Control Strategy of Variable Speed Limits for Improving Traffic Efficiency at Merge Bottleneck on Freeway

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ABSTRACT
Queue forms at merge bottleneck area on freeways if the mainline and on-ramp traffic demand exceeds the capacity of bottleneck. Then bottleneck discharge flow further drops below the capacity of bottleneck which is termed as the capacity drop phenomenon. This study aims to develop control strategies of Variable Speed Limits (VSL) for improving traffic efficiency at freeway merge bottleneck area via preventing the capacity drop. The Cell Transmission Model (CTM) was developed and calibrated with field traffic data to evaluate the effectiveness of VSL. The results showed that by reducing the speed limit in VSL at upstream area, the capacity drop at the merge bottleneck was prevented and the discharge flow rate was kept near the bottleneck capacity. The control strategy of VSL developed in this study significantly reduced the travel delay by 56.10% and was effective in improving the traffic efficiency at the merge bottleneck area.

INTRODUCTION
Variable speed limit (VSL) is a dynamic freeway traffic management technique which has been increasingly used in recent years. Numerous studies have evaluated the potential of using VSL to reduce vehicle delay and improve traffic efficiency at freeway bottleneck areas. Previous researchers have studied the use of VSL to suppress shock waves (Hegyi and Hoogendoorn, 2010; Hegyi et al. 2008; Hegyi et al. 2009; Hegyi et al. 2005; Popov et al., 2008), smooth traffic flow in work zone areas (Kwon et al., 2007; Lin et al., 2004; Kang et al., 2004), and reduce vehicle delay at freeway merge and diverge areas with the
coordination of ramp metering (RM) techniques (Carlson et al., 2010a; Carlson et al., 2010b; Lu et al., 2011; Su et al., 2011). Some researchers have also studied the potential of using VSL for improving traffic efficiency in large scale freeway networks (Carlson et al., 2010c).

Previous studies have developed different control strategies for VSL. Various control algorithms were developed in previous studies with different optimization objectives such as minimizing total travel time (Carlson et al., 2010a; Carlson et al., 2010b; Carlson et al., 2010c), preventing queue formation and maximizing throughput of bottlenecks (Kwon et al., 2007; Lin et al., 2004; Kang et al., 2004), and minimizing difference between total travel time and total travel distance (Lu et al., 2010; Lu et al., 2011; Su et al., 2011), etc. The effectiveness of VSL in improving traffic efficiency is often tested using microscopic simulation models. Most previous studies have reported that the VSL improved the traffic efficiency at freeway bottlenecks.

So far, the most commonly used control strategy is to implement VSL upstream of the target freeway bottlenecks or congested areas. By regulating upstream speed limit on freeway mainline, inflow rate to bottleneck can be reduced, which prevents queue formation at freeway bottlenecks. Theoretically, preventing queue formation will help reducing capacity drop at freeway bottlenecks. Capacity drop refers to a substantial reduction in discharge flow rate observed at an active bottleneck when a queue forms upstream. Previous studies have reported that the extent of capacity drop at an active bottleneck varies from 5% to 20% (Cassidy and Rudjanakanoknad, 2005; Chung et al., 2007). Cassidy (2003) suggested that vehicle delay produced by a bottleneck is reduced only if the outflow rate of the bottleneck system is increased. Preventing capacity drop at bottleneck areas will help achieving a higher system outflow rate and improve traffic efficiency. Consequently, the effectiveness of VSL in improving traffic efficiency at an active freeway bottleneck heavily depends on whether VSL successfully prevents capacity drop.

So far, the capacity drop at bottlenecks did not receive sufficient attention in previous studies when developing control strategies of VSL for improving traffic efficiency. These strategies were not developed for preventing the capacity drop at bottleneck area and the simulation models were not calibrated for the capacity drop at the study sites. Even though several simulation packages may automatically create certain levels of capacity drop at active bottlenecks (Carlson et al., 2010a; Carlson et al., 2010c), they are not calibrated using real-world traffic data at freeway bottlenecks and, as a result, are not able to reflect the extent of capacity drop varies across different freeway segments (Chung et al., 2007).

