Review Article

Exploring the impact of a coordinated variable speed limit control on congestion distribution in freeway

Jing Cao, Dawei Hu, Ying Luo, Tony Z. Qiu, Zhuanglin Ma

School of Automobile, Chang'an University, Xi'an 710064, China
Department of Civil & Environmental Engineering, University of Alberta, Edmonton T6G2W2, Canada

Abstract

Over the past few decades, urban freeway congestion has been highly recognized as a serious and worsening traffic problem in the world. To relieve freeway congestion, several active traffic and demand management (ATDM) methods have been developed. Among them, variable speed limit (VSL) aims at regulating freeway mainline flow upstream to meet existing capacity and to harmonize vehicle speed. However, congestion may still be inevitable even with VSL implemented due to extremely high demand in actual practice. This study modified an existing VSL strategy by adding a new local constraint to suggest an achievable speed limit during the control period. As a queue is a product of the congestion phenomenon in freeway, the incentives of a queue build-up in the applied coordinated VSL control situation were analyzed. Considering a congestion occurrence (a queue build-up) characterized by a sudden and sharp speed drop, speed contours were utilized to demonstrate the congestion distribution over a whole freeway network in various scenarios. Finally, congestion distributions found in both VSL control and non-VS control situations for various scenarios were investigated to explore the impact of the applied coordinated VSL control on the congestion distribution. An authentic stretch of Whitemud Drive (WMD), an urban freeway corridor in Edmonton, Alberta, Canada, was employed to implement this modified coordinated VSL control strategy; and a calibrated micro-simulation VISSIM model (model functions) was applied as the substitute of the real-world traffic system to test the above mentioned performance. The exploration task in this study can lay the groundwork for future research on how to improve the presented VSL control strategy for achieving the congestion mitigation effect on freeway.

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Traffic congestion on freeway is a critical social issue that we face every day. Some freeway locations recurrently experience congestion due to the existence of bottlenecks. From a safety perspective, as data from Persaud and Dzbik (1993) indicate, accident frequency during congested operation can be up to three times as high as that during uncongested operation at similar flow level. Over the past few decades, several dynamic control methods have been developed to address congestion problems. Active traffic and demand management (ATDM) strategies, such as variable speed limit (VSL), ramp metering (RM) and route guidance (RG) have been implemented in recent years to improve traffic freeway efficiency (mobility and/or safety). Among them, VSL operation has been presented in previous literature as a good solution. It is often based on the principle of speed homogenization over the freeway corridor, which is capable of improving freeway mainline capacity and reducing speed variability (Borough, 1997). The VSL strategy adaptively controls the upstream traffic flow of a bottleneck by dynamically regulating the speed limit. The effectiveness of VSL control has been examined from various perspectives. In the first instance, VSL control performances were well reported to homogenize the traffic and improve safety. Despite the potential benefit of VSLs on safety, some studies have also evaluated the impact on mobility. The most frequently used way of demonstrating the impact of VSL on mobility is to calculate the numerical indicators of performance (the total travel time (TTT) on mainline or total time spent (TTS) for all vehicles in the network, etc.). Although VSLs are capable of alleviating congestion and improving mobility in terms of TTT and/or TTS, congestions expressed by the form of queues may appear on mainline in VSL-implemented situations when facing heavy approaching demand flows. Few studies have explicitly evaluated the impact of a VSL control on congestion distribution. To bridge this gap, this study explored the impact of VSL on congestion distributions over a whole freeway network. It is a new visual angle for exploring the contribution of an implemented VSL control strategy. The incentives of queue build-up in the VSL scenario were also analyzed, since congestion was characterized by the existing queue.

Congestion will be aggravated with increased traffic demand regardless of whether VSLs are implemented or not. It has been demonstrated the limiting effect of VSL on congestion mitigating effect under excessively heavy demand flow level (Long et al., 2008; Mazzenga and Demetsky, 2009). Unfortunately, almost all metropolitan areas suffer from the rapidly increasing traffic demand on freeway. This study can be useful for improving the existing VSLs aiming at mitigating congestion even under extremely heavy traffic demand situation.

