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Variable Speed Limits for Motorway Off-ramp Queue Protection

Gongbin Qian[1] and Jinwoo (Brian) Lee[2]

***Abstract*— Motorway off-ramp is a main source of traffic congestion and collisions. Heavy diverging traffic and associated lane changings to off-ramp slows down the mainline traffic speed. When the off-ramp queue spills onto the motorway mainline, it may cause a major breakdown of the motorway capacity and a significant threat to the traffic safety. This paper proposes using Variable Speed Limits (VSL) to protect the motorway off-ramp queue to improve safety in congested diverging areas through microsimulation tests. To support timely activation of VSL in advance of queue spill-over, a proactive strategy is proposed based on off-ramp queue estimation and new arrival prediction in the near term. This process determines the estimated queue size on the off-ramp in the near-term, on which the decision to change speed limits is made. VSL can effectively slow down traffic as it is mandated and enforceable in Queensland, Australia. As a possible scenario, reduced speed limits could make drivers more attentive to the surrounding condition, and prepared for a sudden braking of the leading car. This paper analyses and quantifies this possible effect of VSL on traffic safety and efficiency using the microsimulation approach.**

***Index Terms*— Variable speed limits, VSL, Motorway, Freeway, Queue protection, off-ramp, Traffic control, Managed Motorways**

I. Introduction

Motorway off-ramp is one of main sources of traffic congestion and collision. Heavy diverging traffic slows down the mainline traffic. Off-ramp queue may spill onto the mainline and lead to a major breakdown of the motorway capacity [1]. The risk for rear-end and side-crashes increases as a result of sudden braking or forced lane changing to avoid crashing into the back of the queue. It also affects the mainline throughput. In reality, drivers may attempt to change lane nearly at the last second before the off-ramp entrance [2]. As a result, an off-ramp queue may spread laterally by blocking additional lanes causing a serious disruption to the mainline flow [3].

The main cause of off-ramp queue varies from one site to another and so does its countermeasure. Major geometric improvements such as road widening or additional lanes will effectively increase the exit capacity. Alternatively, improving the interchange signal timing can be a more cost-effective option. However, congestion is inevitable when the exit traffic temporarily concentrates exceeding the interchange capacity. Upon the onset of queue spill-over, motorway drivers must be warned in a timely manner to make appropriate reactions to avoid crash. Advanced queue warning signs via Variable Message Signs (VMS) are widely used in practice, but their effectiveness is largely dependent on the drivers' compliance and credibility of the information [4, 5, 6].

This paper proposes using Variable Speed Limits (VSL) for protection of motorway off-ramp traffic to improve the safety in congested motorway diverging areas. Although various VSL strategies have been introduced in the literature, the primary use aimed at warning of incident or congestion on the motorway mainline, or mitigating the bottleneck problem by regulating the traffic inflow. VSL can be an effective measure to improve safety at congested off-ramps for the following reasons: i) mandated VSL effectively reduces the risk of crash by reducing the approaching speed of motorway traffic; ii) reduced driving speeds restrict the inflow to congestion and thus relieve the queue growth; iii) a possible effect of VSL could make drivers more attentive to the surrounding traffic conditions and prepared for a sudden braking of the leading car.

The traffic condition on motorway off-ramps is heavily dependent on the mainline volume and the downstream interchange capacity. To enable the timely activation of VSL in advance of queue spill-over, a proactive control strategy is proposed based on the real-time off-ramp queue estimation and traffic arrival prediction in the near-term. The queue estimation component approximates the current queue size on the off-ramp. The prediction component forecasts new arrivals for the next control interval. This combined process determines the chance of queue spill-over in the near-term, on which the decision to change speed limit is made.

A brief review of VSL follows this section. The next section introduces the control concept of the proposed strategy. A queue estimation algorithm, developed in a previous study of the authors [7], is presented. A short-term traffic flow prediction is proposed in the following section. This study quantifies the impacts of the proactive VSL versus conventional reactive control and no-VSL scenarios. The study is concluded with findings and recommendations in the last section.

Gongbin Qian is a consultant at China Design Group Co., Ltd. (e-mail: gongbinqian@gmail.com)
Brian Lee is a senior lecturer at Queensland University of Technology (e-mail: brian.lee@qut.edu.au)

Jinwoo (Brian) Lee is a senior lecturer at the School of Civil Engineering and Built Environment, Queensland University of Technology, Brisbane, QLD 4000 Australia (phone: +61-7-3138-9952; e-mail: Brian.Lee@qut.edu.au)

II. Variable speed limits

VSL provides more realistic speed limits when the driving environments are imminently compromised. Since the first experiment undertaken in the early 1960s, numerous VSL have been tested and implemented in a range of different field and simulation environments. Types of VSL may fall into several categories according to the types of event that trigger a speed limit change and the control objectives.

Motorway traffic safety is often threatened by traffic queues resulting from flow breakdowns or incidents. Rear-end crashes occur between stationary or slowly-moving queues and the high-speed vehicles approaching from upstream. Real-time warning information about the queue downstream allows drivers to prepare appropriate responses, preventing them from rushing into the queue end. Most of the existing VSL systems are designed to alleviate this problem. VSLs are used to alert drivers and to lower the operating speed of vehicles, by which the risk and severity of rear-end accidents decrease. Properly designed and operated VSL can effectively reduce the accident frequency and fatality as reported by a number of studies conducted in Australia [8], the United Kingdom [9], Germany [10], Finland [11], Sweden [12] and the USA [13].

Speed reduction could lessen the speed differentials between vehicles, by which a more stable traffic flow can be achieved. Another type of VSL aims at enhancing flow efficiency by using this possible effect of speed limit reduction. The control principle is based on a general hypothesis that reduced speed differentials and increased density in a VSL-applied traffic stream are likely to prevent or delay the onset of congestion, because the frequency and magnitude of traffic turbulences decrease in harmonised traffic streams.

