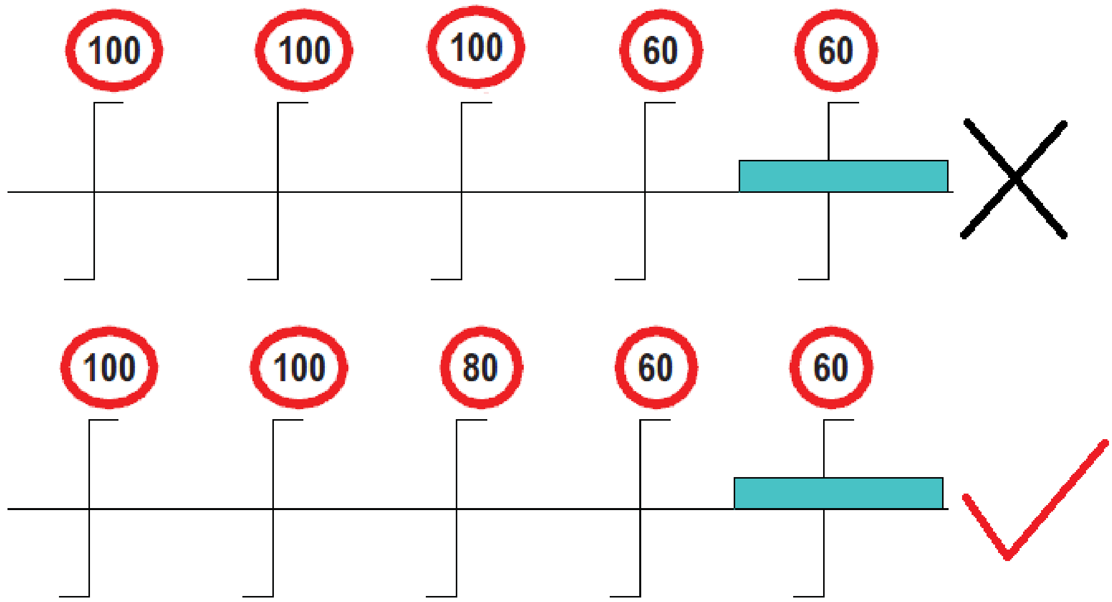
Figure 5: Flow chart of VSL under queuing condition



- Step one: significant for the whole algorithm, the faster and more accurately the queue detection is, the lower the risk of secondary crashes is. There are two types of queue detection algorithms: one is based on loop detector data, and the other is based on image processing. Neither of the two can provide perfect accuracy of queue detection, so the balance between queue detection accuracy and response time is an important issue when choosing and calibrating queue detection algorithms. For the benefit, performance and safety of the motorway, more emphasis should be put on the response time. The candidate algorithm for Queensland practice under queuing conditions employs the combination of occupancy and speed thresholds from loop detector for queue detection. Additionally, it uses configurable consecutive interval and consecutive detector stations to reduce false alarm.

- Step two: under queuing conditions, the activated speed limits are much lower than free flow speed; therefore, these speed limits should only be activated when necessary. An accurate estimation and prediction of queue propagation can make the algorithm more precise and proactive.
- Step three: the logic here is simple, reducing the upstream speed. Because the activated speed limits (less than 60km/h) are much lower than normal speed (over 100 km/h), it is better to have a medium level speed limit (80 km/h) area as a buffer between normal speed and the activated low speed limit. Figure 6 demonstrates the recommended way to reduce speed limits.

Figure 6: Travel Principles for reducing upstream speed limits



3.3 Adverse Weather Conditions

Weather is an important factor affecting motorway capacity and traffic safety. Firstly, weather can profoundly change driving environments. For example, rain can reduce the visibility and increase the braking distance (Chung et al., 2006). Furthermore, drivers tend to have longer responsive times under adverse weather conditions. Therefore, the suitable speed under these conditions should be lower (around 20km/h) than in normal situations.

However, previous studies (Karkowski and Chung, 2007) reveal that drivers do not adapt their driving to adverse weather conditions. For instance, the headway differentials with dry or wet surface are almost the same, and the average speed does not reduce significantly. This mismatch between driving environments and the actual driving behaviour leads to an increasing risk of crashes.

