Implementation of Variable Speed Limits: Preliminary Test on Whitemud Drive, Edmonton, Canada

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Abstract: Congestion has become highly recognized as a worldwide traffic problem, as traffic demand has grown steadily over the past few decades. Variable speed limits (VSLs) are an intelligent transportation system (ITS) measure that limits mainline flow to mitigate bottleneck congestion. Currently, VSLs have become proactive based on short-term prediction. Proactive VSLs succeed in simulation evaluations, but few have been deployed in the field and their real-world effectiveness has not been proven. Various factors may lead to this limitation, such as the absence of reliable field application software, accuracy of prediction models, and high computation time for proactive control. To address this research gap, this study reports a preliminary VSL test and details its implementation results on Whitemud Drive, Edmonton, Canada. First, based on field traffic measurements before VSL control, recurrent bottleneck locations are identified. Second, the proactive control algorithm is briefly introduced. Then, a software application is designed to realize all necessary functions for VSL field implementation. With all these in hand, the preliminary field test was conducted and the VSL control performance and reliability are evaluated. Finally, the results for before and after VSL control implementation are analyzed in depth. The analysis compares average traffic speed, standard deviation of speed, total travel time, and total travel distance. The results from this study confirm that proactive VSL can relieve recurrent traffic congestion effectively. **DOI: 10.1061/(ASCE)TE.1943-5436.0000895.** *© 2016 American Society of Civil Engineers.*

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Introduction

Variable speed limits (VSLs) are an intelligent transportation system (ITS) measure that seeks to relieve roadway congestion by limiting flow and improve safety by homogenizing vehicle speeds. In practice, VSLs have been implemented in the United States and Europe. VSLs can serve as either mandatory or advisory speed limits; in other words, VSLs can either post speed limits that drivers must obey or act as recommended driving speeds that are not legally enforced. These two categories may generate different levels of driver compliance. In addition, in terms of control algorithms, VSLs can be categorized broadly into rule-based and model-based control. Rule-based VSLs preselect thresholds (e.g., traffic flow, occupancy, or mean speed) and make real-time decisions, while model-based VSLs obtain optimal control variables through the optimization of a pre-established model with traffic measurements. So far, most field implementations have used rule-based algorithms.

Rule-based VSL strategies have been widely deployed. For example, the Washington State Department of Transportation (DOT) and Florida DOT established an essential principle of VSL strategies: an upstream variable message sign (VMS) displays a reduced speed limit once congestion happens downstream; then, the VMS shows a normal speed limit when the downstream segment recovers from congestion (Federal Highway Administration 2012; Minnesota Department of Transportation 2014). Updated speed limits and their temporal and spatial variance are constrained by certain safety considerations. Field evaluations have reported that drivers followed VSLs, resulting in reduced stop-and-go frequency and improved traffic safety. However, VSLs in Florida resulted in even more congested traffic situations during rush hours, which was caused by detector failure (Federal Highway Administration 2012). It follows then that the control algorithm is critical and the key to VSL reliability. To improve VSL reliability, Minnesota DOT implemented VSLs that required operators to oversee and verify the calculated VSL suggestions (Minnesota Department of Transportation 2014). VSLs reduced collisions by 30% and increased capacity by 22%. Furthermore, Chang et al. firstly conducted simulation experiments, and then integrated VSLs with travel time information and conducted a field test to alleviate recurrent bottlenecks (Lin et al. 2004; Chang et al. 2011). VSLs achieved a higher throughput and smoother speed transitions. The lessons learned from these mentioned field tests can be summarized as follows: (1) a lack of VSL standards and public education may cause driver confusion and even lower driver compliance; and (2) VSL control algorithms must reliably generate reasonable suggestions; otherwise, VSL leads to low driver compliance or worse traffic conditions. Most rule-based strategies apply predefined trigger conditions to adjust VSLs, but they are not designed to adapt to future temporal and spatial variations of congestion. Thus, recent research focuses on model-based VSL strategies.

Model-based VSL strategies are designed as either responsive or proactive. Various studies have evaluated them using simulation tools (Hegyi et al. 2005; Carlson et al. 2011; Hadiuzzaman et al. 2013).

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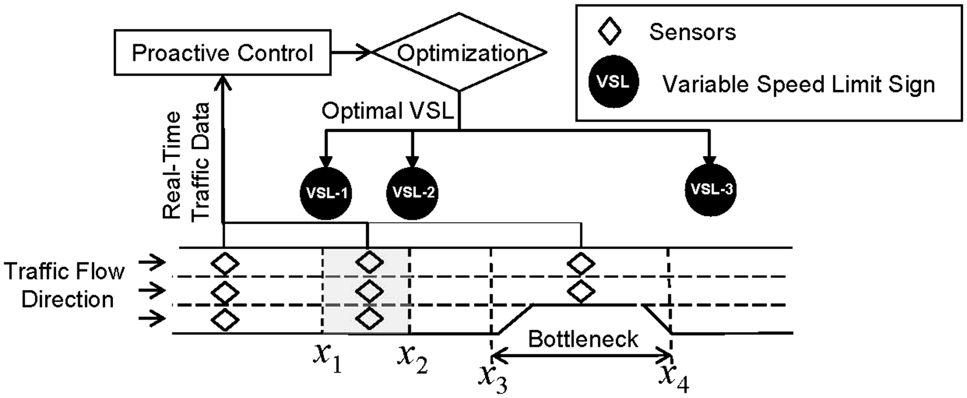

