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Evaluating Performance of a Proactive Optimal Variable Speed Limit Control Using Different Objective Functions

Md. Hadiuzzaman\textsuperscript{a}, Jie Fang\textsuperscript{b}, Ying Luo\textsuperscript{a}, Tony Z. Qiu\textsuperscript{c,*}

\textsuperscript{a} Graduate Research Assistant, Department of Civil and Environmental Engineering, University of Alberta, Edmonton, T6G 2W2, Canada
\textsuperscript{b} Post Doctoral Fellow, Department of Civil and Environmental Engineering, University of Alberta, Edmonton, T6G 2W2, Canada
\textsuperscript{c} Assistant Professor, Department of Civil and Environmental Engineering, University of Alberta, Edmonton, T6G 2W2, Canada

Abstract

Proactive optimal Variable Speed Limit (VSL) control is a promising solution to improve both the freeway capacity and the travel time. Despite this well-recognized fact, most of the previous studies found that the VSL control strategy was capable of improving only the freeway travel time. This finding hinders the overall mobility benefits from the computationally intensive proactive optimal VSL control and its credibility compared to the other control strategies those do not involve real-time traffic state prediction and optimization. To resolve this issue, in this paper, the authors adopt a previously developed novel VSL control strategy that explicitly considers traffic characteristics at active bottleneck, and its upstream-downstream links. Then, the performance of the control strategy has been evaluated within a predictive control framework, considering several objective functions (including stand-alone objective and combination of multiple objectives). Moreover, within the control framework, DynaTAM-VSL has been used as a prediction model. To find the optimal values of control variable at each control horizon, the authors adopt the multi-start Sequential Quadratic Programming, which starts a local solver from multiple start points. A sensitivity analysis is performed to see how the weight parameters of the partial objectives influence the VSL performance, which resolves existing paradoxical results of VSL mobility benefits. In addition, the model is simulated for a range of demand inputs, and analysis is carried out to see how efficient the VSL control is to improve the freeway mobility.

Keywords: Model predictive control; variable speed limit; capacity drop; METANET; DynaTAM-VSL;

1. Introduction

VSL control is a promising solution to improve both the Total Travel Time (TTT) and the Total Flow (TF). However, most of the previous studies reported that the VSL control was capable of improving only the TTT, and
it had little impact on the TF. Moreover, several contradictory results were presented in terms of VSL mobility and safety benefits. In general, it is believed that VSL control can improve safety. However, one cannot conclude that VSL is not capable of improving mobility since the implemented VSL control strategies were heuristics and they were not tightly coupled with the mobility factors. To resolve these issues, it is important to design a control strategy that explicitly considers the mobility factors. Moreover, it is essential to develop a modeling framework that is both accurate and that yields a correct solution when incorporated with the optimization framework. To this end, in this paper, the authors adopt a novel VSL control strategy to manage traffic flows with the purpose of improving freeway capacity, and therefore throughput of traffic. The control strategy is simulated within the Model Predictive Control (MPC) framework, which confirms the expected mobility benefits of the VSL control strategy through the utilization of a traffic flow model and a user-supplied objective function.

However, to achieve the maximum mobility benefits, the traffic flow model must capture all the important traffic dynamics, including free-flow, congestion and transition among them. In the past, several studies proposed traffic flow models with the VSL control variable considering the METANET (Papageorgiou et al. 1990) as base model. For example, Hegyi et al. (2005) proposed the desired speed in the relaxation term of the METANET that reads the value of minimum between the Fundamental Diagram (FD) and the displayed speed limit (control variable). Carlson et al. (2010a) re-parameterized the desired speed with the VSL rate, which is equal to the VSL-induced free-flow speed divided by the non-VSL free-flow speed. However, presence of FD in those traffic flow models results in several disadvantages (see Lu et al. 2011). To evade these disadvantages, this study formulates the DyaTAM-VSL. This model has dropped the FD from the METANET. Alternatively, it has adopted a set of speed limit-dependant link specific parameters. Doing so, the model mismatch caused by discrepancies between field data and FD curve could be effectively avoided. Furthermore, the model has incorporated a set of speed-limit dependant global parameters to address the driver behaviour during the VSL control. Then, the model is simulated within the MPC framework. It shows the achievable mobility benefits considering different objective functions. Finally, the VSL performance is evaluated considering different weights in the partial objective functions, and the ultimate objective was to see when and how the VSL control can improve the TTT and the TF.