Zackor [14] proposed using the "speed harmonization" effect to increase the critical occupancy and thus to delay the onset of bottlenecks under peak-hours traffic conditions. Hegyi et al. [15] suggested that activation of VSL in critical condition could delay the onset of congestion by reducing the mainstream flow arriving at the bottleneck. Papageorgiou et al. [16] reported through their analysis of 27 days of field data that VSL could increase the critical occupancy point and enable higher flows at the same occupancy state. Later, Heydecker and Addison [17] examined the VSL effect on motorway occupancy and how reduced speed limits induce greater occupancy and increased capacity.

A number of studies attempted to mitigate the motorway bottleneck problem by adaptively regulate the traffic inflow to the downstream bottleneck using VSL. Hegyi et al. [15] used a modified METANET for the bottleneck mitigation through a proactive inflow control strategy. Later, Hegyi et al. [18] proposed an improved VSL strategy that triggers the VSL activation based on shockwave detection. Emerging techniques such as the Genetic-fuzzy control was introduced for fine-tuning of VSL control and associated parameters [19].

Carlson et al. [20, 21] proposed Mainstream Traffic Flow Control (MTFC) for optimal motorway traffic flow control using VSL integrated with ramp metering. Their integrated VSL and ramp metering control in the MTFC framework was tested in various test environments [22]. Later, the MTFC-VSL was extended through an enhanced local feedback approach to allow different control periods for ramp metering and VSL [23].

Chen et al. [24] proposed a series of VSL schemes based on the Kinematic Wave theory to resolve motorway bottlenecks under two scenarios. The first strategy is applied to dissipate a downstream bottleneck by regulating the inflow through upstream VSLs. The subsequent strategy aims to resolve the traffic queue generated by the first VSL control and to maintain the stable traffic flow at the downstream bottleneck location. A later study by Chen and Ahn [25] proposed more strategies to control VSL to mitigate non-recurrent motorway bottlenecks by inducing smooth and gradual speed transition and stable discharging flow.

A recent empirical study by Soriguera et al. [26] revealed the low speed limits (40 km/h) could increase the traffic flow density in the critical condition, but also increase the speed differences across lanes for moderate traffic conditions.

More applications of VSL are found in the recent literature. Heavy diverging traffic and extended off-ramp traffic queues impose a significant risk to the safety of motorway traffic. Soekroella et al. [27] proposed a dynamic lane separation strategy to prevent the blocking back problem at motorway off-ramp.

The literature explores various implementations of VSL through field and simulation tests. The main application of VSL has been for advanced warning of hazardous driving environments. To this context, VSL can be an effective countermeasure to protect the off-ramp congestion and queue spillover.

III. Proactive speed limit control

VSL utilises a series of traffic sensors and VMSs mounted on overhead gantries to display speed limits.

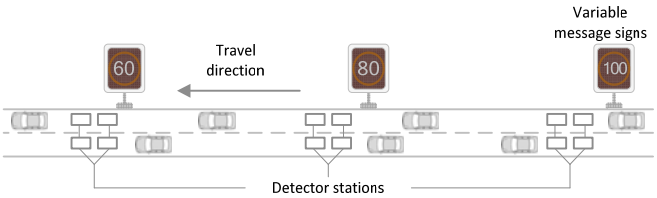

Fig. 1. Variable speed limits

Traffic data is collected in the form of speed, flow and occupancy via inductive loop detectors. High occupancy rates, low speeds, or combination of both are good indicators of an incident or traffic congestion. Decisions to switch speed limits are made by comparing the detector measurements (i.e., flow, speed, or occupancy) to pre-defined activation and deactivation conditions. VSL is activated upon a detection of deteriorated traffic conditions and a new speed limit replaces the existing one at the upstream segments from where the congestion is identified.

It is critical that traffic queues are detected in a timely way to implement appropriate response through VSL. Conventional VSL relies on a simple reactive control that triggers the speed limit change upon an observation of traffic congestion. In the

absence of a reliable forecasting capability, this control approach will only react to congestion or incidents that already have been occurred. Reactive control essentially assumes that the current traffic condition will last for the near-term, which is obviously inaccurate for off-ramp traffic conditions which fluctuates quickly and largely by the interchange traffic signal.

The proposed VSL strategy attempts to overcome this limitation by employing a proactive mechanism for the speed limit activation and deactivation. As shown in Figure 2, the strategy determines the control action based on the forecasted queue size in the near-term.

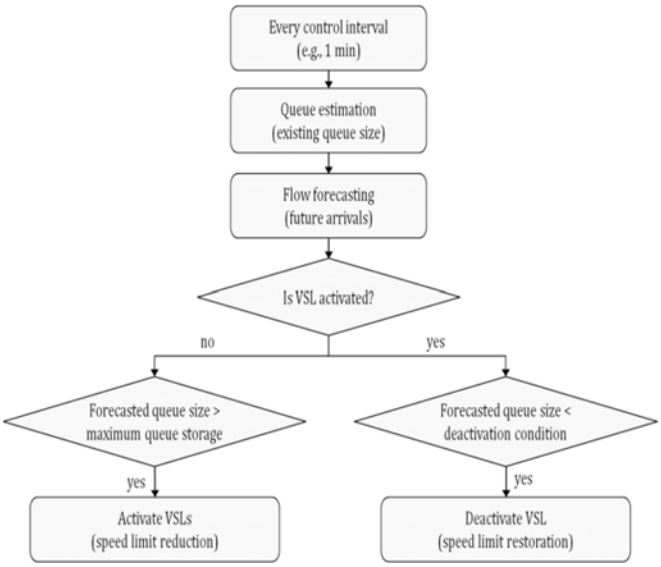

Fig. 2. Proactive VSL control strategy

The queue estimation algorithm estimates the current queue size on the off-ramp in every control interval. Forecasting is performed in every control interval for the next 15-minute forecasting horizon. The future queue size is calculated simply by adding the predicted new arrivals to the current queue size. The speed limit is reduced if the forecasted queue size is greater than the maximum queue storage of the off-ramp. The speed limit is restored to the original setting when the queue size becomes normal.