Fig. 1. *DynaTAM-VSL* mechanism

Whereas, to the authors' knowledge, the only model-based VSL applied in real-world tests is named the SPEed Controlling ALgorithm using Shockwave Theory (SPECIALIST) (Hegyi and Hoogendoorn 2010). It translates the shockwave theory into a practically applicable algorithm. The main steps of SPECIALIST are shockwave detection, solvability assessment, control scheme generation, and control scheme application (Hegyi et al. 2008). In addition, other strategies (Hegyi et al. 2005; Hadiuzzaman et al. 2013) predict traffic states by macroscopic traffic flow models and take proactive VSL control to relieve congestion. Even though model-based VSLs have proved to be effective in simulations, especially proactive ones (Hegyi et al. 2005; Hadiuzzaman et al. 2013), their real-life benefits are still unapparent. The following issues may be attributable:

1. Absence of reliable field application software for proactive VSLs: Most existing software tools can be used for offline evaluation, but few of them have adopted proactive strategies for real-time applications;
2. Accuracy of prediction models: Proactive VSL features a prediction module. Accurate prediction represents traffic evolutions of free flow, congestion and especially the transitions between them; otherwise, the controller may generate false speed suggestions; and
3. High computation time for proactive control: Proactive control, such as model predictive control (MPC), is usually challenged for its excessive computation time during optimization.

To fill in the research gap and overcome the problems mentioned above, this study presents the preliminary test for a VSL strategy implemented on Whitemud Drive, Edmonton, Canada. The whole proactive VSL strategy is composed of traffic sensors, VMSs, a proactive control software tool, a real-time database, and a communication component among modules. Among these components, this paper emphasizes its control software tool. The developed software tool, named *Dynamic network analysis tool for active traffic and demand management-variable speed limit* (*DynaTAM-VSL*), realizes proactive VSL based on MPC and is suitable for field applications. Fig. 1 explains the *DynaTAM-VSL* mechanism. VMSs display the VSL calculated based on predicted downstream traffic conditions. VSL-1 and VSL-2 generally provide lower speed limits than VSL-3. Ideally, all arriving vehicles slow down to the VSL-1 and VSL-2 values before the bottleneck, then accelerate to the VSL-3 value after the bottleneck. In this way, they can travel quickly and smoothly through the bottleneck segment.

This paper reports the preliminary test of the proactive VSL implementation. The preliminary test concentrates on evaluating VSL control performance and reliability. During the field test, five VSLs were deployed along the test bed. The results from this field test serve as a reference for future implementation and move VSL forward to the next phase of permanent applications. The remainder of this paper is organized into sections: the next section describes the VSL field test plan and some field observations of the study site; the "Variable Speed Limit Control Algorithm" section briefly introduces the control algorithm; the "*DynaTAM-VSL* Software Implementation" section details the *DynaTAM-VSL* software structure; then, the "Analysis of Online Test Results" section analyzes the performance and reliability of *DynaTAM-VSL*; finally, the last section discusses the concluding remarks and plans for future research.

Proactive Variable Speed Limit Field Test Plan

Variable Speed Limit Implementation Procedure

The deployment of an ITS strategy includes hardware implementation, software design and realization, communication setup, and database design and management. Real-time or historical traffic data, video records, incident, and weather data are fused and transmitted to the database and software by a certain communication technique. The traffic control countermeasures are then transmitted back to the traffic facilities, e.g., signs and signals. However, to generate reasonable control countermeasures (VSLs in this case), the following steps are required.

Step 1: Process Traffic Data

On one hand, traffic data from the sensors need to be checked for consistency and be imputed if necessary. On the other hand, traffic data are collected at a certain interval, which may not match the required time interval in the application. Thus, data smoothing and aggregation must be conducted before being inputted to the control algorithm.

Step 2: Identify Possible Bottleneck Location(s)

Bottlenecks limit the traffic flow on roadways. VSLs are designed to avoid or postpone the activation of bottlenecks. Bottleneck activation can be identified by occupancy-to-flow ratio (Hall and Agyemang-Duah 1991), occupancy thresholds (Zhang and Levinson 2004), or speed drop (Lorenz and Elefteriadou 2001; Lertworawanich and Elefteriadou 2003; Banks 2006). Once the bottleneck location is identified, the cause of the bottleneck needs to be determined. The common cause is driver behavior changes in response to different geometric features, e.g., curve, weaving, or lane drop. Ultimately, all this information supports the placement of VMSs. The basic considerations for determining the location of VMSs are the following: (1) relative distance between a VMS and a bottleneck; (2) normal vehicular deceleration and acceleration rates; and (3) visibility of VMSs. Placing a VMS upstream of a bottleneck is recommended. With VMS location information in hand, the design of the control algorithm is explained in Step 3.

Step 3: Design the Variable Speed Limit Control Algorithm

The proactive VSLs aim to provide drivers with speed suggestions that are reasonable, reliable, and beneficial for traffic mobility and safety. An accurate traffic prediction model should be able to predict future traffic states based on measurements. Equally important, the prediction model should be embedded in a predictive control framework. In this study, a modified *METANET* model was applied as the traffic prediction model and embedded in the MPC framework as described in previous research (Hadiuzzaman et al. 2013).

Step 4: Calibrate and Validate Prediction Model Parameters

The control algorithm always contains some unknown parameters or thresholds. Therefore, these parameters or thresholds need to be calibrated and validated by comparing real and predicted traffic states. This step confirms that the control algorithm represents real traffic evolutions and takes effective control measures.

Step 5: Realize Expected Functions in DynaTAM-VSL Software

The *DynaTAM-VSL* software should fulfill all necessary functions, including representing detailed network information, managing traffic data, simulating traffic scenarios, measuring performance and optimizing control strategies.

Step 6: Implement and Evaluate Control Performance

The VSL control is planned to be implemented and evaluated in two stages. The first stage is to perform an offline test without sending VSL results to the traffic network. This stage fixes possible bugs, and makes necessary modifications and adjustments to the software. Essentially, this phase resembles a field scenario with 0% driver compliance. Afterward, the second stage implements VSLs at the study site, with drivers shown recommended driving speeds. This stage focuses on further analysis of the control performance with respect to traffic mobility. During the second stage, the following issues need to be checked: detector data availability and accuracy, database connection, VSL suggestion reasonability, and VSL control performance. This study concentrates on the second stage.