2. Literature Review

In the past decade, several macro- and micro-simulation studies have been conducted to examine the effects of VSL control on the safety and mobility. Alessandri et al. (1999) performed a macro-simulation using link throughput as a cost function, and reported that VSL control was capable of preventing congestion and improving flow, but that it had little impact on total travel time (TTT). Hegyi et al. (2005) evaluated VSL control using TTT as the cost function, and the authors reported a 21% decrease of the TTT. Interestingly, Long et al. (2008) performed another macro-simulation study using the same traffic flow model and optimization technique as did in Hegyi et al. (2005), but the authors did not find any improvement in TTT. Park and Yadlepiti (2003) tested VSL control logic at work zones using VISSIM microscopic simulation. Lee et al. (2006) assessed the safety benefits of VSL using PARAMICS micro-simulation software. They found that, for highly congested locations, VSL control provided a reduction in crash potential (CP) by 25%, but that it increased travel time. Allaby et al. (2007b) reported similar findings. In contrast, Abdel-Aty et al. (2008) found that VSL led to a considerable reduction in CP during non-congested conditions, but no significant impact for congested conditions. That study identified a consistent decrease in travel time during non-congested conditions using VSL control. Hegyi et al. (2007) implemented a MPC-based VSL control in PARAMICS software that resulted in a 32% reduction in TTT.

Carlson et al. (2010b) evaluated VSL performance within the macroscopic AMOC (Advanced Motorway Optimal Control) software tool. Simulation of the proposed optimal VSL control in the Amsterdam ring-road A10, which is about 32 km long resulted in 47.0% reduction of travel time. In another study, Carlson et al. (2010c) showed 15.3% reduction of travel time using the optimal VSL control compared to the no-control case. Zegeye et al. (2011) proposed a MPC-based traffic control approach for the balanced reduction of travel times,
emissions, and fuel consumption for freeway networks using VSL control. To find the optimal values of VSL control variable, four different objective functions were considered. To solve the MPC optimization problem, the authors used the SQP. However, the VSL control shows travel time improvement by 36.0% when the objective of the controller was set to reduce the TTT only. With the all other objective functions, VSL control increased the travel time by 10.0-20.0%. Recently, Hadiuzzaman and Qiu (2012) proposed a Cell Transmission Model (CTM)-based VSL control, and also used the MPC to dynamically change the speed limit in real-time. Their VISSIM simulation results showed 10.0-15.0% travel time reduction and 5.0-7.0% flow improvement considering different control scenarios. In another study, Hadiuzzaman et al. (2012) proposed several modifications in the METNAET for the MPC-based VSL control for relieving congestion caused by active bottlenecks. The proposed VSL control showed 39.0% travel time reduction and 6.0% flow improvement.

A number of empirical studies have been conducted in the U.S. since the 1960s in several states. Ulfarsson et al. (2005) studied the effects of VSL control on mean speed and speed variance on the I-90 in Washington. The authors concluded that VSL entailed benefits when used for adverse conditions. In Colorado, VSL has been employed in the Eisenhower Tunnel on I-70 since 1995. Since VSL deployment truck-related accidents have declined steadily by 6-7% on the steep downhill grade (Smulders 1992). Recent field deployment of VSL in Seattle has resulted in a 30% reduction in injury collisions and a 22% increase in roadway capacity (WSDOT 2011). VSL has also been used in Germany (Robinson 2000; Bertini et al. 2006). An analysis of the data showed that safety levels improved by 20%-30%. The Dutch experiment examined homogenization of the traffic flow along a stretch of highway using enforced VSL (Hoogen and Smulders 1994). Test results showed that speed control was effective in reducing speed and speed variation, as well as the number of shock waves. An empirical evaluation of the implemented VSL control strategies was conducted by Papageorgiou et al. (2008). That study concluded that there was no clear evidence of a positive impact of VSL on traffic flow. However, the authors suggested that a more robust and efficient VSL control strategy could be developed and implemented to investigate the mobility benefits of VSL control. In 2009, a field trial was held in the Netherlands over a six-month period on the A12 freeway. It was reported that traffic safety had been improved substantially and it is indeed possible to resolve shockwaves by applying VSL (Jonkers et al. 2011). However, it was also suggested that not all shockwaves can be resolved by applying a lower speed limit.