IV. Off-ramp queue estimation

This section introduces a queue estimation algorithm, which was developed for motorway off-ramps in a previous study of the authors. Only the basic concept is introduced in this paper and more details about the algorithm can be found elsewhere [7].

The queue estimation algorithm approximates the spatial occupancy distribution over the link using the local occupancy measurements from two loop detectors: one in the middle of the link and the other one at the link entrance. The time occupancy is a direct measurement obtained from loop detectors, which is computed as the proportion of the time period in which the detector is occupied by vehicles. The space occupancy is the proportion of road space covered by vehicles, and is not a direct measurement obtained from loop detectors.

Figure 3 shows some examples of the queue estimation for different queue sizes. In the figures, the mid-link loop detector is denoted as H_1 and the link entrance detector as H_2. O_1 and O_2 are the time occupancy measurements from detector H_1 and H_2, respectively. The solid lines indicate the observed time occupancy and the dash lines indicate the estimated space occupancy by the proposed algorithm.

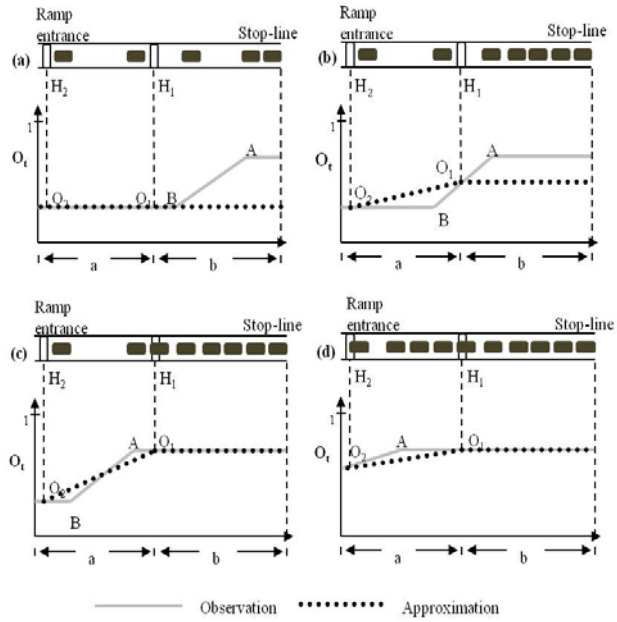

Fig. 3. Queuing vehicles and occupancy approximation

In figure (a), a short queue formed at the stopline does not affect the detector measurements, O_1 and O_2. As the queue grows and approaches H_1, the vehicles passing H_1 need to reduce speed, which will increase O_1, as displayed in figure (b). In figure (c), the queue end locates between H_1 and H_2. Since H_1 is under the queue, O_1 induces a very high time occupancy, whereas the traffic passing H_2 is not affected by the queue yet. Figure (d) shows a nearly saturated condition that the queue impedes the upstream traffic. As a result, both O_1 and O_2 will produce very high time occupancies implying that all the vehicles in the link are affected by the queue.

The proposed queue estimation approximates the space occupancy by plotting a connection line between O_1 and O_2, and another horizontal line from O_1 to the stopline direction as displayed as the dash lines in figures. This processing assumes a uniform occupancy of O_1 for the downstream segments between H_1 and the stopline. It also assumes that the space occupancy changes proportionally at the rate of $\frac{O_1+O_2}{2}$ for the upstream segments between H_1 and H_2, whereas the estimated space occupancy is equal to either O_1 or O_2 if $O_1 = O_2$.

Let "a" denotes the link length of the upstream section between H_1 and H_2 and "b" denotes the downstream section between H_1 and the stop line. The area covered by the dash lines, or estimated space occupancy, $\overline{O}'$, be computed using the following equation:

$$\overline{O}' = \frac{(a+2b) \times O_1 + a \times O_2}{2(a+b)}$$

Applying the relationship between the space occupancy and density, which can be defined as $\overline{O}' = aD$ (a is a linear coefficient and D is the traffic density, the above equation can be re-written as the following:

$$D = \frac{(a+2b) \times O_1 + a \times O_2}{2\alpha(a+b)}$$

Eventually, the link density is expressed using two measurable quantities, namely, the local time occupancy measurements from H_1 and H_2 in the above equation.

V. SHORT-TERM TRAFFIC FLOW FORECASTING

In transport, the importance of short-term traffic forecasting has been recognised from the 1970s [28]. Afterwards, diverse approaches have been suggested to address the problem of short-term traffic forecasting for a variety of advanced traffic management and traveller information applications. Existing forecasting techniques can be classified into parametric and nonparametric approaches [29]. A simple autoregressive integrated moving average (ARIMA) model is developed in this study. ARIMA is one of the most commonly used parametric technique, of which the original form was developed by Box and Jenkins [30].

A. Autoregressive Integrated Moving Average

A time series model using ARIMA uses a sequence of data, measured in successive and uniform time intervals to make predictions for the future status. The fundamental ARIMA (*p, d, q*) consists of p degree of the autoregressive (AR) process, d degree of differences, and q degree of the moving average (MA) process. The autoregressive process for a time series $\{Yt\}$ is displayed as following:

$$Y_t = c + (\phi_1 B + \phi_2 B^2 + \cdots + \phi_3 B^3) Y_t + e_t$$

$$Y_t = c + \phi_1 Y_{t-1} + \phi_2 Y_{t-2} + \cdots + \phi_p Y_{t-p} + e_t$$

Where, B is the backshift operator, $B^p Y_t = Y_{t-p}$; e_t is the noise term which cannot be explained by this model; p is the degree of the AR term; $\phi_1 \cdots \phi_p$ are the autoregressive coefficients; and c is a constant.