The existing VSL control strategy was proposed to improve the mobility on freeway (Hadiuzzaman et al., 2013). To address the dynamic traffic control problem, this existing VSL algorithm adopted a model predictive control (MPC) framework (Camacho and Bordons, 1995; Garcia et al., 1989). Microscopic traffic simulation was found to be the most suitable and cost-effective tool for performing this study. Furthermore, a new local constraint more compatible with the field situation was added. The applied VSL control strategy was implemented in the VISSIM micro-simulation platform using a special-purpose software module developed in C++ with the Component Object Model (COM) interface.

The remainder of this paper is organized into five sections. Section 2 summarizes the literature reviews on the effect of VSL control. Section 3 presents a brief introduction on the applied VSL control strategy and discusses the queue formation in VSL control implemented scenario. Section 4 exhibits the simulation results in the studied freeway corridor. Section 5 summarizes the concluding remarks. Section 6 presents the on-going research work.

Aiming at stabilizing traffic flow and mitigating traffic breakdowns to improve freeway traffic efficiency, VSL systems have been successfully implemented in many areas around the world. VSLs regulate the speed limit accommodating time-varying traffic conditions within the control period (Kang and Chang, 2006). It has been reported in previous literature that the main benefits of VSLs are improving network throughput, smoothing traffic flow, saving TTT, reducing speeding violations, and reducing crash potential (CP) (Abdel-Aty et al., 2005, 2006; Hegyi et al., 2005).

Tracing the development of VSL since 1990, many VSLs were targeted at improving traffic safety only. The effectiveness of real-world implemented VSLs in the United States and several European countries was summarized (Robinson, 2000). Evaluation results showed that it increased safety levels more significantly than it improved mobility. Several other simulation-based evaluations of freeway VSLs have also been conducted to explore the effect of VSLs on safety improvements. For example, Lee et al. (2006) assessed the safety benefits of VSL using PARAMICS. They selected an optimal speed limit based on several safety-related thresholds and found that CP decreased by 5%–17%, but travel time increased up to 10%. Abdel-Aty and Dhindsa (2007) concluded that, on a segment of I-4 in Orlando, Florida, changing speed limits by 5 mph increments produced best safety improvement results versus changing in 10 or 15 mph increments, which produced negative safety impacts. Beyond that VSL reduced the CP in non-congested conditions; Abdel-Aty et al. (2008) reported a 1% decrease in travel time during VSL control in non-congested conditions, but no significant improvement was found in congested conditions.

In spite of that the benefit of VSLs on safety has been well evidenced, it is still necessary to incorporate the traffic mobility. Several studies examined model predictive control (MPC)-based VSLs, wherein extended METANET models were employed to describe the traffic dynamics (Carlson et al., 2010; Hadiuzzaman et al., 2013; Hegyi et al., 2005, 2007; Long et al., 2008). They concluded VSLs were able to improve traffic mobility during congestion. Hegyi et al. (2005) evaluated VSL control with TTT as a mobility indicator; these authors...
applied the proposed VSL control for a hypothetical 12 km long network and reported a 21% decrease in TTT. Long et al. (2008) performed another simulation study on a hypothetical 5 km work zone with the same VSL control model and optimization technique developed by Hegyi et al. (2005). The results of Long’s study showed that TTS decreased by 5%–10% in the low volume period; however, no significant improvement was found in the high volume period. Hegyi et al. (2007) then evaluated a model predictive control-based VSL control in the PARAMICS micro-simulation tool and found a 32% reduction in TTT. Carlson et al. (2010) tested the control performance of VSL control on a hypothetical three-lane motorway by setting TTS and penalty terms, such as maximum ramp queue and high-frequency control oscillations as the objective function. The results of Carlson’s study showed that VSL improves traffic flow efficiency, especially when integrated with coordinate ramp metering control. Recently, Hadiuzzaman and Qiu (2013) proposed a cell transmission model (CTM)-based VSL control and documented a 10%–15% travel time reduction and 5%–7% flow improvement. Based on this MPC-based VSL control, Islam et al. (2013) proposed several modifications in the METANET model design for relieving congestion caused by active bottlenecks to find significantly traffic safety improvement, travel time reduction and flow improvement.