Study Site

The westbound direction of an urban freeway corridor, called Whitemud Drive, in Edmonton, Canada, was selected as the test bed for this study. The westbound section from 111 Street to 170 Street has six on-ramps and six off-ramps. Whitemud Drive is a three-lane freeway with a posted speed limit of 80 km/h. Serving as a part of Edmonton's inner ring road, the annual average daily traffic (AADT) of its westbound section alone was greater than 90,000 vehicles in 2014 (Alberta Transportation Planning Branch 2015). Also, it experienced a total of 277 accidents in 2012. Due to high peak-hour demand and notable variations in geometric features (i.e., sharp curve, weaving, or lane drop), this freeway corridor often suffers from recurrent congestion.

The City of Edmonton has installed vehicle detection stations (VDSs) and traffic video cameras along this corridor. The VDSs

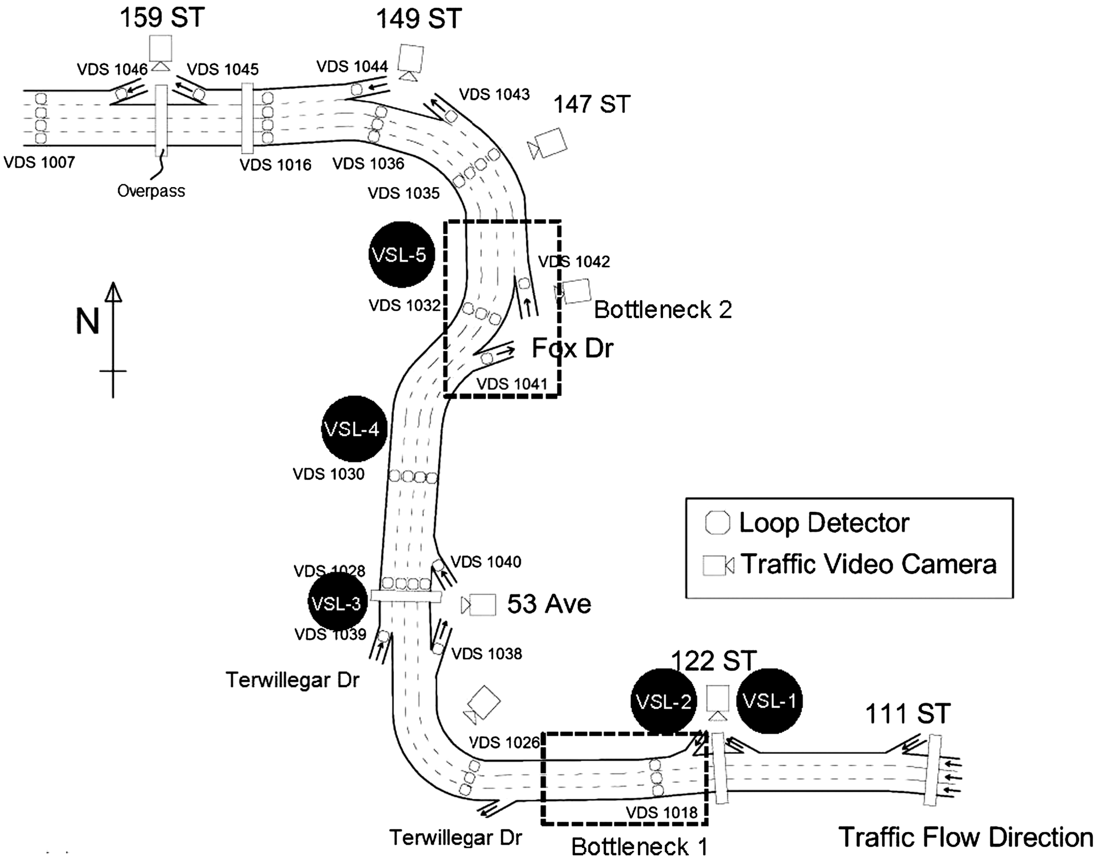

Fig. 2. Study site

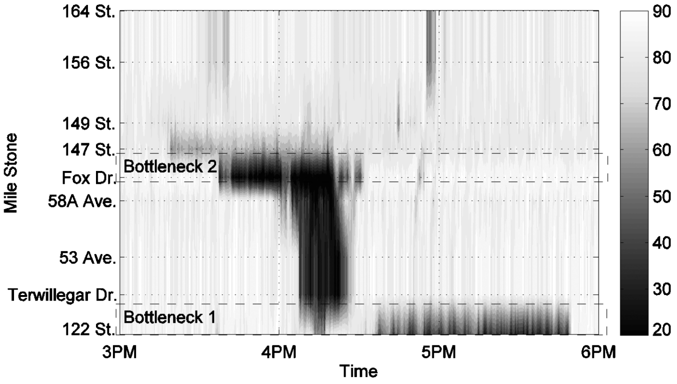

Fig. 3. Speed contour maps, May 14, 2015

are placed on the roadway mainline, on-ramps, and off-ramps. They collect traffic data, such as volume, speed, and occupancy every 20 s, and send the data to the City's central computer system for archival. Complete historical data from VDSs are available from 2011 to 2015. Fig. 2 schematically shows VDS and camera locations.

Bottleneck Identification

The scope of this study is limited to relieving recurrent bottlenecks. As Edmonton often experiences adverse weather conditions in winter, during the bottleneck identification before the test, the weather records for bottleneck identification were checked to ensure there was enough visibility for driving. Also, the traffic incident records of this corridor were checked to eliminate the impact of incidents. From the daily measurements, on an average weekday, the morning and afternoon peaks start at 6:30 a.m. and 4:30 p.m. respectively. After the onset of the congestion, the speed drops fast, from 80 km/h to as low as 20 km/h. Fig. 3 shows the speed contour maps for westbound sections, plotted from loop detector data on May 14, 2015. As observed, two recurrent bottlenecks are often activated. One is a two-sided weaving segment from the on-ramp of 122 Street to the off-ramp of Terwillegar Drive. The other one originates near Fox Drive. Its upstream segment carries high traffic demand but little traffic exits using the Fox Drive off-ramp. At the same time, the number of lanes drops from four to three. In this sense, this segment can be defined as a virtual lane drop segment.