In summary, although the safety benefits of VSL control have been well-established, the mobility benefit has not. Specifically, it remains to be determined whether or not VSL control can improve network throughput without compromising TTT during the congestion periods. Furthermore, no analysis can be found that shows the sensitivity of the performance measures—TTT and TF on the weights of partial objectives.

3. Design of VSL Control Algorithm

3.1. Control strategy

The VSL control strategy has been adopted from (Hadiuzzaman and Qiu 2012) that aim at maximizing the bottleneck capacity. It explicitly considers the FDs at bottleneck, and its upstream-downstream links. During the high traffic demand ($q_{in} > Q_b$) as density increases on freeway, small disturbances caused by merging and weaving manoeuvre before the bottleneck readily causes speed drop. It results in flow breakdown, and reduces discharge flow from the link immediately upstream of the bottleneck. Queue will build up from the bottleneck geometric starting point. Due to flow conservation, the discharge flow from the bottleneck will be limited to $Q'_b$. Here, $Q_b$ and $Q'_b$ define the bottleneck capacity and the dropped capacity.

The following control strategy is used based on the traffic characteristics illustrated above, and can be adopted to avoid capacity drop at active bottlenecks (lane drops, weaving, merging, etc). If the demand is too high from both the upstream and on-ramp, and congestion is unavoidable without control, it is necessary to create
a discharge section \( L_{\text{discharge}} \) with adequate length (500–700 m) immediately upstream of bottleneck. To this end, a critical VSL must be defined as shown in Fig. 1. The objective is to limit the feeding flow to the bottleneck. In order to maximize the bottleneck flow, the discharge flow of the three lanes is maintained at a level close to the bottleneck capacity: \( q = 3d_{b}^{(d)} = 2d_{b}^{(u)} \approx Q_{b}^{c} \). Here, \( d_{b}^{(d)} \) and \( d_{b}^{(u)} \) are the transition flows at the link boundaries \( (L_{\text{critical}} \rightarrow L_{\text{discharge}}) \) and \( (L_{\text{discharge}} \rightarrow L_{\text{bottleneck}}) \), respectively. As can be seen, controlling of upstream traffic can improve the bottleneck flow. The critical VSL manipulates the speed limit to control the flow into the discharge section, and to make sure that the bottleneck reaches capacity flow. The critical VSL link \( (L_{\text{critical}}) \) is a very short section, usually, 200–250 m in length.

3.2. Traffic flow model

The main ingredient of a predictive VSL control is a macroscopic traffic flow model that can simulate and forecast traffic in the real-time. To simulate traffic flow with the DynaTAM-VSL, it is required to divide the freeway into several links \( (1, 2, \ldots, M) \). As regards the discretization in time, a simulation time step of about \( T = 20 \) s is used, where \( t = kT \) for a time instant \( t \) and the corresponding time step counter \( k \). The evolution of traffic flow \( q_{i}(k) \) (vphpl), density \( \rho_{i}(k) \) (vpkpl) and space-mean speed \( v_{i}(k) \) (kph) for link \( i \) at time step \( k \) is described by the following dynamics.

3.2.1 Density dynamics

\[
\rho_{i}(k+1) = \rho_{i}(k) + \frac{T}{L_{i}} \left[ \lambda_{i} - q_{i}(k) - \lambda_{i}q_{i}(k) + r_{i}(k) - s_{i}(k) \right]
\]

\[
q_{i-1}(k) = \min \{v_{i-1}(k)\rho_{i-1}(k) + r_{i}(k) - s_{i}(k), Q_{\text{max},i,u_{i}} - w_{i,u_{i}}(\rho_{\text{Jam},i} - \rho_{i}(k))\}
\]

\[
q_{i}(k) = \min \{v_{i}(k)\rho_{i}(k) + r_{i+1}(k) - s_{i+1}(k), Q_{\text{max},i+1,u_{i+1}} - w_{i+1,u_{i+1}}(\rho_{\text{Jam},i+1} - \rho_{i+1}(k))\}
\]

In Eq.2, the link specific parameters, i.e., capacity \( (Q_{\text{max},i,u_{i}}) \) and congestion wave speed \( (w_{i,u_{i}}) \) are dynamic. These parameters vary for different links \((i)\) and for different speed limits \((u_{i})\) and are to be calibrated with the traffic data collected in the control case.
3.2.2 Speed dynamics