In brief, the existing VSL related systems are potentially beneficial to congestion relief, which is in the form of queue. A few previous studies took queue in consideration when developing or evaluating VSLs. For example, Lin et al. (2004), aiming to achieve the objectives of queue reduction on work zone by approximate the maximum queue length, presented two online algorithms for VSL controls. And Juan et al. (2004) concluded that VSL was capable of reducing the queue time and length in their simulation research. Although Mazzenga and Demetsky (2009) also concluded VSLs alleviated dangerous drops in speed and reduced queue length, they have revealed that VSLs were less effective under heavy congestion. This finding agreed with the results (Long et al., 2008) that the VSL control did not work well under excessively heavy demand flow level. Consequently, the authors were interested in exploring the impact of a coordinated VSL control on the congestion (marked by queue) distribution with a heavy demand level in this study.

3. VSL control strategy and congestion analysis

3.1. Studied corridor

Whitemud Drive (WMD), the main east-west freeway in southern Edmonton, Alberta, Canada, is selected for in-depth study. This freeway experiences recurrent heavy congestion during the morning and afternoon commute peak hours (7:00 AM to 9:00 AM and 4:00 PM to 6:00 PM) due to high traffic demand coupled with several active bottlenecks. The study site consists of the westbound 11-km section (between 122 St. and 159 St.) of WMD with six interchanges and a static posted speed limit of 80 km/h, and experiences a directional average annual daily traffic (AADT) of approximately 100,000 vehicles. The section outfits with 8 loop detector stations on the mainline, each consisting of dual-loop detector groups in each travel lane (Fig. 1). All on-ramps and off-ramps are equipped with loop detectors. These loop detectors measure speed, volume, occupancy every 20 s. The collected traffic data was used to calibrate the micro-simulation model, the substitute of the real world in this study, to guarantee the consistency with real-world situation.

3.2. Methodology-VSL control algorithm

With the goal of optimizing network performance under prevailing traffic conditions, Hadiuzzaman et al. (2013) proposed a MPC-based VSL control algorithm in a previous study. In this proposed VSL algorithm, a METANET-extended dynamic traffic model was used to perform traffic state prediction and coordinate variable message signs. The METANET model
was first proposed by Papageorgiou et al. (2008) and has been widely applied in the MPC-based VSL studies as the prediction model within MPC. The applied VSL control algorithm is briefly explained below. Please refer to Hadiuzzaman et al. (2013) for further detailed model information.

\[
v_i(k+1) = v_i(k) + \frac{T}{T}(u_i(k) - v_i(k)) + \frac{T}{T}(u_i(k)(u_i(k) - v_i(k)) - \frac{1}{T} \left( \frac{TP_{i+1}(k) - \rho_i(k)}{\rho_i(k) + \kappa} \right) \]

(2)

3.2.1. Traffic state prediction model

This exiting model assumes a freeway consists of \( m \) homogeneous links \( (L_1, L_2, \ldots, L_m) \) and several on-ramps \( r_i \) and off-ramps \( s_i \) (Fig. 2). With a certain prediction interval of \( T \), e.g.

\[
v_i(k+1) = v_i(k) + \frac{T}{T}(u_i(k) - v_i(k)) + \frac{T}{T}(u_i(k)(u_i(k) - v_i(k)) - \frac{1}{T} \left( \frac{TP_{i+1}(k) - \rho_i(k)}{\rho_i(k) + \kappa} \right) \]

(4)

\( T = 1 \text{ min}, \) for link \( i \) with \( \lambda_i \) lanes, the evolutions of traffic density \( \rho_i(k) \) (veh/(km·min)), traffic speed \( u_i(k) \) (km/h) and transition flow \( q_i(k) \) (veh/h) at each time step \( k \) were estimated. \( r_i(k) \) and \( s_i(k) \) respectively denote the on-ramp meter flow and the off-ramp flow at each time step \( k \).