Accordingly, the application of speed reduction VSL under adverse weather conditions will regulate drivers' speed to a safe level. This is the objective of weather-based VSL.

The methodology for adverse weather condition VSL is very simple. When adverse weather is confirmed by weather stations, weather-based VSL allow operators to manually modify the speed limit, or automated speed control logics embedded in the system computer are activated.

4. Micro-Simulation Results

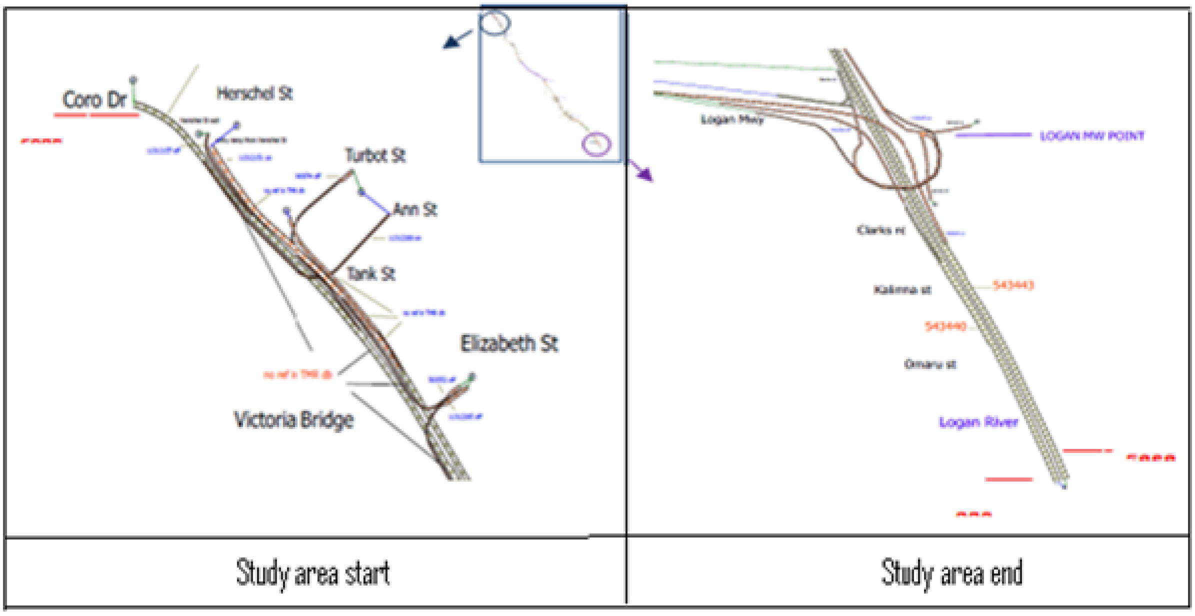
In this section, simulation results of high flow conditions and queuing conditions for a Queensland motorway are presented. The motorway model and simulation platform are introduced first. Then, the results for both high flow conditions and queuing conditions are presented.

4.1 Network Description and Simulation Model

4.1.1 Pacific Motorway

A 30-km section of the northbound Pacific Motorway (M3) which connects Logan city and the Brisbane CBD was selected as the study network (See Figure 7). The M3 services a large volume of commuter traffic in both morning and evening peak periods, leading to heavy recurrent congestion and a high frequency of incidents. For these reasons, local authorities consider the M3 as an ideal motorway to deploy VSL to alleviate serious congestion problems in southeast Queensland, Australia.

Figure 7: the Pacific Motorway in Brisbane



The M3 has five mainline lanes at its start and end, and mostly three mainline lanes in between. It experiences a volume of 130,000 vehicles daily. Installed on the motorway are 49 dual-loop detector stations in the northbound mainline, spaced approximately 650m apart, and single-loop stations on the on- and off-ramps. Speed, volume and occupancy are recorded every minute for all mainline stations, while volume and occupancy are recorded for all ramp stations. There are two default speed limits in the study network, 80 km/h for the sections near the Brisbane CBD and 100 km/h for other sections.

4.1.2 Simulation Model

The preferred modelling platform in use is Aimsun 6.1, which is a sophisticated micro-simulator with high user flexibility with plenty of toolkit (e.g. scripting and API).