This study aims to present a control strategy of VSL for improving traffic efficiency. The VSL was designed to prevent the capacity drop at the target bottleneck by monitoring the traffic condition at the bottleneck area. The strategy was tested in the Cell Transmission Model (CTM) at a merge bottleneck on freeways and field data were considered to calibrate the simulation. The impacts
of VSL on traffic flow at bottleneck were analyzed and the effectiveness of VSL on traffic efficiency improvement was evaluated in this study.

CONTROL STRATEGY OF VSL

Effects of VSL on Traffic Efficiency
Travel delay that all vehicles experienced in a freeway system is illustrated by the queuing diagram, as shown in Figure 1. The vertical coordinate of the curve represents the cumulative number of vehicles that would have exited the system by time t, if queues were not formed in the system. The slope of traffic demand curve represents the discharge flow rate in the absence of a queue in the system and is only determined by the traffic demand. The curves that represent the discharge flow rate after capacity drop and the bottleneck capacity were also shown in Figure 1.

It was observed in the figure that the travel delay experienced by a vehicle \( n \) after capacity drop (i.e., \( t_{\text{delay}} \)) is more than that if bottleneck capacity does not drop (i.e., \( T_{\text{delay}} \)). The shaded area in Figure 2 represents the total delay encountered by all travelers in the system. Traffic efficiency on freeway is improved by implementing VSL only if the control strategy of VSL increases the discharge flow rate of the target freeway system. The area between the traffic demand and the two discharge flow curves was the travel delay that the VSL can potentially save. In other words, the VSL control only saves the vehicle delay which was generated due to the capacity drop at bottlenecks.

Theoretically, if capacity drop does not occur at the bottleneck area, using VSL control will not reduce vehicle delay and improve system efficiency. The
VSL control simply transfers the delay from the target bottleneck to an upstream bottleneck which is created by the VSL. If the mainline traffic flow is so restrictively controlled by VSL that the inflow rate to the target bottleneck is “starved”, i.e., vehicles pass through the target bottleneck at a flow rate which is much lower than the discharge flow rate after capacity drop, the system delay can be increased by the overly-restrictive scheme of VSL. If the traffic is under-restricted by VSL, i.e., the queue at the target bottleneck does not fully dissipate and capacity drop is not prevented, the system delay is not reduced even though the VSL relieves the congestion at the target bottleneck area.

Control Strategy Development

Previous studies reported that several traffic flow parameters, such as density and occupancy, can be used as indicators to help identifying the occurrence of capacity drop (19, 23). VSL control can be initiated when these traffic flow parameters reach a pre-determined threshold value which suggests that a capacity drop will follow.

For a merge bottleneck on freeways, the VSL scheme is to increase the bottleneck discharge flow rate through preventing capacity drop at the bottleneck. Basic control strategies for a VSL system is illustrated in Figure 2 to help transportation professionals develop control strategies for improving traffic efficiency.

![FIGURE 2. Control strategy of VSL for improving efficiency](image-url)
Real-time traffic flow condition at the bottleneck area was monitored to identify if the capacity drop will occur. Then the VSL starts up to eliminate the capacity drop through two procedures: first, determine the VSL scheme to eliminate the queue at the bottleneck area to recover the bottleneck capacity; and second, determine the VSL scheme to keep the discharge flow near bottleneck capacity. If the queue upstream of the VSL control section discharges, which indicates the travel demand being smaller than capacity, the VSL shuts down. The speed limits in VSL is determined by the traffic conditions at the study area, so the VSL scheme is termed as local feedback based control strategy.

VSL MODELING

Cell Transmission Model

The CTM is an innovative transformation of a set of equation developed by Lighthill and Whitham [3] and Richards [6] using a piecewise linear relationship between flow and density at the cell level. The road was discretized into homogeneous sections (or cells) and the cell length equals the distance traveled by free-flowing traffic in one time interval. The free-flow speed, maximum flow (or capacity), speed of backward wave, and maximum (or jam) density were specified in the CTM.

A freeway corridor with a merge bottleneck was set up in the CTM, as shown in Figure 3. Vehicles depart from mainline start cell M0 and ramp start cell R0, and arrive at the destination cell M10. Cell M3 was the section that the VSL implemented. The speed limit in the cell can be controlled by the VSL scheme. Cell M4 and M5 were considered as vehicle acceleration section as proposed by xxx to allow mainline vehicles being free-flowing when reaching the bottleneck.