In summary, based on field observations and bottleneck information, the weaving segment after the 122 Street on-ramp and the segment around Fox Drive were selected as critical segments for VSL control implementation. Five sets of portable VMSs were placed. Their locations are presented in Fig. 2. The VSLs in this study function as advisory driving speeds. Driving speeds during peak periods are recommended to drivers but not enforced.

Variable Speed Limit Control Algorithm

For the purpose of implementation, *DynaTAM-VSL* applies the control algorithm developed by Hadiuzzaman et al. (2013), which was proven to be effective in simulations (Hadiuzzaman et al. 2013; Fang et al. 2014; Wang et al. 2014). It is designed to mitigate congestion during peak hours. Its main objectives are to reduce vehicle travel time as well as to accommodate more vehicles in the traffic network. Within an MPC-based control framework (as manifested in Fig. 4), the control algorithm collects traffic flow data, predicts future traffic states, and optimizes and applies control variables. Referring to the modules shown in Fig. 4, the data-collection module performs traffic data extraction, imputation, smooth processing, and aggregation; the traffic-state prediction module applies a *METANET*-based traffic flow model to predict traffic evolutions in the near future; and the optimization module calculates the optimal control set according to a specific objective function.

Traffic measurements $\boldsymbol{x} = [\rho_i(k), v_i(k)]$ (ρ is traffic density and v is traffic speed) are collected at each time step k. At each time step of prediction horizon N_p, the prediction module takes current measurements $\boldsymbol{x}$ and predicts traffic state $\hat{x}$ based on the density and speed dynamics [Eqs. (1)–(3)], which were modified by Hadiuzzman et al. (2013) from the original *METANET* model (Messmer and Papageorgiou 1990). In order to replicate the control consequence under VSLs, the prediction module includes the vector of VSL values $\boldsymbol{u}$. On the other hand, at each control time index k_c, the control algorithm optimizes the vector of VSL values $\boldsymbol{u}*$. The selected objective function J [Eq. (4)] is expected to achieve optimal traffic states by finding the future trend of VSL values. The optimization problem considers temporal, spatial and discrete constraints

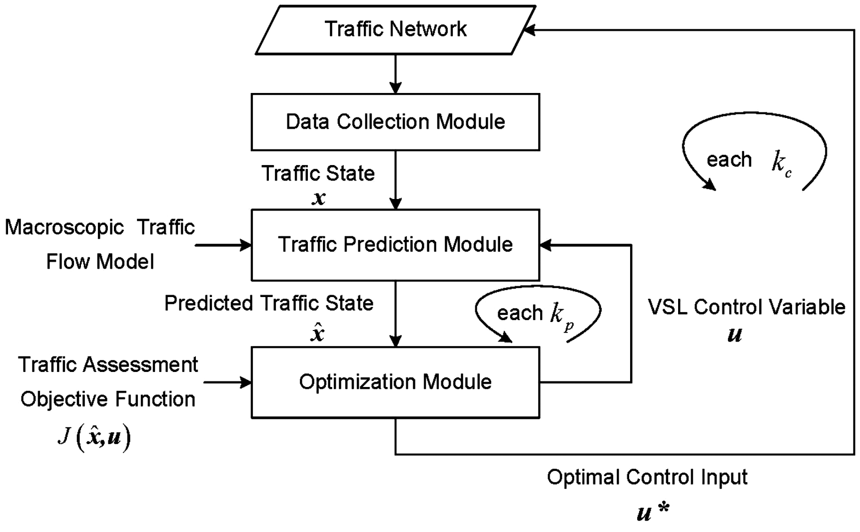

Fig. 4. MPC-based control framework

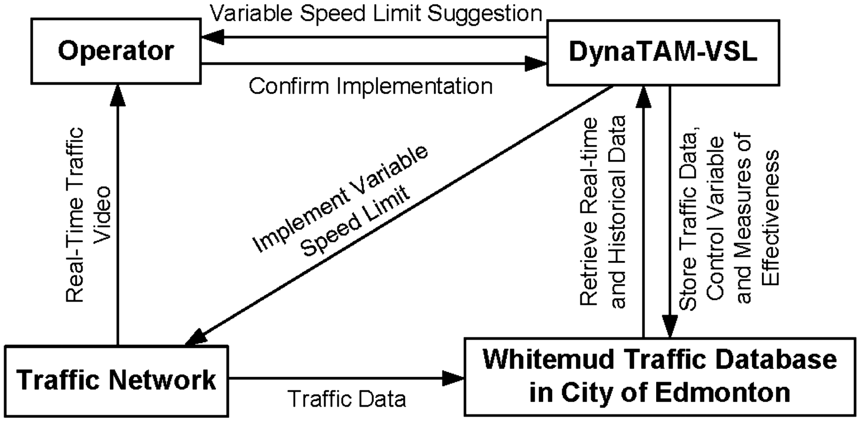

Fig. 5. Integration of *DynaTAM-VSL* with all components

$$\rho_i(k+1) = \rho_i(k) + \frac{T}{L_i\lambda_i}[\lambda_{i-1}q_{i-1}(k) - \lambda_i q_i(k) + r_i(k) - s_i(k)] \tag{1}$$

$$q_i(k) = \min\left\{ v_i(k)\rho_i(k) + \frac{r_{i+1}(k) - s_{i+1}(k)}{\lambda_i}, Q_{\max,i+1}, \omega_{i+1}[\rho_{Jam,i+1} - \rho_{i+1}(k)] \right\} \tag{2}$$