Assuming triangular fundamental diagrams (FD) flow versus density curve, density dynamics follows the flow conservation law, as shown in Eq. (1).

\[
\rho_i(k+1) = \rho_i(k) + \frac{T}{\lambda_i}(q_i(k) - q_i(k) + r_i(k) - s_i(k))
\]

(1)

Speed dynamics for scenarios without VSL control were derived from the original METANET model, shown in Eqs. (2) and (3). Hadiuzzaman et al. (2013) replaced the speed-density relation as it appears in the original METANET with the optimal control variable \( u \). In doing so, the VSL control variable becomes a free control variable. Thus, speed dynamics of the freeway links have been modeled with VSL control using Eq. (4):

\[
V_{i+1}(\rho_i) = \alpha_r \exp \left(-0.5 \left( \frac{\rho_i}{\rho_{i,\text{free}}} \right)^2 \right)
\]

(3)

where \( \tau \) is reaction term parameter (h), \( \nu \) is anticipation parameter (km/h), and \( \kappa \) is positive constant (veh/(km·min)). These are global parameters that are calibrated from measured data.

The average flow \( Q_i(k) \) within a link \( i \) at any time step \( k \) was estimated from the fundamental relation of traffic characteristics shown as:

\[
Q_i(k) = \rho_i(k)u_i(k)\lambda_i
\]

(5)

Because of the assumption of a triangular FD in this algorithm, Eqs. (6) and (7) have been used to estimate the transition flow among successive links, wherein \( Q_{\text{max},i,\text{in}} \) denotes the capacity of each link \( i \) under the speed limit with \( u_i \).

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**Fig. 2** – Freeway section with \( m \) divided links.
\[ q_{i-1}(k) = \min \left\{ u_{i-1}(k)\rho_{i-1}(k) + r_i(k) - s_i(k), Q_{\max,i}u_i, w_i \rho_{i-1}(k) - \rho_i(k) \right\} \]  
\[ q_i(k) = \min \left\{ u_i(k)\rho_i(k) + r_{i+1}(k) - s_{i+1}(k), Q_{\max,i+1}u_{i+1}, w_{i+1}\rho_{i+1}(k) - \rho_i(k) \right\} \]

In this VSL algorithm proposed by Hadiuzzaman et al. (2013), the fact of capacity drop has been introduced while calculating transition flows among successive links. For a bottleneck segment, the queue discharge flows are lower than the capacity in free-flow conditions. This is known as the two-segment, the queue discharge flows are lower (or higher) than the speed detected by the immediate upstream link to the bottleneck link in the congested condition was estimated using Eq. (8):

\[ q_{i-1}(k) = \min \left\{ u_{i-1}(k)\rho_{i-1}(k) + r_i(k) - s_i(k), Q_{\max,i}u_i, w_i \left( \rho_{i-1}(k) - \rho_i(k) \right) \right\} \]  

\[ q_i(k) = \min \left\{ u_i(k)\rho_i(k) + r_{i+1}(k) - s_{i+1}(k), Q_{\max,i+1}u_{i+1}, w_{i+1}\left( \rho_{i+1}(k) - \rho_i(k) \right) \right\} \]

### 3.2. Constraints

Based on considerations of safety, driver acceptance, and traffic flow characteristics, the existing methodology constrains the VSL control variable based on the following three inequality constraints:

- To guarantee drivers' safety, the optimal speed limit of the VSL must be lower than the maximum speed \( V_{\text{max}} \):
  \[ u_i(k) \leq V_{\text{max}} \]

- To maintain operating efficiency, the optimal speed of the VSL should be higher than the minimum speed \( V_{\text{min}} \):
  \[ u_i(k) \geq V_{\text{min}} \]