The speed dynamics (Eq. 3b) has been derived from the basic METANET model. Particularly, the FD as it appears in the METANET has been replaced with the control variable \( u_i(k) \). Also, another modification is proposed that is related to the convection term of the speed dynamics. Lu et al. (2011) considered several other possible convection terms in the speed dynamics of the METANET model. However, with all the modifications proposed in this study, it is found that the modified convection term in Eq. 3 results in best speed prediction.

\[
v_i(k+1) = v_i(k) + \frac{T}{\tau} \left( u_i(k) - v_i(k) \right) + \frac{T}{\tau} \frac{v_i^2(k)}{L_i} - v_i(k) \left[ \frac{1}{\tau} \frac{\rho_{i+1}(k) - \rho_i(k) + \kappa}{\rho_i(k) + \kappa} \right]
\]

Where, \( \lambda_i \) is the number of lanes in link \( i \), \( L_i \) (km) is the length of link \( i \), \( V_{free,i} \) (kph) denotes the free-flow speed and \( \rho_{c,i} \) (vpkpl) denotes the critical density of link \( i \). Moreover, \( \tau \) (hr), \( \kappa \) (vpkpl), and \( v \) (km²/h) are the global model parameters to be calibrated using the field data. Moreover, the reaction time parameter \( \tau \) in Eq.3b is replaced by the downstream speed limit-dependent parameter \( \tau_i(k) \) according to:

\[
\tau_i(k) = \begin{cases} 
\tau_{low} & \text{if } \Delta u = [u_i(k) - u_{i+1}(k)] > 0 \\
\tau & \text{if } \Delta u = [u_i(k) - u_{i+1}(k)] = 0 \\
\tau_{high} & \text{if } \Delta u = [u_i(k) - u_{i+1}(k)] < 0 
\end{cases}
\]

3.2.3 Constraints

The following simplified constraints are to be considered during the VSL control to address system dynamics and traffic characteristics:

\[
0 \leq \rho_i(k+1) \leq \rho_{jam,i} \\
0 \leq v_i(k+1) \leq v_{free,i,u_i} \\
\rho_i(k+1)v_i(k+1) = q_j(k+1) \leq Q_{max,j}u_j \\
v_{min} \leq u_i(k) \leq v_{free,i,u_i} \\
u_i(k) - u_{i-1}(k) \leq V_{max,diff} \text{ (e.g., 10 kph)} \\
u_i(k) - u_{i+1}(k) \leq V_{max,diff} \text{ (e.g., 10 kph)}
\]

4. Model Calibration in Control Case

To prepare the data for calibrating the DynaTAM-VSL model, a simulation model for the evening peak periods (11:00-13:00 PM) was used, namely, the microscopic traffic flow simulator VISSIM v5.3. The 11-km Whitemud Drive (WMD) urban freeway section in Edmonton, Canada was coded in VISSIM. The WMD is a test site that covers westbound immediately west of the 111 street to east of the 159 street. To replicate the real life bottleneck formation along the studied freeway section, several customized link behavior types were defined, namely, for the freeway merge section, the lane drop condition and the weaving section. The VISSIM model was used to generate the calibration data in the control case. The test site was discretized into 13 links (L1-L13). In the WMD VISSIM model, for each link, one loop detector was placed on each lane, and was located at the
middle of the corresponding link. These detectors provided the mean speed and flow. Density was estimated from the fundamental relationship of traffic variables. Moreover, each link was operated with one VSL sign, and they were placed at the beginning of the links. In this paper, the authors assume that each of the freeway links is operated with separate VSL sign regardless of bottlenecks. It allows us to extract maximum information about the MPC-based VSL control (under maximum flexibility) and potential impact. Note that, in the case of very short links, the links should be aggregated into several clusters of links and each cluster should be operated with one VSL sign (e.g., link 1 and 2 get the same speed limit, 5 and 6 also, etc.).