where i = link number ($i = 1, 2, \ldots, N$); T = discrete time step in hours (h); L = segment length in kilometers (km); λ = number of lanes in lanes (ln); q = traffic flow in vehicles per hour per lane (veh/h/ln); r = on-ramp flow in vehicles per hour (veh/h); s = off-ramp flow (veh/h); ω = shockwave speed (km/h); $Q_{\max}$ = link capacity (veh/h/ln); and ρ_{Jam} = jam density (veh/km/ln)

$$v_i(k+1) = v_i(k) + \frac{T}{\tau}\{V[\rho_i(k)] - v_i(k)\} + \frac{T}{L_i}v_i(k)[v_{i-1}(k) - v_i(k)] - \frac{\upsilon T[\rho_{i+1}(k)\text{-}\rho_i(k)]}{\tau L_i[\rho_i(k)+\kappa]} \tag{3}$$

where $V[\rho_i(k)]$ = fundamental relationship between density and speed; τ = reaction term parameter (h); υ = anticipation parameter in km^2/h; and κ = positive constant in vehicles per kilometer per lane (veh/km/ln). They were the model's global parameters, calibrated from the measured data

$$\min J = \alpha_{TTT}TTT - \alpha_{TTD}TTD \tag{4}$$

where α_{TTT}, α_{TWT}, and α_{TTD} = weighting factors; TTT = total travel time, and $TTT = T\sum_{j=1}^{N_p-1}\sum_{i=1}^{N}\lambda_i L_i \rho_i(k+j)$; TTD = total travel distance, and $TTD = T\sum_{j=1}^{N_p-1}\sum_{i=1}^{N}\lambda_i L_i \rho_i(k+j)v_i(k+j)$.

In this study, the control horizon N_c is 1 min and the prediction horizon N_p is 5 min. Every minute, optimal control inputs are generated by prediction and optimization for next 5 min. The rolling horizon scheme in MPC assumes that only control inputs for the first minute are actually applied in the traffic network. The control inputs calculated for the next 4 min are not actually implemented but only work as initial guesses for the next cycle. Detailed introductions to the prediction model, control algorithm, and solution technique have been presented by Hadiuzzman et al. (2013) and are not repeated here.

DynaTAM-VSL Software Implementation

DynaTAM-VSL software can analyze, simulate, and optimize traffic networks in offline or online mode. It was coded with C++ based on an object-oriented design. Fig. 5 demonstrates the integration of *DynaTAM-VSL* with all components. Details of the integration are described next.

Real-Time Data Collection and Storage

The traffic data collection devices take measurements from the traffic network and send them to the City of Edmonton's database. *DynaTAM-VSL* retrieves necessary data from the database and organizes and stores them. It utilizes a standard template library (STL) to organize the data structure so that fewer pointers and structured text files are needed. In case of occasional sensor failures or data transmission problems, *DynaTAM-VSL* performs a data consistency check and imputation prior to its use in the control algorithm. Lastly, *DynaTAM-VSL* stores the data in the structured query language (SQL) server as Whitemud Traffic Database using Microsoft *Access*. In addition, the database applies a hash_map to improve the efficiency of data searches and path storage.

Optimization of Control Algorithm

DynaTAM-VSL extracts real-time and historical traffic data to estimate current traffic states. With the information in hand, the current traffic state is illustrated in the user interface. The color of each link indicates the severity of traffic congestion. Subsequently, future traffic states are calculated by the prediction model. The proactive control performs using the rolling horizon concept of MPC, as explained in the last section. The optimization problem is solved by decision tree (Hadiuzzaman et al. 2013). A branch on the decision tree corresponds to the optimal VSL values for successive prediction steps. Based on the constraints, the decision-tree algorithm firstly enumerates all possible branches. Comparing the resulting values of the objective function, the controller then updates the optimal speed limit.

Variable Speed Limit Implementation

When obtaining the optimal values for VSL control variables, *DynaTAM-VSL* stores the optimal speed limit values and their control performance measurements in its database. At the same time, it sends a message containing the suggested speed limits to an operator in the Transportation Management Center (TMC) of the City of Edmonton. To ensure a reasonable speed limit suggestion, this operator is in charge of confirming and posting suggested speed limits. The operator can decide whether to accept the proposed speed limits by observing the real-time traffic via traffic video cameras. If the operator accepts the request, the VSLs are displayed on the VMSs using wireless communication, under the National Transportation Communications for Intelligent Transportation System Protocol (NTCIP). Any action by the operator is recorded in the database.

Analysis of Online Test Results

Flow Pattern

As traffic flow fluctuates from day to day, this analysis selected weekdays in the year of 2015 with similar traffic flow patterns to evaluate VSL control performance. For the no-control case, no VMS was placed on the roadside. In the VSL-control case, VMSs were placed and activated during peak hours. The preliminary VSL tests were conducted from August 11 to September 4, 2015. The VSL control was operated during morning and afternoon peaks