- For safe operation, the change of speed limit between two consecutive time steps should be lower than the maximum difference in speed limit:
  \[ |u_i(k) - u_i(k+1)| \leq V_d \]

Above three constraints ignored the fact that the drivers cannot decelerate (or accelerate) to a posted speed limit much lower (or higher) than the speed detected by the immediate downstream sensor. The present study aimed to bridge this gap using another added local constraint:

- To ensure the posted speed limits are more achievable and suitable for the actual traffic situation, the optimal speed limit cannot exceed the speed detected from the downstream sensor more than \( V_d \):
  \[ |u_i(k) - u_{i+1}(k-1)| \leq V_d \]

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### 3.2.3. Objective function

The objective function was tied to control targets. The most frequently used objective function in previous VSL studies is to minimize only the TTT on the mainline or TTS for all vehicles in the freeway network. It would result in a lower flow on the mainline and cannot guarantee maximum utilization of freeway capacities when the objective function is to minimize only the TTT (or TTS). Indeed, it could reduce throughput from the freeway. Alternatively, TTD (total travel distance) is a surrogate measure of throughput. Unfortunately, it would increase flow to nearly the capacity level that would create flow instability when the objective function is to maximum only the TTD. Therefore, Hadiuzzaman and Qiu (2013) proposed an objective function which is to minimize a weighted summation of TTT and TTD, as shown in Eq. (9):

\[ J = \sum_{j=1}^{N_y} \sum_{i=1}^{M} \left[ \alpha_{TTT} T_{ji}(k-1+j) - \alpha_{TDD} T_{ji}(k-1+j)u_i(k-1+j) \right] \]

where \( \alpha_{TTT} \) and \( \alpha_{TDD} \) are the weighting factors for the two terms in the objective function.

### 3.3. Congestion analysis

Although this applied VSL control algorithm was aimed to relieve congestion on freeway mainline, queue phenomena (the expression of congestions) may still occur under the VSL implemented situation. The tail of any formed queue (congestion) can propagate upstream during the high traffic demand periods, as more vehicles are joining the queue tail at a faster rate. Consequently, a propagating mainline queue may grow and eventually block upstream ramps. The blocked upstream on-ramps will lead to the creation of upstream on-ramp queues, or, worse still, if a queue covers the whole on-ramp space and queue spillover is imminent, which could block other traffic streams on the adjacent street network. This leads to increased travel time as more vehicles have to wait in the on-ramp to get access to freeway mainline. Meanwhile, the backward propagating queue (congestion) covering an off-ramp blocks-off traffic has a route that does not go via the queue front. The blocked off-ramps will cause the vehicles intend to leave the mainline by off-ramp joining the congested mainline region and contribute to a more congestion situation. This blocking effect could reduce freeway throughput. Therefore, to improve the VSLs aiming at relieving freeway congestion, it is necessary to investigate of queue phenomena under the VSL implemented situation.

In this applied coordinated VSL implemented scenario, the incentives of congestion (queue build-up) can be divided into two types. One is VSL-control driven which is due to the speed limit by VSL control implementation, and this is the same with isolated VSL control mode. It has been verified in the research of Hadiuzzaman and Qiu (2013) that queues will form at the critical VSL sign in the isolated VSL control mode due to extremely heavy traffic demand and the flow control implementation. Fig. 3(a) illustrated a spilling queue contributed by the implemented VSL control. The other is bottleneck driven which is due to the existing bottleneck, and this scenario exists even without VSL control implement. The stochastic nature of freeway bottleneck
breakdown and queue characteristics have been investigated in past years. Elefteriadou et al. (1995) and Evans et al. (2001) found that freeway breakdown at bottlenecks can occur at any given flow near the traditional pre-specific capacity during high demand periods (even when flow is lower than the pre-specified capacity) and that breakdowns do not necessarily occur at maximum flow. Thus, even with this coordinated VSL control, queue may form at bottlenecks. Fig. 3(b) illustrated a spilling queue directly contributed by an existing bottleneck.