The moving average (MA) term is the disturbance component of the time series, averaging the successive error terms, as followings:

$$Y_t = c + \left(\theta_1 B + \theta_2 B^2 + \cdots + \theta_q B^q\right) e_t$$

$$Y_t = c + e_t + \theta_1 e_{t-1} + \theta_2 e_{t-2} + \cdots \theta_q e_{t-q}$$

Where, q is the degree of the MA term; and $\theta_1 \cdots \theta_p$ are the moving average coefficients.

The I component makes the date stationary. I represents the degree of difference to transform the data into a stationary series. A d degree of differencing can be expressed as:

$$(1-B)^d Y_t = c + e_t$$

B. The Data

The loop detector data was collected for the model development for a period of three weeks from the 21st of March to the 10th of April in 2011. The loop detectors are located approximately 120 metres from the off-ramp stopline. The forecasting model was developed using the traffic count data in the 15-minute interval to forecast the new arrival for the next 15 minutes interval. The 15-minute forecasting interval was used for consistency with the traffic signal timing update interval of the off-ramp (interchange) signal controller. Longer forecasting periods than 15 minutes will restrict the response speed to abrupt changes in the traffic flow while shorter periods may result in instability in the forecasting accuracy due to random noises.

C. Model Development

One of the fundamental requirements for the time series modeling is that the data series or the transformed series by differentiating the original data must be stationary. That is to say, if the randomness of the dataset outweighs the trends, time series models are not a suitable option. This study analysed the data stationarity by visually checking the time-series plots. A stationary time series means that the data fluctuates around an expected mean value within a certain range of amplitude. Figure 4 illustrates the daily variation of traffic flow over one-week period on the Moggill Road off-ramp. This off-ramp was selected for a case study due to the heavy exit traffic and frequent queue spillover during the afternoon peak-hours. The traffic flow data show clear uphill and downhill trends during peak hours and late-night hours, where the statistical properties would be different from the other periods. Such seasonality is an evidence of non-stationarity of time-series data. The graph confirms that transformation of the original data is required.

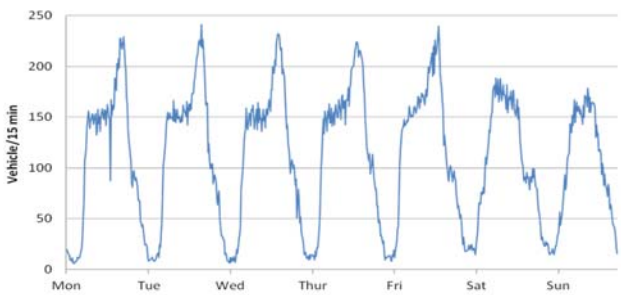

Fig. 4. Traffic flow daily variation on the Moggill Road Off-ramp

"d" Parameter

Figure 5 shows the first, second, and third order differentials of the original data (i.e., d=1, d=2, and d=3, respectively) for one day. For example, the first order differentiation implies a

transformation of the original data into the change in the 15-minute interval traffic count between two consecutive intervals. It is seen from the graph that the processed data show varying levels of fluctuation around "0" regardless of the time-of-day. Furthermore, the first order differential produced the least and relatively consistent amplitudes, which indicates a good presence of the stationarity in the processed data.

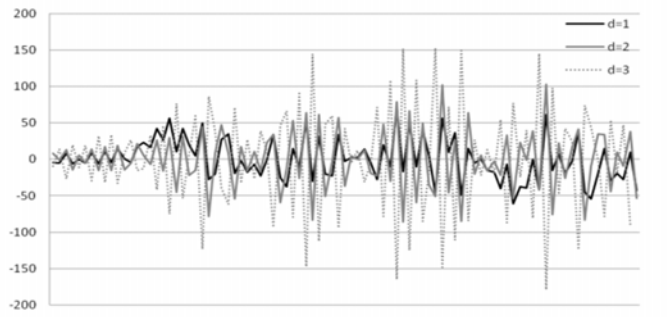

Fig. 5. Test results of the degrees of difference parameter.

"p" And "q" Parameter

According to the ARIMA model expression, "*p*" and "*q*" parameters decide the levels of relationship between the current status and the historical observations, respectively. A general method to analyse and select these two parameters is using autocorrelation and partial autocorrelation statistics. Autocorrelation refers to the way the observations in a time series are related to each other and is usually calculated from the difference between the observation in the current interval and a previous observation in "*p*" interval, as shown in the following equation:

$$r_p = \frac{\sum_{t=1}^{n-p}(Y_t - \bar{Y})(Y_{t+p} - \bar{Y})}{\sum_{t=1}^{n}(Y_t - \bar{Y})^2}$$

Where, r_p is the autocorrelation for degree of *p*; Y_t is the current status; and $\bar{Y}$ is the mean of the series.

The partial autocorrelation measures the degree of association only between the current status and a previous observation in "*q*" interval. In other words, the calculation of partial autocorrelation uses the same equation with autocorrelation but remove all the observation of Y1, Y2,… and Yq-1. It should be noted that normally a higher degree of "*p*" and "*q*" will not necessary improve the prediction accuracy. This is because of the time-varying trend of traffic count data, which implies that is the future traffic count is highly dependent on the most recent condition. The selected parameter values are *p=2* and *q=1* in this study.