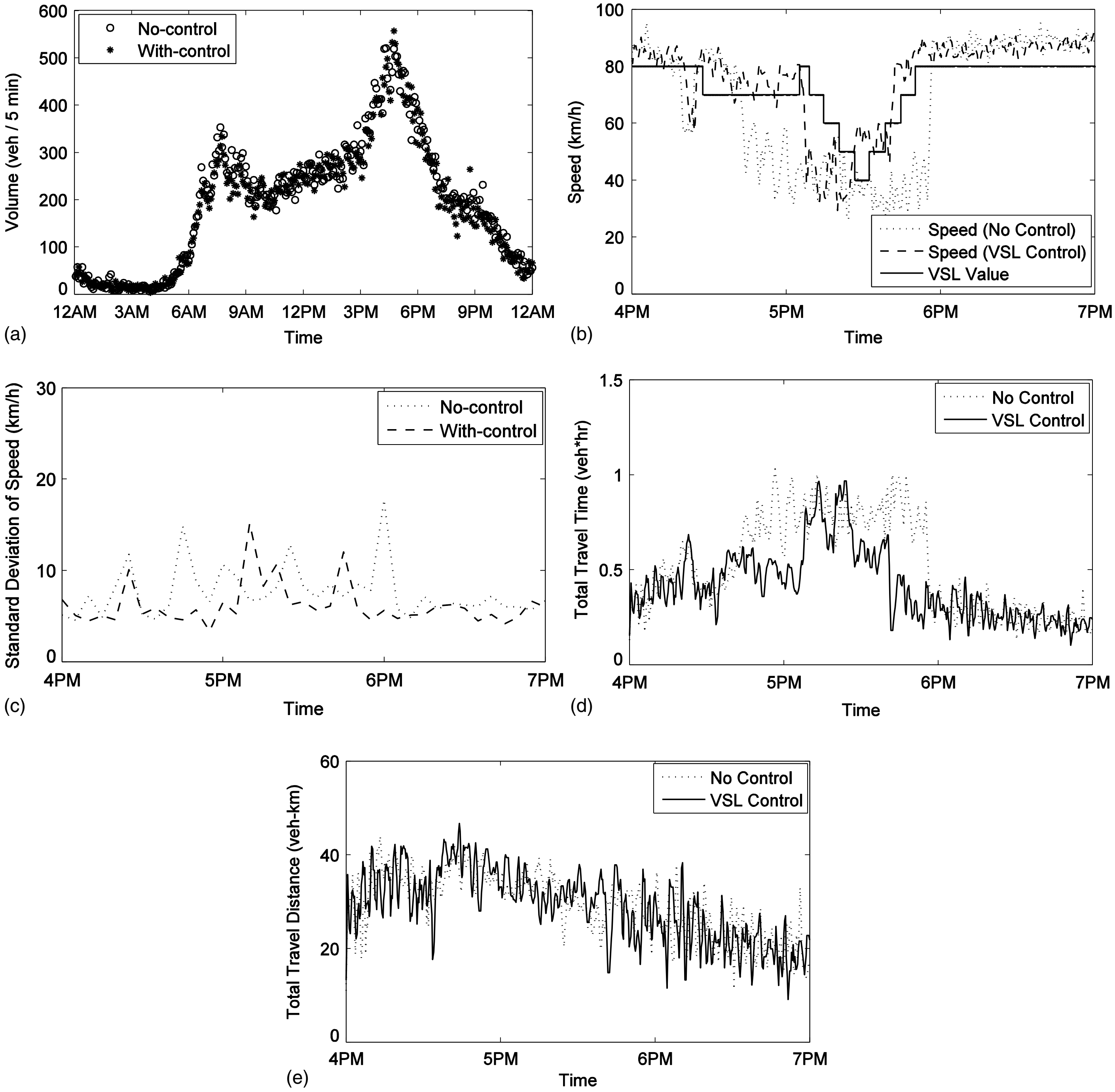

Fig. 6. Comparisons between no-control (May 14) and VSL-control (Aug 12) scenarios at Bottleneck 1: (a) distributions of traffic volume; (b) speed profiles and VSL rates for VSL-1 and VSL-2; (c) time-varying standard deviation of speed; (d) evolution of TTT during the afternoon peak; (e) evolution of TTD during the afternoon peak