To calibrate the dynamic link specific parameters, the WMD VISSIM model was run with different speed limit values assigned to each link, and each time simulation was run for a period of 2.5 hrs. Traffic data was collected every 20 sec. The measured data were used to calibrate the following link specific parameters: $[Q_{\text{max},i,j}, v_{\text{free},i,j}, w_i,u_i, \rho_{c,i,u_i}, \rho_{\text{jam},i}]$. The method to calibrate these parameters can be found in Dervisoglu et al. (2009). Fig. 2 shows an example of the calibrated critical density and capacity (the first and the second value within the bracket), and the free-flow speed for a typical link on WMD. The numeric digits 1, 2, 3, 4, 5, 6, and 7 correspond to the speed limit of 80, 70, 60, 50, 40, 30, and 20 kph. For all the links, it was found that $Q_{\text{max}}$ and $v_{\text{free}}$ decreases, and $\rho_c$ increases with lowering the speed limits.

![Fig. 2. Link specific parameters with the different speed limits](Note: On the figures, FFS stands for free-flow speed)

To generate the traffic data for calibrating the global parameters $[\tau_{\text{low}}, \tau_{\text{high}}, \gamma, K]$ of the speed dynamics (Eq. 3), an appropriate speed limit using flow-density-speed threshold-based VSL control algorithm were assigned to each link in the micro-simulation model. This candidate VSL control algorithm has been adopted from Allaby et al. (2007a) with slight modification to cover the entire range of speed limits considered in this study. Based on the traffic data collected every 20 s from detector $i$ (correspond to link $i$), the control algorithm determines the appropriate speed limit to be displayed at VSL sign $i$ (correspond to link $i$). Moreover, to find the optimal global parameters, the objective function (6) was chosen to minimize the speed and density errors. This paper implemented the multi-start Sequential Quadratic Programming (SQP) (Boggs and Tolle 1995) to minimize the function over a constrained parameter space. During the parameter optimization, $\gamma = 0.8$ and $K = 450$ were assigned to Eq. 6. With the search interval $\beta_{\text{min}} = [0.00055, 0.00055, 0.00055, 0, 20]$ and $\beta_{\text{max}} = [0.03, 0.03, 0.03, 90, 120]$, the optimal global parameters were found to be: $\beta_{\text{optimal}} = [0.0046, 0.0069,$
0.0092, 5.9, 26.1]. The optimization with the SQP algorithm was performed in MATLAB installed on an Intel (R) Core(TM) i5 CPU. Convergence was achieved after 50 iterations which took about 135.2 s computation time. The optimal value of the objective function, $f(\beta^{optimal})$, was 1304.

$$f(\beta) = \sum_{k=1}^{M} \sum_{i=1}^{K} [(\rho^m(k) - \rho(k|\beta))^2 + \gamma (v^m(k) - v(k|\beta))^2]$$

(6)

In the above equations, $\rho^m(k), v^m(k)$ are the measured density and speed; $\rho(k), v(k)$ are the simulated density and speed; $\gamma$ is the weighing factor to be tuned. Moreover, in this study, $K = 450$ and $M = 13$ were assigned in the above equation during the parameter optimization.

5. MPC-based VSL Control Framework

Fig.3 shows a snapshot of the proposed MPC control framework assuming the controller is at certain time step $k$.

The optimal control variable is calculated via a digital computer, and the result is implemented in a real-time traffic at each controller sampling time $T_c$. The traffic flow model—$f(x(k), u(k))$—takes feedback of actual traffic measurement $x(k)$ as input from the traffic system. Based on the predicted demand $\hat{D}(k)$ and initial guessed values for the speed limits $u(k)$, the controller predicts future process output $\hat{x}(k)$ over a prediction horizon $N_p$. The objective is then to find the future trend for the control variable that will results the future trend of the output. The optimal speed limits $\left[ u^*(k), u^*(k+1), \ldots, u^*(k+N_p-1) \right]$ correspond to the output that results the best performance, i.e., $J(u(k))$ of the traffic system over the entire prediction horizon. In fact, an optimization problem is solved to compute the open loop sequence of present and future control moves. The optimization is solved taking into consideration the constraints (equality—$\phi$ and inequality—$\xi$) on the $u$. 
The control inputs \( u^*(k, k+1, \ldots, k+N_c-1|k) \) is then picked and implemented on the traffic system over the control horizon \( N_c \). After that, in a rolling horizon framework, the prediction and the control horizon are shifted one control step (\( T_c \)) forward, and the whole process starts all over again. To ensure the traffic prediction stability, during the optimization, we assumed that after the \( N_c \), the same control variable \( u^*(k+N_c-1) \) remains effective until the \( N_p \). By defining the control horizon \( N_c \), the number of control variables to be determined is reduced without shortening the \( N_p \).