The Aimsun network for the M3 contains 48 sections and 15 on-ramps northbound. The network was edited by Queensland's Department of Transport and Main Roads, and model parameters calibrated by QUT's Smart Transport Research Centre (Chung et al., 2011). Once the demand scenario was prepared, the model was ready for testing.

A complete scenario to depict the real traffic demand on the network was developed in terms of traffic state according to the PTDS (Public Transport Data Source) database. The selected case day was 15th March 2010, this being a regular business day (Monday) with major educational institutions running, good weather prevailing (no rain) and no incidents reported. The complete scenario was conducted for a period of 17-hour with time intervals of 15 minutes.

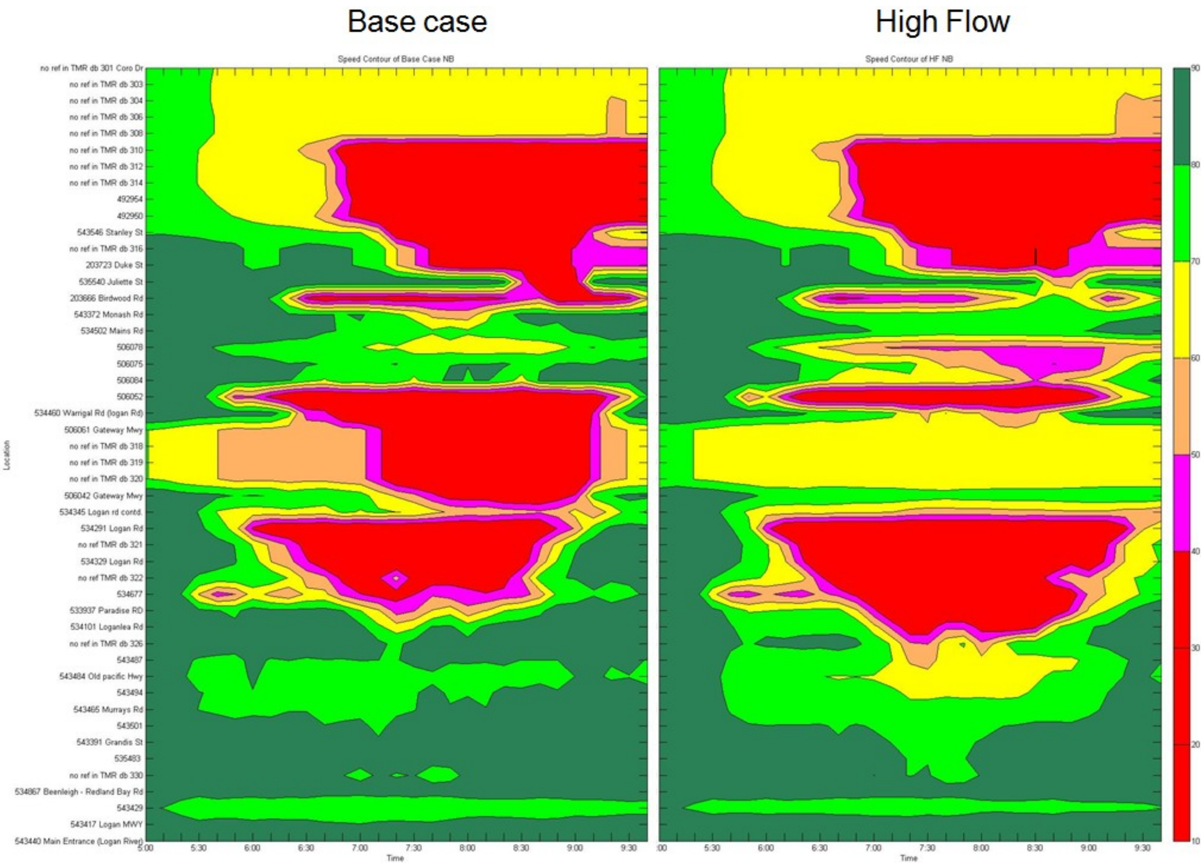
4.2 Results of High Flow Conditions

In order to evaluate the performance of VSL under high flow conditions, a 5-hour morning peak period was selected, when the northbound of the Pacific Motorway experiences high levels of recurrent congestion. Two scenarios were tested for comparison:

- Base case scenario – without any traffic management activated; and
- High flow VSL scenario – with a speed harmonisation VSL activated (Queensland Dept. of Transport and Main Roads, 2008).