D.Model Calibration and Validation

ARIMA models consist of two types of coefficient including the AR coefficient, $\phi_1 \cdots \phi_p$, and the MA coefficient, $\theta_1 \cdots \theta_p$. These coefficients were determined using SPSS for the forecasting model to produce the best outcomes for given traffic flow data. The study uses two measure of performance for calibration and validation including mean absolute percentage error (MAPE) and root-mean-square error (RMSE). MAPE is a measure of the estimation accuracy in percentage (%). A small MAPE value indicates the more accurate estimation. RMSE is a measure of estimation stability in terms of number of vehicles. A smaller RMSE value indicates a higher degree of estimation reliability.

$$MAPE = \frac{1}{n}\sum_{n}\left|\frac{(Observation - Estimation)}{Observation}\right| \times 100\%$$

$$RMSE = \sqrt{\frac{1}{n}\sum_{n}(Observation - Estimation)^2}$$

For validation, additional traffic count data was collected for a period of one week (from the 26th of September to the 2nd of October in 2011). The calibrated ARIMA (2,1,1) model resulted in 8.12% of MAPE and 14.13% of RMSE. The number of sample points (15-minute traffic count data) was 672. The results indicate a reasonably good accuracy. Figure 6 shows a sampled one-day actual and predicted traffic counts for illustration purpose.

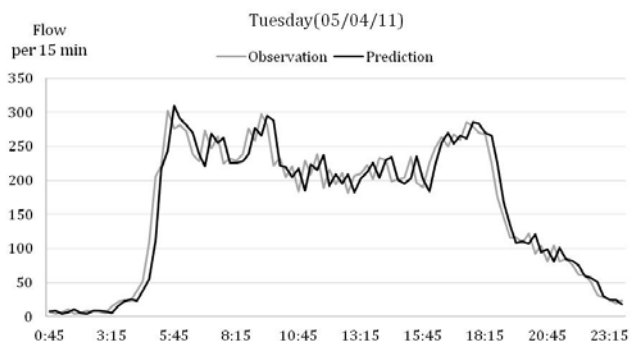

Fig. 6. Actual vs predicted traffic count (the 5th of April, 2011)

VI. SIMULATION TESTBED AND SCENARIOS

The proposed VSL strategy was tested under a microsimulation environment using Aimsun [31]. Moggill Road off-ramp on Western Motorway in Brisbane, Australia, was chosen for a case study. The off-ramp traffic frequently spilled onto the motorway mainline during the afternoon peak hours causing serious safety and congestion issues. Figure 7 depicts a sketch of the motorway segment. The motorway mainline in the diverging area consists of two travel lanes. The posted speed limit is 90km/h for the mainline and 60km/h for the off-ramp. The Moggill Road off-ramp is approximately 110-metre long from the stopline to the diverging point. There

are three lanes including an exclusive left-turning lane and two tight-turning lanes.

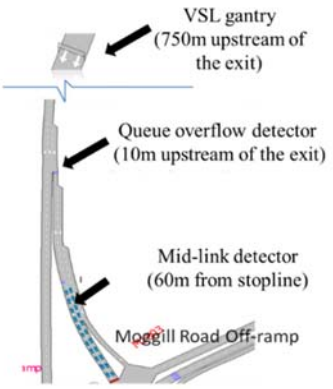

Fig. 7. Sketch of the study area

The right-turning traffic at the interchange is the main source of excessive delay and extended traffic queues on the off-ramp during the afternoon peak-hours. Figure 8 illustrates the traffic queue sizes, counted from CCTV images on the 6th April, 2011.

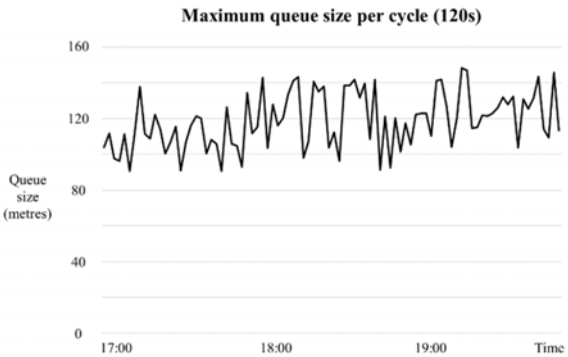

Fig. 8. Maximum queue size per cycle (CCTV observation, April 6, 2011)

A. Simulation Model Development and Calibration

The VSL strategy was implemented in the Moggill Road simulation network. Total simulation period was 2 hours and 15 minutes representing the afternoon peak from 16:00 to 18:15. The last 15 minutes was used as a clearance period. The actual loop detector data was used to model the traffic demand. The test network includes the interchange intersection and an approximately 1.3 km segment of the motorway.

Reactive and Proactive Variable Speed Limit Control

The original speed limit in the study area is 90 km/h. There was no existing VSL or speed limit gantry in the area when the study was undertaken. For the microsimulation modelling, one VSL gantry was installed 750 metres upstream from the entrance to the off-ramp. The location was chosen to allow sufficient distance and time for drivers to make appropriate reactions according to the current design guideline of the local motorway agency.

Two VSL control strategies were modelled and tested against the base scenario assuming disabled VSL operation. The reactive control utilises the time occupancy measurement from the queue overflow detector (Figure 7) to activate and deactivate VSL. The activation threshold was set at 20% of time occupancy and the deactivation threshold was set at 15% of time occupancy based on the observations from the actual detector data.

The proactive control estimates the queue size at every 15-second interval. The estimated queue size is added to predicted new arrivals for the next 15-second interval, which is then compared to the maximum queue size (i.e., 14 vehicles per lane) to decide the speed limit reduction.

Both the reactive and proactive controls were designed to reduce the speed limit to 60 km/h from its normal setting (90 km/h) without a transient speed limit. The 30 km/h decrement is in accordance with the guidelines of Standards Australia. Australian Standard 1742.4 suggests the safest speed limit of the upstream of the incident site with the increment of 30 km/h [32].

Traffic Signal Control

The traffic signal control at the interchange intersection was a semi-actuated mode that adjusts the green time for the off-ramp approach based on the number of traffic counts at the stopline detectors. This actuated phase was frequently extended to its maximum setting (38 seconds) in the afternoon peak-hours. As a result, the traffic signal control was operated nearly as a fixed-time mode. To simplify modeling, the traffic signal control at the interchange was modeled as a fixed-time mode with a 120 seconds of cycle time and 38 seconds of the green time for the off-ramp traffic.