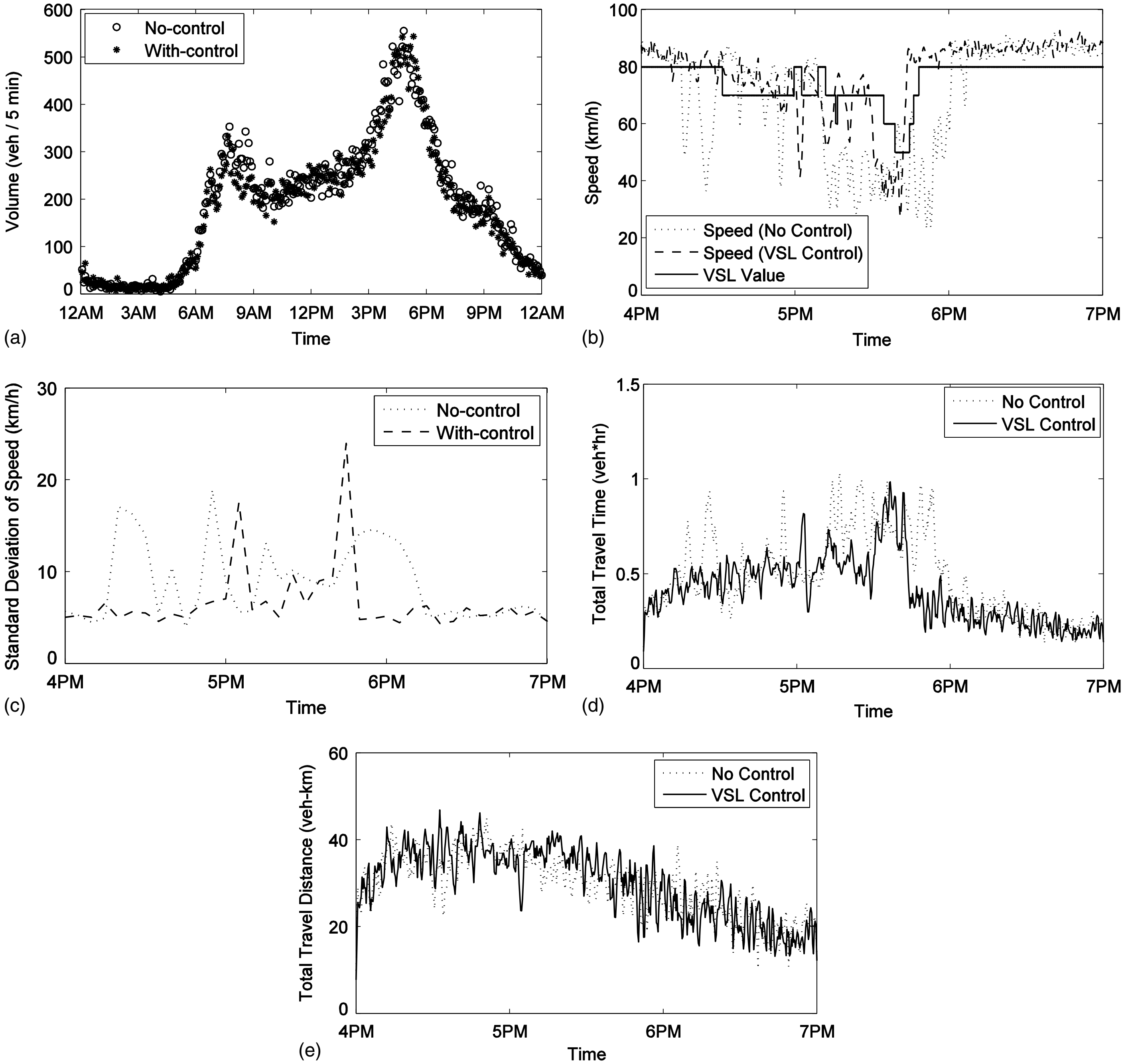

Fig. 7. Comparisons between no-control (May 20) and VSL-control (Aug 26) scenarios at Bottleneck 1: (a) distributions of traffic volume; (b) speed profiles and VSL rates for VSL-1 and VSL-2; (c) time-varying standard deviation of speed; (d) evolution of TTT during the afternoon peak; (e) evolution of TTD during the afternoon peak

(6:30–8:30 a.m. and 4:30–6:30 p.m.). Recurrent congestion happened at Bottleneck 1 during afternoon peaks. Hence, the time period from 4:30 to 6:30 p.m. was selected for the analysis below. Figs. 6(a) and 7(a) plot 5-min aggregated volume variations from VDS 1018 over time. These figures present the no-control (May 14 and May 20) and VSL-control (August 12 and August 26) cases, respectively. Both days experienced recurrent congestion at Bottleneck 1. The plots indicate that traffic patterns were stable regardless of the VSL deployment. As a result, they are comparable in the before-and-after VSL evaluation.

In addition, a statistical significance *t*-test was applied to identify whether the flow patterns from the VSL-control and no-control cases are significantly different. A confidence interval of 95% was chosen. Its corresponding t-critical value for the two-tailed test was 1.98. Table 1 summarizes the statistical test results for 2 days with similar flow patterns. Since all *t*-statistics values are lower than the t-critical value, it verifies that there was no vital difference between the flow profiles of each of the two days compared.

Table 1 also lists the results for VSL performance evaluation, including average speed, TTT (vehicle hours, veh h) and TTD (vehicle kilometers, veh km). The detailed analysis is presented next.

Speed Comparison

Theoretically, the deceleration and acceleration when vehicles pass a congested bottleneck cause a drop in capacity. VSLs reduce

Table 1. VSL Performance during the Test

Comparison		Demand pattern	Average speed at Bottleneck 1 (km/h)		TTT at Bottleneck 1 (veh h)		TTD at Bottleneck 1 (veh km)	
VSL control	No control	*t*-statistic value	VSL control	No control	VSL control	No control	VSL control	No control
August 12	May 14	0.82	73.06	59.87	169.75	221.07	10,957	10,986
August 17	May 25	0.12	72.66	69.12	169.62	183.39	11,181	11,083
August 18	May 05	0.34	76.73	64.44	160.23	205.18	11,616	11,131
August 20	May 14	0.47	79.40	59.87	144.31	221.07	10,860	10,986
August 25	May 05	0.19	74.67	64.44	170.03	205.18	11,475	11,131
August 26	May 20	0.86	74.04	65.27	167.87	198.13	11,472	11,289
August 27	May 14	0.55	73.96	59.87	169.28	221.07	11,537	10,986

upstream discharge flow by lowering the speed limits, and subsequently increase speed limits after vehicles pass downstream bottlenecks. VSLs reduce vehicle travel time and avoid or relieve the occurrence of congestion and capacity drop. In this way, VSLs smooth speed transitions and reduce stop-and-go conditions. Figs. 6(b) and 7(b) present the speed profiles at Bottleneck 1, as well as the VSL rates. As desired, on the whole, the speeds on bottleneck segments under VSL control were higher than those under the no-control scenario. The bottleneck speeds were increased by VSL control and the drastic speed drop was prevented. Quantitatively, VSLs increased the average speed from 59.87 to 73.06 km/h at Bottleneck 1 on August 12. Likewise, the average bottleneck speed was increased from 65.27 to 74.04 km/h on August 26. VSL control smoothed the speed transitions between free flow and congestion and ensured a stable traffic flow and safe driving environment. In addition, the variation trend of VSL rates was close to that of bottleneck speeds. This indicates that the traffic prediction model built in the control can predict traffic changes, particularly for speed drops. During the test, VSL-1 and VSL-2 were given the same VSL rates. For VSL-1, the segment speed in historical peak-hour data was generally free flowing. The suggested speed was lower than its peak-hour speed. It proves the suggested speed limits are reasonable and achievable. Reasonable and achievable speed suggestions encourage drivers to cooperate in improving traffic mobility, rather than confuse them and result in worse conditions.

Standard deviation of speed (SDS) was revealed to be the highest statistically significant variable that impacts traffic collisions. Accordingly, Figs. 6(c) and 7(c) compare time-varying SDS at Bottleneck 1 under no-control and VSL-control cases. SDS in the VSL-control scenarios was lower than that in no-control scenarios most of the time although peaks still existed.