A comprehensive "before and after" comparison was conducted (for detail refer to (Chung et al., 2011)). The results include speed contour comparison and operational analysis. Figure 7 illustrates the speed contour comparison, and Table 1 lists the results of operational analysis including travel time, speed deviation, fuel consumption and emissions.

Figure 8: Speed contour comparison of high flow conditions



An analysis of Figure 8 indicates that most of the network experiences a slightly increased speed. However, the traffic situation from Murrays Road to Logan Road (12 sections in total) deteriorates (longer and expanded congestion) when VSL is activated. In this area, there are 6 on-ramps with high demand and 4 off-ramps with large flows, so a large number of lane-changing and merging are necessary. When VSL is activated, lower speed limits increase traffic density which makes it difficult for lane-changing and merging. Consequently, congestion is even more significant.

Conclusions are summarised as follows. VSL is able to achieve speed harmonization and better environmental impacts. However, it makes congestion more significant for the section with high ramp-density and large ramp flows. Therefore, the speed harmonisation type of VSL is suitable for those motorway sections which have low ramp-density or where the ramp flows are small.

Table 1: Results of operational analysis

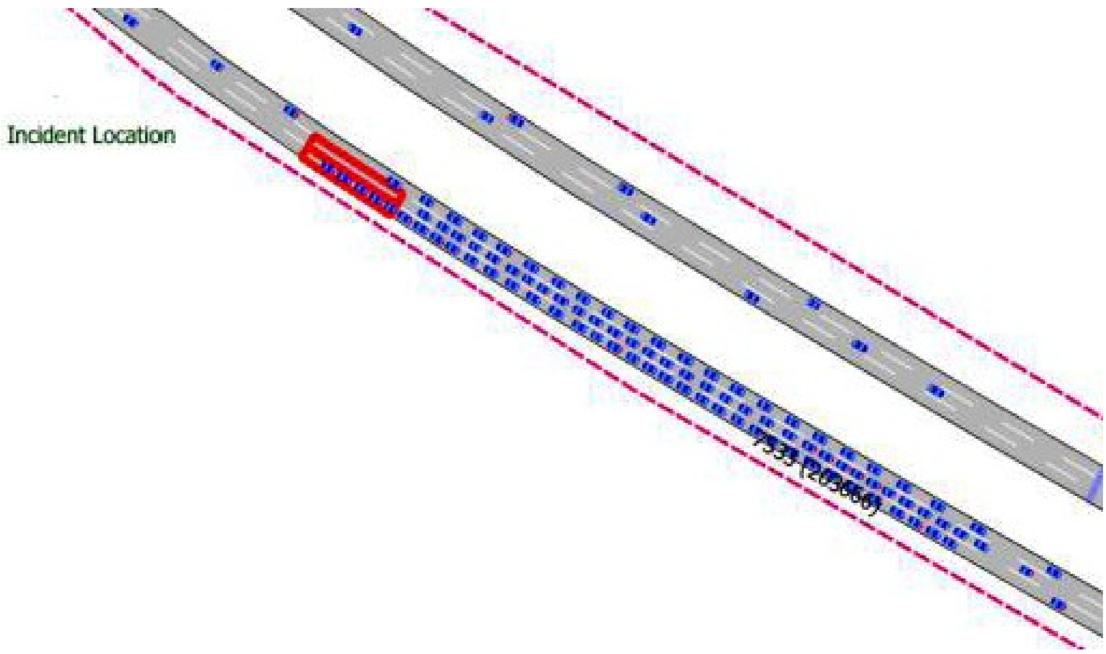
	Base Case	High flow VSL scenario	Change (%)
Travel Time	71.06 s/km	70.77 s/km	-0.41%
Speed Deviation of CS	7.46 km/h	6.61 km/h	-11.39%
Fuel Consumption	98803 L	90812 L	-8.08%
Emission of CO2	230073 kg	222050 kg	-3.49%