Model Calibration

The calibration of the simulation model was carried out by comparing the congestion level on the motorway mainline between simulation and actual condition. The actual motorway traffic condition was approximated through consultation with the local agency and observation of the CCTV recordings, because there is no traffic detector currently installed in the diverging area on the motorway mainline.

Adjusting the lane changing parameters was essential to replicate similar congestion level in the diverging area including the mainline blockage. Two simulation parameters define the lane changing behavior of drivers in Aimsun including “Distance Zone 1” and “Distance Zone 2”. Distance Zone 1 defines the distance that exit drivers will attempt to change to the auxiliary lane if there is a sufficient gap. If drivers are not able to find an acceptable gap, they will attempt a forced lane change in the area defined as Distance Zone 2. Exit

vehicles may come to a full stop and wait for a gap for lane change within Distance Zone 2. This behaviour replicates the last-minute lane change to cut-in, which potentially interrupts the mainline traffic flow.

The default parameters for Distance Zone 1 and Distance Zone 2 are 20 seconds and 3 seconds, respectively. This setting induced severe congestion and mainline blockages in preliminary tests. Figure 9 (a) shows the speed contour of the mainline traffic on the right-hand lane (or inner lane) with the default parameters. Although the off-ramp queue frequently affects the mainline traffic in the study area, the speed contour presented in Figure 9 (a) substantially exaggerated the congestion level. The actual motorway traffic condition was approximated through consultation with the local agency and observation of the CCTV recordings. The parameter values were adjusted to 40 seconds and 15 seconds for Distance Zone 1 and Distance Zone 2, respectively, after a few trial and errors to better replicate the actual traffic condition of the study area. Figure 9 (b) shows the speed contour of the study area with adjusted parameter values.

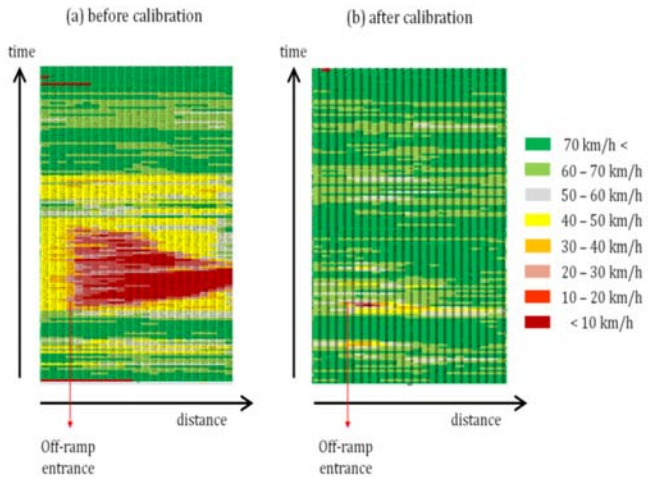

Fig. 9. Simulation model calibration

B. Modeling Driver's Response to Variable Speed Limits

The primary effect of VSL is reducing driving speeds. Aimsun offers speed control options for individual vehicles or a group of vehicles passing a speed limit gantry. This study uses the Application Programming Interface (API) to model the dynamic speed limit change and drivers' reactions to VSL.

As a possible outcome of speed limit reduction, it may increase driving sensitivity of drivers as VSL alerts drivers of potential hazards ahead. This study assumes that a certain proportion of drivers, who have encountered a reduced speed limit, react more sensitively to their leading car's maneuvering. The "sensitivity factor" parameter in the Aimsun's car following model was adjusted to replicate this possible effect of VSL. This factor is denoted as the symbol, "*a*", in the improved Gibbs car following model [31, 33]. When "*a*" is lower than 1, the driver underestimates the deceleration of the leader and as a consequence the driver becomes more aggressive. On the other hand, when "*a*" is great than 1, the driver overestimates the deceleration of the leader and as a consequence the driver becomes more careful and maintains a longer headway from the leader. This parameter was increased to 1.3 to model the VSL-affected drivers in this study for an extra analysis.

Driver's compliance is another important factor that influences the VSL performance. Abundant literatures report various levels of the driver's responses to queue warning messages or similar traveler information. Cheng and Firmin [34] conducted an interview with drivers and revealed 41% of the drivers considered the information was useful and would willing to accept the information. A higher reaction rate at 57% was reported by Wall and James [35] for similar message signs with the queue warning information. This study tests three different compliance rates including 100%, 90%, and 80%.

VII. SIMULATION RESULTS

This section presents the test and performance evaluation of the proposed VSL control. The relative effectiveness and benefit of the strategy are quantified in terms of selected performance measures.

A. Measure of Performance

The study uses time-to-collision and vehicle travel time as the primary performance measures to quantify the impacts of VSL on traffic safety and efficiency, respectively.

Travel time

This study records travel time for every individual vehicle from entering the 1.3 km point upstream the diverging area till departing the off-ramp or the mainline.

Time to Collision

Time-to-collision (TTC) describes the severity of traffic conflicts. It is defined as the expected time for two vehicles to collide if they keep driving at their current speed on the same path. A large TTC value indicates a small possibility of rear-end crash because the following driver will have sufficient time to apply braking. On the contrary, a small TTC value indicates a higher risk of crash. A small TTC value can be observed when two vehicles moving very closely each other or when a following vehicle is moving significantly faster than its leading vehicle so that an emergency braking is required to avoid a rear-end crash. The TTC between two vehicles travelling on the same lane can be expressed as the following equation.

$$TCC = \frac{Headway_d}{V_{Head} - V_{Follow}}$$

where, $Headway_d$ is the distance between the heading car and following car; V_{Head} is the present speed of the heading car at

calculation; V_{Follow} is the present speed of the following car at calculation.