Congestions are evidenced by the low speed in queue periods, and queue formations are evidenced by a sudden and sharp drop in speed. Thus, this study would employ speed contour maps to describe congestion distributions on WMD. Field data observations revealed that, during congestion, speed of queued vehicles was almost below 40 km/h. Therefore, it was defined in this study that the traffic state would be treated as in congestion when the speed was lower than 40 km/h. Fig. 4 shows an example of the speed profile in a morning peak hours using the field data on WMD.

4. Simulation results and discussion

The calibrated VISSIM 5.3 micro-simulation model is used as a platform for simulating the traffic scenarios on the studied freeway corridor, WMD, for details of calibration tasks please refer to the research of Hadiuzzaman et al. (2013). To implement the assigned speed limits during the simulation run time, the VISSIM COM application programming interface (API) is used. A visual C++ application program is developed to load the traffic network through the VISSIM API, start the simulation process, and implement the VSL control. In Fig. 5, the framework of simulation platform for VSL control implemented is shown.

This VSL control strategy was implemented on WMD. Fig. 6 schematically exhibits the locations of the four speed limit signs installed on the VSL implemented WMD. ADS4, the sign furthest downstream, would announce the end of the VSL control with static speed limit of 80 km/h, while other three (ADS1, ADS2, and ADS3) post the coordinated dynamic

![Fig. 3 - Illustrating queue possibilities. (a) Queue caused by VSL control. (b) Queue caused by bottleneck.](image)

![Fig. 4 - Speed profile in congested state on WMD.](image)
Fig. 5 — Framework of simulation platform.

Fig. 6 — Layout of studied freeway corridor (Note: not to scale).
speed limits. As the implemented freeway speed limits in Canada are multiples of 10 km/h, the speed limit can be updated in increments/decrements of a value that is also a multiple of 10 km/h only. Here, $V_d$ is 10 km/h. Moreover, the updated posted speed limit $V_{\text{max}} = 80$ km/h and $V_{\text{min}} = 20$ km/h.

The simulation in this study ran more than 2 h. The 2-h simulation ran with demands that corresponded to the rush-

Fig. 7 – Speed profiles and speed contours for Scenario 1. (a) Speed profile of ADS1 without VSL control. (b) Speed profile of ADS2 without VSL control. (c) Speed profile of ADS3 without VSL control. (d) Speed profile of ADS1 with VSL control. (e) Speed profile of ADS2 with VSL control. (f) Speed profile of ADS3 with VSL control. (g) Speed contours without VSL control. (h) Speed contours with VSL control.
hour traffic flow level. The applied demand was set to high to replicate the queue phenomenon. After a 15 min warm-up with demand of 4000 veh/h, a high demand, approximately 4800 veh/h on mainline and 700–1000 veh/h on ramps was assigned in VISSIM simulation and lasted for an hour.

The applied coordinated VSL control in this study targets the whole freeway network. After performing ten pairs of the simulations under above mentioned traffic demand level but with different seeds (pre-set using C++ program), it was found that the implemented VSL transformed the congestion distribution over the whole freeway network. Each pair of simulation included a simulation with VSL control and a simulation without VSL control, both of which ran with a same seed in the C++ program. With the objective of

![Fig. 8 - Speed profiles and speed contours for Scenario 2. (a) Speed profile of ADS1 without VSL control. (b) Speed profile of ADS2 without VSL control. (c) Speed profile of ADS3 without VSL control. (d) Speed profile of ADS1 with VSL control. (e) Speed profile of ADS2 with VSL control. (f) Speed profile of ADS3 with VSL control. (g) Speed contours without VSL control. (h) Speed contours with VSL control.](image-url)
analyzing the impact of the applied VSL control on congestion distribution, the speed limits and congestion distributions over the entire corridor were graphically demonstrated in this study. Figs. 7 and 8 respectively depict the speed profiles and speed contours in two representative pairs of scenarios. The speed profiles describe the speed limits, the inflow speed detected from the immediate upstream sensor of the VSL sign, and the outflow speed detected from the immediate downstream sensor; while the speed contours are used to clarify the congestion distributions. As mentioned previously (Fig. 4), traffic state with speed lower than 40 km/h was treated as congested traffic state in the studied freeway corridor. In other words, traffic state with red in the speed contours was treated as in congestion.