Calibration for Capacity Drop

In this study, we have shown that the delay that the VSL can potentially save is determined by the magnitude of capacity drop. The VSL control strategy also relies on the occurrence condition of capacity drop. Thus, field traffic data at a merge bottleneck on I-5 freeway in San Diego county, California were collected to calibrate for the capacity drop in the CTM.

According to field data, the traffic information shown in Table 1 were set up in the CTM to develop the simulation platform for VSL test. When traffic
demand from mainline and on-ramp exceeds the capacity of cell M6 (i.e., 2160*4=8640 veh/h) in Figure 3, the capacity drop occurs which makes the maximum flow rate of cell M6 drop to a lower value (i.e., 1980*4=7920 veh/h). Then the VSL at cell M3 starts up and runs with the control strategy developed in the above section.

Table 1. Traffic information for model calibration

<table>
<thead>
<tr>
<th>Traffic information</th>
<th>Mainline</th>
<th>On-ramp</th>
</tr>
</thead>
<tbody>
<tr>
<td>Free-flow speed (km/h)</td>
<td>100</td>
<td>100</td>
</tr>
<tr>
<td>Maximum flow (veh/h)</td>
<td>2160</td>
<td>1667</td>
</tr>
<tr>
<td>Speed of backward wave (km/h)</td>
<td>22</td>
<td>20</td>
</tr>
<tr>
<td>Maximum density (veh/km/lane)</td>
<td>120</td>
<td>100</td>
</tr>
<tr>
<td>Critical density (veh/km/lane)</td>
<td>21.6</td>
<td>26.8</td>
</tr>
<tr>
<td>Discharge flow after capacity drop (veh/h)</td>
<td>1980</td>
<td>-</td>
</tr>
<tr>
<td>Percentage of dropped capacity (%)</td>
<td>8.3%</td>
<td>-</td>
</tr>
<tr>
<td>Density threshold for capacity drop (veh/km/lane)</td>
<td>22.5</td>
<td>-</td>
</tr>
</tbody>
</table>

RESULTS AND DISCUSSION

Simulation without control of VSL was conducted in the calibrated CTM. The results of traffic flow rate at each cell were shown in Figure 4. When mainline and ramp traffic demand exceeds the capacity of the merge bottleneck, queue starts forming at the bottleneck area. When the traffic density in cell 6 exceeds the threshold, the capacity drop occurs and the bottleneck discharge flow rate drops from capacity (8.66 veh/clock tick) to a lower value (7.93 veh/clock tick). As a result, the mainline traffic flow rate in each cell upstream of the bottleneck also decreases dramatically.

Simulation results of traffic flow rate in CTM with the control of VSL were shown in Figure 5. The same as that in Figure 4, the capacity drop occurs when traffic demand exceeds the bottleneck capacity. Differently, the VSL implemented in the upstream cell starts up immediately and reduces the traffic flow that goes through the cell, which is area A in Figure 5. The reduction of flow into the merge bottleneck and the queue at the bottleneck eliminates gradually.

When the bottleneck capacity recovers, the VSL then adjust the speed limit to keep that the traffic of mainline and ramp approximately equals the capacity of bottleneck, which is area B in Figure 5. As shown in the figure, by using the VSL, the discharge flow rate at the bottleneck can be keep to a higher value as compared to that without VSL.

The time-space diagrams of traffic density in the CTM with and without VSL were shown in Figure 6. When there is no VSL scheme, as shown in in Figure 6 (a), the backward and forward moving kinematic wave can be clearly identified. Congestion propagates towards upstream when traffic demand exceeds bottleneck capacity and dissipates when mainline traffic demand decreases. When under the control of VSL, the congestion mitigates from the merge bottleneck to
the upstream of the bottleneck produced by VSL. The queue at the merge bottleneck was prevented during the rest simulation period.

**Figure 4. Results of traffic flow rate in CTM without VSL**

The discharge flow rates at the merge bottleneck with and without VSL were shown in Figure 7 (a). In the initial stage, the discharge flow rates in both conditions are the bottleneck capacity. When the capacity drop occurs, the discharge flow rate without VSL drops to a lower value and lasts for a long time period (which is T2-T1), while the discharge flow with VSL recovers to the capacity and lasts until time T3. The queue in the freeway system completely eliminates at time T4 under control of VSL while eliminates at time T 5 without control of VSL.