An accident-prone situation can be identified by relatively small TTC values. A threshold value should be chosen to distinguish relatively safe and critical situations. Hirst and Graham [36] suggested a TTC of 3 or 4 seconds as the threshold. A study by Hogema and Janssen [37] found a TTC less than 3.5 seconds could be a good indicator of the critical traffic condition. This study collects TTC values less than 4 seconds, which are then categorised into 4 bins by 1 second, i.e., 0 to 1 second, 1 to 2 seconds, 2 to 3 seconds and 3 to 4 seconds. Smaller TTC values indicate more dangerous or critical conditions and higher possibilities of the rear-end crash.

B. Simulation Results

For each test scenario, 20 simulation replications were run with different seed numbers and thus different traffic patterns. This section presents the averaged results from the 20 replications. Table I and Table II show the summary of the simulation results.

TABLE I
SIMULATION RESULTS SUMMARY

MOE		Base scenario	Reactive VSL	Proactive VSL
Time To Collision* (TTC)	Total (0 – 4 s)	230.4	147.8	139.9
	0 to 1 s	3.9	3.1	2.8
	1 to 2 s	26.0	18.5	13.9
	2 to 3 s	68.7	41.2	40.6
	3 to 4 s	132.0	85.1	82.7
Travel time (sec)	Mainline traffic	70.6	75.5	76.9
	Exit traffic	151.5	152.9	148.7

* Occurrence of TTC with a specific TTC range

TABLE II
T-TEST CROSS VALIDATION OF MEAN DIFFERENCE

		Base scenario vs reactive	Base scenario vs proactive	Reactive vs Proactive
Time To Collision* (TTC)	Total (0 – 4 s)	<0.001*	<0.001*	0.46*
	0 to 1 s	0.538	0.436*	0.075*
	1 to 2 s	0.038*	0.001*	0.085*
	2 to 3 s	<0.001*	<0.001*	0.965
	3 to 4 s	<0.001*	<0.001*	0.719
Travel time (sec)	Mainline traffic	0.919	0.437*	0.341*
	Exit traffic	<0.001*	<0.001*	0.038*

*: $P < .05$

Overall, the VSL strategy with both reactive and proactive controls produces significant improvements in the safety measure over the base scenario. The proactive control reduced the TTCs over the base scenario and the reactive control. The t-test cross validation results indicate that the mean difference is statistically significant between the base scenario and the proactive control for all the performance measures.

The total TTC (i.e., 0 to 4 seconds) reduced by 36% and 39% with the reactive VSL and the proactive VSL, respectively. The TTC from 0 to 1 second, which indicates the most critical condition, decreased by 19% and 29% with the reactive VSL and the proactive VSL, respectively.

The travel time evidently increased among the mainline traffic by operating VSL. VSL inevitably increase the travel time of the vehicles travelling within the VSL-affected areas. The mainline traffic was evidently affected by reduced speed limit and their travel time increased as a result.

For exit traffic, the proactive control slightly reduced the travel time by 2.8 seconds and 4.2 seconds per vehicle over the base scenario and the proactive control, respectively. Once the off-ramp traffic backs up onto the motorway mainline, the queue would disturb not only the exit traffic but also the mainline traffic. The queue may be extended along the motorway mainline causing increased travel time of both the exit vehicles as well as the mainline traffic. Reduced off-ramp queues and the risk of queue spill-over may have contributed to the reduced travel time of exit vehicles.

The simulation results also show that the proactive VSL control outperforms the conventional reactive control. The improvement is most significant in smaller TTCs, from 0 to 2 second, which indicates more critical situations and higher possibilities of the rear-end crash. This result implies that the queue estimation and prediction enabled timely activation of VSL when the off-ramp queue is imminent to spill onto the motorway.

Figure 10 compares the average VSL activation periods with the reactive and proactive control schemes.

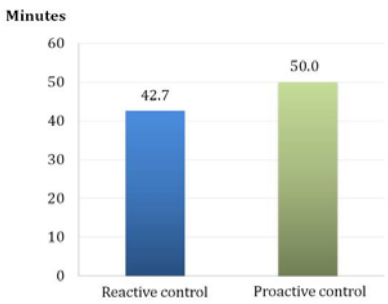

Fig. 10. VSL activation periods (in minutes)

The proactive control was designed to reduce the speed limit when queue is expected to spill over. This control resulted in a 17% increase of the VSL activation period from 42.7 to 50 minutes out of the 135 minutes of the analysis period. To further demonstrate the differences between the two control strategies, Figure 11 illustrates the observed instances of VSL activation and deactivation and corresponding off-ramp queue size. The figure clearly shows that the proactive control tends to activate VSL earlier than the reactive control. The figure also shows that the reactive control causes additional fluctuations in the displayed speed limit, which could be another drawback.

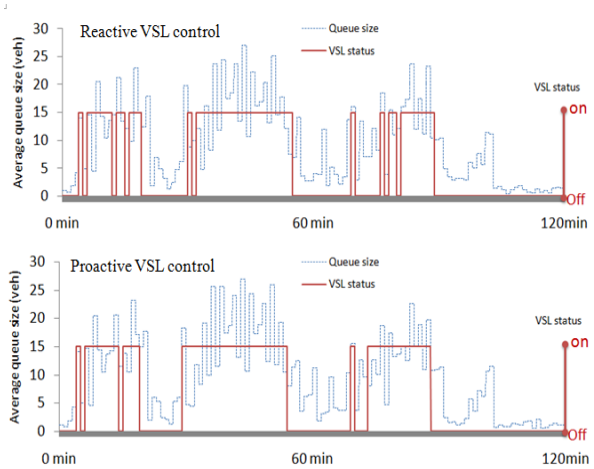

Fig. 11. Comparison of the VSL activation and deactivation instances

The simulation results presented in Table I assumed the perfect compliance of the speed limit (i.e., 100% compliance rate), because VSLs are enforceable in Queensland. A sensitivity analysis was conducted to assess the effect of varying levels of compliance. Table III provides the simulation results with the VSL compliance rate at 100%, 90%, and 80%.