6. Optimization Results

Previously TTT was mostly used for the evaluation of the MPC-based VSL control. However, minimizing TTT as an objective function, could keep density lower by reducing flow, which in turn is a conflict with the control goal considered in this paper. Oppositely, maximizing Total Travel Distance (TTD)—a surrogate measure of TF tries to increase flow by maintaining higher density, and the traffic state might go to the congested region (right side of FD). So, the vehicles might need to spend more time in the network. Therefore, within the MPC-based VSL control framework (see, Fig.3), the authors perform the traffic simulation using the DynaTAM-VSL, and the network performances were evaluated with the different objective functions with the typical values of \( N_p \) and \( N_c \): (1) minimize TTT (Eq.7), (2) maximize TTD (Eq.8), and (3) simultaneously minimize TTT and maximize TTD (Eq.9). The effectiveness of the MPC-based VSL control was evaluated as follows. For the no-control case, the measured traffic data from the micro-simulation model were used to estimate the TTT and TF. For the VSL control case, with the same demand inputs as in the no-control case, the DynaTAM-VSL was simulated within the MPC framework to optimize the traffic performance measures. To make the no-control and the VSL controlled scenarios comparable, the authors used equal demand inputs for both scenarios. In fact, the micro-simulation model for which the traffic state at uncontrolled case was observed was taken sufficiently larger than the VSL controlled network. So, the future demand at the origin of the controlled network was deduced from the actual traffic state. The simulation was run for a period of 2.5 hrs with each of the above objective functions. The following control parameters were considered during the evaluation of traffic performances: \( N_p = 15 \) and \( N_c = 3 \). \( T \) and \( T_C \) were 20 s and 1 min, respectively.

\[
J_1(u) = T \sum_{j=1}^{N_c-1} \sum_{i=1}^{M} \lambda_i L_i \rho_i(k+j)
\]

(7)

\[
J_2(u) = T \sum_{j=1}^{N_c-1} \sum_{i=1}^{M} \lambda_i L_i \rho_i(k+j) \psi_i(k+j)
\]

(8)

\[
J_3(u) = T \sum_{j=1}^{N_c-1} \sum_{i=1}^{M} \lambda_i L_i [\alpha_{TTT} \rho_i(k+j) - \alpha_{TTD} \rho_i(k+j) \psi_i(k+j)]
\]

(9)

Table 1 presents the mobility improvement in the WMD with the different objective functions. The estimated TTT and TF in the no-control case are 1805 veh-hr and 18374 vphpl, respectively. As expected earlier, minimizing \( J_1 \) causes huge improvement in the TTT. Specifically, with this objective function, around 27.0% travel time reduction is achieved. It confirms the results published by (Hegyi et al. 2005; Hegyi et al. 2007; Carlson et al. 2010b). However, in this case, TF has been deteriorated significantly. As the TTT minimization causes reduction in vehicle density over the freeway links. Oppositely, maximizing \( J_2 \) results in huge
improvement in the TF. This is around 19.5%. However, in this case, the controller has compromised the TTT improvement; rather it has worsened the TTT by 13.5% compared to the no-control case. Consequently, if an individual wants to improve the TTT and the TF simultaneously, it requires a trade-off combining both the TTT and TTD in the objective function as in $J_3$. Moreover, the authors minimize $J_3$ with the different $\alpha_{TTT}$ values as presented in Table 1. The objective function can take different values in the weighing coefficient $\alpha_{TTT}$, those are to be determined based on the control policy by traffic engineers. If $\alpha_{TTD}$ is assumed to be 1, then $\alpha_{TTT}$ is the ratio between TTD and TTT, which equals to speed ($v$). In this paper, the authors use the lowest value of $\alpha_{TTT}=20$ to maintain the operating efficiency. Whereas, to guarantee the travelers' safety, the highest values of $\alpha_{TTT}=80$ is used which is the current static speed limit in the WMD.