The oblique cumulative discharge vehicle count with and without VSL were shown in Figure 7 (b). The discharged vehicles per time under control of VSL are higher than that without VSL. The delay suffered by a vehicle under VSL is smaller than that without VSL. The shade area in Figure 6 (b) represents the delay saved by the implementation of VSL control strategy for the freeway system during the simulation period.
The results of traffic under the control of VSL were compared to that without VSL. Several measurements were used for comparison purpose and the results were summarized in Table 2. The average discharging capacity at the merge bottleneck was improved by 3.66% with the VSL scheme and the average travel speed also significantly increases. The total vehicle hour travelled was reduced by 25.53% under the control of VSL while the total travel delay was saved by 56.10%, as compared to that without VSL.

Table 2. Comparison of simulation results with and without VSL

<table>
<thead>
<tr>
<th>Measurement</th>
<th>No VSL</th>
<th>With VSL</th>
<th>Diff.</th>
<th>Percent</th>
</tr>
</thead>
<tbody>
<tr>
<td>Average discharging capacity (veh/h)</td>
<td>2077</td>
<td>2153</td>
<td>76</td>
<td>3.66</td>
</tr>
<tr>
<td>Average travel speed (km/h)</td>
<td>57.53</td>
<td>77.24</td>
<td>19.71</td>
<td>34.26</td>
</tr>
<tr>
<td>Total vehicle hour travelled (veh·h)</td>
<td>35.88</td>
<td>26.72</td>
<td>-9.16</td>
<td>-25.53</td>
</tr>
<tr>
<td>Total travel delay (h)</td>
<td>16.31</td>
<td>7.16</td>
<td>-9.15</td>
<td>-56.10</td>
</tr>
</tbody>
</table>
Figure 6. (a) Results of traffic density in CTM without VSL; and (2) results of traffic density in CTM with VSL.
The local feedback based control strategy of VSL developed in this study was tested to be effective for reducing travel delay and improving traffic efficiency at a freeway merge bottleneck, using the simulation technique in the CTM. By preventing the capacity drop at the bottleneck area, the VSL can significantly increase the system throughput, increase the average travel speed, and save the travel time of vehicles.

The control strategy of VSL that aims at preventing the capacity drop at the target bottleneck can also be used in other types of bottlenecks on freeways for improving the traffic efficiency. Prior to any of those tests, the magnitude of capacity drop needs to be firstly identified and the simulation model needs to be calibrated with field data to make the simulation results be creditable and be consistent field applications. The authors recommended that further studies could focus on these issues.
CONCLUSION

This study developed a control strategy of VSL for improving traffic efficiency at the merge bottleneck on freeways and evaluated the effectiveness of the strategy. The effects of VSL on traffic efficiency at freeway bottleneck areas were first analyzed. It was concluded that the improvement of traffic efficiency highly depends on if the VSL scheme increases the discharge flow rate of the target bottleneck. Then the control strategy of VSL that aims to prevent the capacity drop at the merge bottleneck was developed for improving the bottleneck traffic efficiency. The CTM was used to conduct the simulation for VSL and field traffic data were used to calibrate the CTM.

The results showed that by reducing the speed limit in VSL at upstream area, the capacity drop at the merge bottleneck is prevented and the discharge flow rate can be kept near the capacity of the bottleneck. The control strategy of VSL developed in this study reduced the total vehicle hour travelled by 25.53% and reduces the total travel delay by 56.10%, as compared to that without VSL. The VSL was effective in reducing travel delay and improving traffic efficiency at merge bottleneck areas.

ACKNOWLEDGMENTS

This research is jointly supported by the China’s Science and Technology Plan of Action for Traffic Safety (Project #: 2009BAG13A07-5), China’s National Basic Research Program of China (Project #: 2012CB725402), as well as the Excellent Doctoral Dissertation Found at the Southeast University.

REFERENCES


Cassidy, M. Freeway On-Ramp Metering, Delay Savings, and Diverge Bottleneck. In Transportation Research Record: Journal of the Transportation