TABLE III
Simulation Results – Speed Limit Compliance Impact Analysis

MOE		Proactive VSL with 100% compliance	Proactive VSL with 90% compliance	Proactive VSL with 80% compliance
Time To Collision (TTC)	Total (0 – 4s)	139.9	141.1	145.5
	0 to 1s	2.8	2.8	3.0
	1 to 2s	13.9	14.4	16.6
	2 to 3s	40.6	40.8	41.0
	3 to 4s	82.7	82.8	83.3
Travel time (sec)	Mainline traffic	76.9	76.4	76.0
	Exit traffic	148.7	148.9	150.1

The benefit of the proactive control could gradually diminish as more drivers violate the speed limit sign. The impact of reduced compliance will be more significant on the safety side. The 90% compliance scenario incurred only minor changes in the simulation results. TTC increased slightly and travel time of the exit vehicles also increased by 0.2 seconds (0.13%). However, travel time of the mainline traffic decreased by 0.5 seconds (0.65%). Further reduction in the compliance resulted in more significant increase in TTC by 5.33% over the 90% compliance rate and by 6.46% over the 100% compliance rate in average.

Finally, as a possible outcome of reduced speed limits, the impact of drivers' driving sensitivity is analysed. Table IV compares the simulation results of the proactive VSL when the driving sensitivity was adjusted higher for 0%, 15%, and 30% of drivers. Note that modified driving sensitivity is tested with the proactive control for demonstration purpose only. The first test scenario (0% drivers with increased driving sensitivity) reflects the performance of the proactive control before the parameter adjustment, presented in Table I.

TABLE IV
Simulation Results – VSL Impacts on Drivers' Driving Sensitivity

MOE		Proactive VSL – 0% drivers with increased driving sensitivity	Proactive VSL – 15% drivers with increased driving sensitivity	Proactive VSL – 30% drivers with increased driving sensitivity
Time To Collision (TTC)	Total (0 – 4s)	139.9	122.6	112.7
	0 to 1s	2.8	2.5	2.3
	1 to 2s	13.9	11.8	10.1
	2 to 3s	40.6	34.2	31.2
	3 to 4s	82.7	74.1	69.1
Travel time (sec)	Mainline traffic	76.9	78.9	80.4
	Exit traffic	148.7	152.9	156.3

The table shows that the safety could be substantially improved by increased driving sensitivity. The total TTC reduced by 12.4% and 19.4%, with 15% and 30% of drivers with increased driving sensitivity. As a trade-off, the travel times of both the exit and mainline traffic increased by 2.6% and 4.6%, respectively. The drivers with an increased sensitivity tend to accelerate slower and maintain a longer safety distance. As a result, the queue length may grow and the overall travel time could increase. Although it is merely a simulation test of possible driving behaviour, the results may imply that a clear indication of VSL through for example, flashing light signs, could contribute to improving the safety.

VIII. CONCLUDING REMARKS

The motorway off-ramp queue can be a serious threat to the motorway safety and flow efficiency. This study proposes a countermeasure using the mainline VSL to improve safety in congested motorway diverging area. VSL is an effective measure to slow down the vehicles approaching a downstream queue and contribute to reduced chance of off-ramp queue spillover and congestion in the diverging area. An additional benefit of VSL is its possible contribution to drivers' increased sensitivity to surrounding traffic conditions. This study analysed and quantified this possible effect of VSL on traffic safety and efficiency using the microsimulation approach.

The proposed VSL control is proactive in that the control decision is made based on forecasted traffic condition on the off-ramp. The existing queue size is estimated as the first step, which is then updated with predicted new arrivals for the next

control interval. The prediction adopts the ARIMA (2,1,1) model that was developed using the actual vehicle count data.

A simulation study was carried out to evaluate the proposed VSL control against the base case scenario where the VSL was disabled and a conventional reactive VSL control. Both reactive and proactive VSL controls attributed improved safety measures over the base scenario without a significant adverse effect on traffic efficiency. The proactive control enables activating VSL in advance of queue spill-over. The smaller TTC values, which may imply critical conditions, reduced significantly as a result of the proactive speed limit adjustment. Additionally, the proactive control also reduced fluctuation in the displayed speed limit caused.

A major difference of VSL from other traveller information systems is that the posted speed limits are mandated and enforceable in Australia. The effectiveness and benefit of VSL may further increase as more drivers follow the posted sign and the enforcement will play an important role for the effectiveness of VSL.

The proposed strategy inevitably slows down the mainline traffic and possibly increases the chance of breakdown. Actual operation of the proposed strategy must take into account the mainline traffic condition. For instance, the operation of the strategy can be coordinated with the mainline VSL as conditional on the motorway traffic condition to allow the speed reduction only when the mainline has sufficient capacity to accommodate higher volumes of traffic.

For future research, it is recommended to study how drivers, having various levels of experience and driving skills, would react to VSL and providing the lane use information together with VSL for a more effective safety measure. For motorway off-ramps where queue spill-over is frequent, the lane use information will be useful to encourage exit vehicles to change lane early to avoid last-minute lane change attempts.

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Gongbin Qian is a graduate student researcher at the Queensland University of Technology working towards a Ph.D. in traffic engineering. His research area includes freeway traffic management, traffic flow modeling, and microsimulation analysis.

Jinwoo (Brian) Lee received a PhD degree in Civil Engineering from the University of Toronto, Toronto, Canada in 2007 with a focus on Transportation Engineering and Intelligent Transportation Systems. He is currently a senior lecturer in Transport Engineering and Planning at the Queensland University of Technology, Brisbane, Australia.