It can be seen that considering $J_3$ the MPC-based VSL control results in the TF improvement without compromising the TTT. As, one of the main objectives of the proposed VSL control strategy is to see whether VSL control can significantly improve the freeway capacity, the weight factor $\alpha_{TTT}=20$ is used in the rest of this paper. In the previous empirical studies, it was found that capacity at the bottlenecks could be dropped by 30% due to shockwave formation. The simulation results with the DynaTAM-VSL prove that the MPC-based VSL control can confirm maximum utilization of freeway through the capacity improvement, so the flow has been improved significantly compared to the no-control case.

### Table 1. Performance of MPC-based VSL Control with different Objective Functions

| Objective function | TTT (veh-hr) | TF* (vphl) | %Improvement | %Improvement |
|--------------------|-------------|------------|--------------|--------------|
| Base case (no-control) | 1805 | 18374 | - | - |
| Min $J_1$ | 1312 | 16576 | 27.3 | -9.8 |
| Max $J_2$ | 2047 | 21950 | -13.4 | 19.5 |
| Min $J_3$ ($\alpha_{TTT}=20$; $\alpha_{TTD}=1$) | 1432 | 20290 | 20.6 | 10.4 |
| Min $J_3$ ($\alpha_{TTT}=55$; $\alpha_{TTD}=1$) | 1341 | 20049 | 24.6 | 9.1 |
| Min $J_3$ ($\alpha_{TTT}=80$; $\alpha_{TTD}=1$) | 1362 | 20035 | 25.7 | 9.0 |

*Summation of the flows over the discretized links; and the flow at each link is taken as the average over the simulation periods ($t=4:00-6:30$ PM).

Fig. 5 confirms the effectiveness of the MPC-based VSL control with the DynaTAM-VSL as prediction model considering $J_3$ ($\alpha_{TTT}=20$; $\alpha_{TTD}=1$) as an objective function and the demand inputs as shown in Fig.4.
Fig. 5. No-control (left figures) and VSL controlled (right figures): (a) flow profile; (b) speed profile; and (c) density profile

When simulating the freeway by use of the micro-simulator without any control measures, heavy congestion appears in the freeway. The density evolution is displayed in Fig.5(c). The excessive mainline demand, coupled
with the high demand from the ramps to the mainstream, causes congestion shortly after the beginning of the simulation. Fig. 5(c) (right one) indicates that with the VSL control there are three high density regions. But, in contrast to the no-control case, these regions are much less extended in space and time when the VSL control is implemented. Moreover, without any control, speeds in the most of the links are maintained at 20 kph; and this prevails from $t=4:05-6:00$ PM. The VSL control has maintained the speeds at 50 kph or above most of the times.

7. Concluding Remarks

Predictive VSL control could improve both the travel time and traffic flow. To achieve this goal, it requires selection of proper objective function and maintaining a prudent relationship among the partial objectives. Moreover, the control strategy should explicitly consider the mobility factors. To this end, in this paper, the authors adopt a previously developed VSL control strategy that limits the flow from upstream to avoid capacity drops and shockwave formation from the bottleneck. Thus, it could improve flow significantly and reduce the travel time. Simulation of the DynaTAM-VSL model with the different objective functions within the MPC framework established a guideline to tune the predictive VSL control parameters. The simulation results proved that the combined objectives with appropriate weight could maintain a prudent relationship between the travel time and the throughput. Thus, it can help us achieving improvement in the throughput without compromising the TTT during the congestion periods, which resolves the existing paradoxical results. Specifically, for the WMD, improvement in the TTT and TF were around 21.0% and 11.0%, respectively, with the 1 min control horizon and 5 min prediction horizon for ($\alpha_{TTT}=20; \alpha_{TTD}=1$). It was observed that assigning more weight to the TTT, it is possible to achieve a consistent improvement in the TTT. However, it impacts negatively to the TF improvement. The result was found very consistent with the expectation that confirms the accuracy of the proposed VSL control framework.

Although the proactive optimal VSL control is a promising solution to improve freeway congestion, the real-life benefits of such control application are not available. This may be attributable to various reasons including absence of real-life application software. To promise the aforementioned function, DynaTAM—a field application software tool is being developed at the University of Alberta, Canada. As the Realistic and fast Traffic Simulator (Ref-TS), it has adopted the DynaTAM-VSL that has been presented in this paper. A field operation test (FOT) in the WMD using the DynaTAM will be performed this year. However, before the FOT, the authors will investigate what should be the optimal values of control parameters with the combined objective functions and the traffic flow model will be re-calibrated with the practical traffic data.

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