Comparison of Travel Time and Travel Distance

Shorter travel time is the main direct benefit for drivers, and more discharged traffic is a major concern for traffic agencies. Hence, the objectives in the VSL optimization problem are to minimize TTT and, meanwhile, maximize TTD. TTT is related to traffic density. Thus, during one control horizon, minimizing TTT reduces mainline density and mitigates congestion, but may prevent vehicles from entering the traffic network. In contrast, TTD is related to traffic flow. Maximizing the TTD at the same time can improve traffic throughput and accommodate more vehicles in the mainline. Although no-control and VSL-control cases may result in similar TTD across the whole time period, their TTDs for each step of the control horizon may be distinguished.

On August 12, when only Bottleneck 1 was considered, TTT was reduced from 221.07 veh h to 169.75 veh h in the control case for the whole afternoon peak. Meanwhile, TTD was similar in both cases as their traffic demands were similar. These results suggest that the VSL control improves traffic mobility. Also, at the corridor level, TTT achieved 1,134.7 vehicle hours (veh h) in the no-control case and 1,104.9 veh h in the VSL-control case in total. The implemented VSL decreased TTT by 2.6%. Similarly, TTD reached 77,482.7 vehicle kilometers (veh km) in the no-control case and 87,928.8 veh km in the VSL-control case. Similar observations can be found for August 26. Thus, upstream flow control can benefit downstream traffic flow.

Figs. 6(d and e) exhibit the evolutions of TTT and TTD at the bottleneck. When Figs. 6(d and e) are analyzed combined with Fig. 6(b), the performance of VSL can be demonstrated. After 4:30 p.m., when the traffic demand gradually increased, *DynaTAM-VSL* worked by applying VSL values from high to low. Due to its prediction module, *DynaTAM-VSL* is capable of predicting traffic states in the near future and applying corresponding control variables. That is why the VSL decreased before a speed drop could occur at the bottleneck. The speed control in advance can reduce traffic flow and prevent speed drop at the bottleneck. This effect is obvious between 4:30 to 5:10 p.m. in Fig. 6(b). During this period, the driver compliance was high, and the TTT in the VSL-control case was less than that in the no-control case. However, as the demand increased after 5:10 p.m., the bottleneck speed suddenly dropped from 80 to 40 km/h, approximately. The VSL value decreased simultaneously. Restricted by the VSL maximum variance (10 km/h) and VSL rate duration (5 min) in the algorithm, VSL changes could not keep up with the speed drops. When the VSL reached 40 km/h, the traffic flow was limited to a low level so that speed at the bottleneck started to increase. The time when the bottleneck speed returned to free-flow speed in the VSL-control case was 15 min earlier than in the no-control case. VSL control shortened the congestion duration and saved drivers' travel time.

At the beginning of the field test, for operators' convenience, the updated VSL values were implemented for 5 min and then another cycle started. After a problem with the VSL rate duration was found, the duration was reduced to 1 min from August 17 onward. Thus, Fig. 7(b) shows a more-reasonable profile of speed suggestions but more frequent speed variations. The frequent speed variation may risk traffic safety. TTT on the bottleneck was decreased from 198.13 to 167.87 veh h on August 26. Figs. 7(d and e) show the benefits from VSL control in detail. In addition to the two comparisons earlier, the performance evaluation results are given in Table 1.

In summary, this proactive control approach can predict bottleneck states and forecast whether a bottleneck will be triggered. When an active bottleneck is signaled, the VSL rates are lowered to prevent upstream flow from reaching bottleneck capacity. When the bottleneck activation signal is lifted, the control reverts to higher VSL rates and discharges more vehicles from the mainline. The measures of effectiveness under proactive control, including average speed, SDS, TTT, and TTD, outperformed those under no control.

Conclusions and Future Plan

Excessive peak-hour demand triggers recurrent bottlenecks and constrains discharge flow on freeways. Simulation tests have exhibited the benefit of proactive freeway control algorithms for relieving recurrent bottlenecks. Compared with reactive freeway control algorithms, proactive algorithms take advantage of their prediction module. Unfortunately, real-life performance of proactive control is still unapparent, so this paper presents a field evaluation of proactive VSL control realized by *DynaTAM-VSL*. The preliminary test was completed on a freeway corridor and indicated that proactive VSL control is reasonably effective.

There are four major findings of this research: (1) in the preliminary test, *DynaTAM-VSL* suggested reasonable and reliable speed limits and favorable driver compliance; (2) *DynaTAM-VSL* achieved improved average speed at the bottleneck and reduced TTT over the corridor; and (3) proactive control benefits from its prediction module, which considers future traffic evolutions in advance.

Based on *DynaTAM-VSL* and the results from the preliminary test, future work will make an effort to enhance the control algorithm so that it can be adopted for various scenarios. The VSL maximum variance constraint and duration of the control variable were observed to be important for VSL performance during the test. The selection of their values needs to balance their mobility and safety consequence. Traffic situations usually evolve very fast. Small VSL variance or long control duration prevent VSL control from providing reasonable rates. However, frequent VSL variations may lead to traffic safety problem. Thus, the constraints need more careful consideration. The test in the next phase will be devoted to field evaluation after some necessary adjustments. Further research will focus more on safety impact brought by VSL deployment. The time gap between the two phases will deal with strategy adjustments and deeper public education. In addition, further research will be conducted involving incidents and inclement weather conditions in the VSL algorithm. Incidents or inclement weather conditions result in nonrecurrent bottlenecks, which are also a major concern for freeway operation. In particular, Edmonton experiences adverse weather conditions in winter, with driving visibility seriously affected. Incorporating incident and weather factors in the control algorithm could help VSLs to suggest more feasible speed limits. Then, the VSL strategy can adjust the optimal discharge flow, mitigate bottleneck severity, and ensure traffic safety and mobility at the same time. Moreover, in future field tests, *DynaTAM-VSL* will be compared with a rule-based VSL, which can strengthen the argument for VSL effectiveness.

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