In both illustrated scenarios (Scenarios 1 and 2), the congestions mainly occurred on link \( L_7 \) and its downstream (\( L_8 \) to \( L_{13} \)) when no VSL control was implemented, and the downstream spilling congestions occupied on \( L_8 \) to \( L_{13} \) occasionally met the upstream congestions on \( L_7 \). Somewhat differently, some light congestion occurred on \( L_7 \) in Scenario 1. From the speed contours in both Figs. 7 and 8, it can be clearly seen that the congestion distribution in terms of spatial extent (queue length) and time duration changes by the implemented VSL control.

For Scenario 1, the original congestion was almost relieved. Only short duration congestions still existed with VSL control, in which the queued vehicle speed was higher than without VSL control. In addition, it should also be noted that the congestion with VSL on \( L_7 \) occurred much later than without VSL and its duration was shorter. The other heavy congestion, however, occurred at the upstream in the studied corridor due to the flow control by the VSL implemented. So far, it could be concluded that the applied VSL control can transfer congestion occurrence location (Fig. 7(g) and (h)). The implemented VSL in Scenario 1 improved throughput on the original congested region in the non-VSL case, but reduced throughput on the upstream region of this applied freeway corridor.

For Scenario 2, a limited number of congestions were transferred to upstream (Fig. 8(g) and (h)). Although the congestions in VSL control case still mainly existed in the same location with non-VSL control case, the congestion distribution varied significantly. On one hand, with the implemented VSL control, the congestion at downstream network (\( L_8 \) to \( L_{13} \)) was slightly relieved and never reached the congestion on \( L_7 \). On the other hand, the occurrence of congestion in the VSL case on \( L_7 \) was earlier but with a longer duration than the non-VSL control case. It is noteworthy that, however, the maximum queue length duration was cut down, which can help improve the traffic throughput on the freeway network.

In conclusion, the congestion distribution in terms of occurrence time, location, duration, and extent (queue length) over a freeway network would be obviously impacted by the implemented VSL control. But the difference is that this study, from a visual assessment (Figs. 7 and 8), found that the implemented VSL transformed the congestion distribution varying with different scenarios even under the similar traffic demand level. The difference in congestion distribution pattern on a whole freeway network was due to the coordinated VSL optimization algorithm. This finding inspired the authors to further improve the existing coordinated VSL control algorithm considering dynamic congestion extents (queue length).

**Fig. 9** – Scheme of VSL control structure with queue estimation.
5. Conclusions

This study focused on the impact of the applied coordinated VSL control strategy on congestion distributions over the whole freeway network. The employed coordinated VSL control strategy in this study was derived by adding a new local constraint to an existing VSL control strategy and targeted optimized utilization of traffic infrastructure over a whole network. This study presented two representative pairs of scenarios analyzing the impact of the implemented VSL control on the congestion distribution.

The major findings in this study are summarized:

- In coordinated VSL control scenarios, the incentives of congestion can be divided into two types: one is due to the dynamic speed limit by VSL control implementation; the other is due to the stochastic nature of breakdown at an existing bottleneck location.
- The applied coordinated VSL control changes the congestion distribution significantly in terms of the congestion occurrence time, location, duration, and/or extent (queue length).
- The impact of this applied coordinated VSL control on congestion distribution over a whole freeway network varies considerably with scenarios even on similar demand level.

6. Future work

As relieving congestion is one of the important objectives for VSL control, these simulation results inspire the authors to improve the existing VSL control strategy by considering the congestion distribution. Future work will make an effort to modify this applied VSL control strategy, in which the congestion extent (queue length) will be involved. Fig. 9 illustrates the scheme of the further developed VSL control structure.

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