4.3 Results of Queuing Conditions

In order to evaluate the performance of VSL under queuing conditions, an incident was artificially created and modelled in Aimsun on a section of north bound of the Pacific Motorway. The incident was created in the middle of the section and is 400 meters from the first upstream detector. Furthermore, the section itself had enough distance from off and on-ramps such that the ramp traffic did not affect the incident detection. Figure 9 indicates the section and the incident position in the network. The incident was created in afternoon off peak periods. In this incident two lanes are blocked for a duration of 20 minutes(Chung et al., 2011). Two scenarios were also tested for comparison:

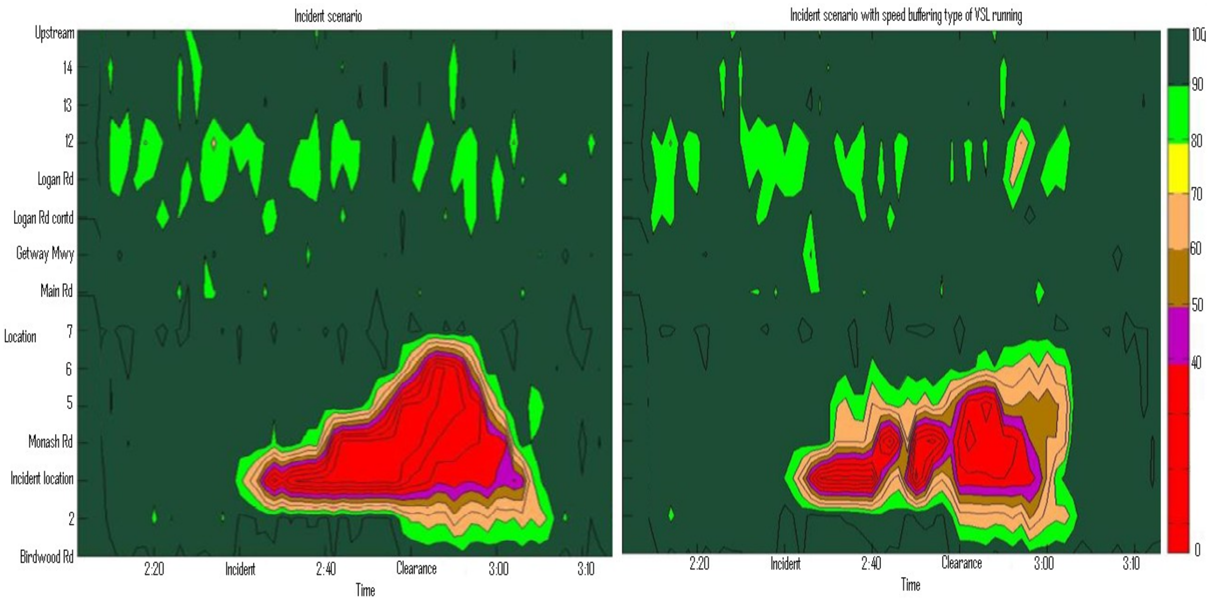
- Incident scenario – without any traffic management; and
- Queuing condition VSL scenario – with a speed buffering VSL activated (Queensland Dept. of Transport & Main Roads, 2008).

Figure 9: Incident scenario



The speed contours of both scenarios are shown in Figure 10. With the speed buffering VSL activated, the upcoming traffic flow approaches the end of the queue at a lower speed and speed differences at the end of queue significantly decline. This is predicted to reduce secondary crashes. Apart from this safety improvement, the bottleneck caused by the incident become lighter, allowing traffic to pass the incident location in a much smoother manner.

Figure 10: Speed contour comparison of queuing conditions



5. Conclusions

VSL is a promising motorway traffic management tool for improving traffic safety by offering drivers more realistic speed limits when the driving environments are compromised by traffic congestion, incidents or adverse weather.

This paper identifies three types of VSL based on their impact on traffic flow, as well as three corresponding applicable conditions for VSL under Queensland practice. The design objectives and methodologies for each condition are then analysed. Micro-simulation results for high flow conditions and queuing conditions reveal that the candidate algorithms for Queensland conditions are able to meet the proposed objectives.

Important conclusions concerning the use of each type of VSL are as follows:

- Speed harmonisation VSL is a suitable management tool for high flow conditions, and is suitable for motorway sections which have low ramp-density or where the ramp flows are small;
- Speed buffering VSL can improve traffic safety and reduce secondary crashes under queuing conditions. Simulation results also indicate that this VSL could contribute to the clearance of incidents.

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