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Evaluating the Effects of Different Control Strategies on Traffic Operations at Isolated Merge Bottlenecks

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Abstract

The primary objective of this study was to develop variable speed limit (VSL) and ramp metering (RM) strategies that particularly focused on preventing the capacity drop and increasing the discharge flow rate at freeway merge bottlenecks, and to evaluate the effects of the proposed control strategies on traffic operations. A cell transmission model was developed to evaluate the effects of the proposed control strategies on traffic operations. The CTM was adjusted and calibrated using real-world traffic data to accurately capture the capacity drop phenomenon. With space-time diagrams and traffic characteristic diagrams, the occurrence mechanism of traffic congestion at the bottleneck under different control strategies was compared. The simulation results showed that total travel time and vehicle delay were reduced under the proposed control strategies. It was found that the VSL control and RM control were effective in improving traffic operations at freeway isolated merge bottlenecks. In addition, the RM control outperformed the VSL control in reducing traffic congestion when the on-ramp flow rate was low.

Keywords: Freeway isolated merge bottleneck; Capacity drop; Cell Transmission Model; Variable Speed Limit; Local Ramp Metering

1. Introduction

Variable speed limit (VSL) and ramp metering (RM) are dynamic freeway traffic management techniques which have been increasingly used in recent years. Previous studies have developed different control strategies for using VSL and/or RM to improve traffic operations at freeway bottleneck areas. Various control algorithms were developed with different optimization objectives, such as minimizing total travel time (Carlson et al. 2010 a, b, c), preventing queue formation and maximizing the throughput of bottlenecks (Kang et al. 2004; Kwon et al. 2007; Lin et al. 2004) and minimizing the difference between total travel time and the total travel distance (Lu et al. 2011; Su et al. 2011). So far the most commonly used control strategies of VSL and RM were developed either based on the optimization algorithms, such as the mainstream traffic flow control (MTFC), or the ALINEA algorithms, such as the density based ramp metering (DERAM) (Carlson et al. 2010; Hadjipollas et al. 2006). Previous studies generally suggested that using these control strategies improved traffic operations on freeways. Marios et al. and George et al. evaluated the operational effects of various RM and VSL algorithms on a chosen highway section using VISSIM. It was found that the both RM and VSL control was effective in reducing the

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total travel time. However, the RM control was more effective in reducing travel time than the VSL control (Hadjipollas et al. 2006). Kang developed a control system which integrated the VSL with the RM. The integrated algorithm control responded well to time-varying traffic conditions and yielded more throughputs, resulting in increased average speed and decreased speed variation (Kang et al. 2011). The research conducted by Carlson et al. also suggested that traffic operations can be substantially improved when an integrated VSL and RM control was used (Carlson et al. 2010a). Researchers in the Texas department of transportation compared different ramp metering algorithms and found that with queue flush, the existing strategy of ramp metering at the maximum rate is more beneficial than ALINEA (Nadeem 2004).

Capacity drop, which is defined as the drop in the discharge flow rate after bottleneck activation, has been frequently observed in freeway bottlenecks, especially at isolated merge sections. It refers to a substantial reduction in discharge flow rate observed at an active bottleneck when a queue forms upstream (Banks 1991; Cassidy and Rudjanakanoknad 2005; Chung et al. 2007; Hall and Agyemang 1991; Persaud et al. 1998). It is found that the extent of capacity drop at an active bottleneck can vary from 5% to 20% (Cassidy and Rudjanakanoknad 2005; Chung et al. 2007). Previous studies have reported that vehicle delay can be reduced if the capacity drop was prevented and a higher outflow rate was achieved (Kerner 2002). Cassidy also suggested that preventing capacity drop at bottleneck areas is the only way to achieve a higher system outflow rate and improve traffic efficiency (Cassidy and Rudjanakanoknad 2005).

When developing the control strategies of freeway bottlenecks, the effects of capacity drop should be carefully considered. However, the capacity drop at bottlenecks did not receive sufficient attention in previous studies when developing control strategies for freeway control systems. Even though previous studies have developed various control strategies for VSL or RM, none of them specifically focused on reducing capacity drop at freeway merge bottlenecks. In addition, the effects of control strategies on freeway traffic operations have often been tested using traffic simulation techniques. However, most of the simulation models used in previous studies did not consider the capacity drop at freeway bottlenecks. Even though several simulation packages may automatically create certain levels of capacity drop at active bottlenecks, they are not calibrated using real-world traffic data and, as a result, are not able to reflect the extent of capacity drop varies across different freeway segments.

The primary objective of this study was to develop VSL and RM strategies that particularly focused on preventing the capacity drop and increasing the discharge flow rate at freeway merge bottlenecks, and to evaluate the effects of the proposed control strategies on traffic operations. In the next section, capacity drop at a real isolated merge bottleneck area was analyzed. A calibrated Cell Transmission Model (CTM) for evaluating the operational effects of control strategies was then developed in section 3. Control strategies in VSL and RM at freeway isolated merge area bottleneck were proposed in section 4. In section 5, the evaluation and comparison of the proposed VSL and RM control were discussed. A summary and discussion of the research results were given in section 6.

2. Capacity Drop at Isolated Bottleneck Area

Freeway isolated merge bottleneck was one of the most commonly observed bottlenecks. In this condition, the upstream traffic demand is high and the downstream traffic is usually in a free-flow state. The dissipate flow rate is only determined by the arrival of upstream vehicles. More specifically, when a queue starts to form at the bottleneck location, the downstream flow will not propagate towards the bottleneck to disturb the whole dissipate rate. For the isolated bottleneck, when traffic demand exceeds the capacity, a queue starts to form. The discharge flow rate in this condition is lower than the maximum flow rate prior to the queue formation due to capacity drop.

The real-time traffic flow data were collected from a merge bottleneck from milepost 44.10 to 45.59 on the I-5 freeway in San Diego County, California, United States (see Figure 1). The real time traffic data were collected from 16:00 to 19:00 pm on July 22, 2009. Traffic flow parameters were used as indicators to help identify the occurrences of capacity drop. When a bottleneck appears, the upstream speed and downstream dissipation rate will decrease; and the occupancy will increase with the accumulation of vehicles. Following the procedure proposed by Simon et al., we classified the bottleneck formation into three states, including the free flow period, the transition period, and the bottleneck period (Simon et al. 2012). The conditions for identifying each traffic state can be expressed as: (1) free flow state: in which both upstream and downstream speed are greater than or equal to 40 mi/hr; (2) transition to bottleneck or recovery from bottleneck: in which the upstream speed is between 30 mi/hr and 40 mi/hr, while the downstream speed is greater than or equal to 40 mi/hr; and (3) bottleneck period: in which the upstream speed is lower than or equal to 30 mi/hr, while the downstream speed is greater than or equal to 40 mi/hr.

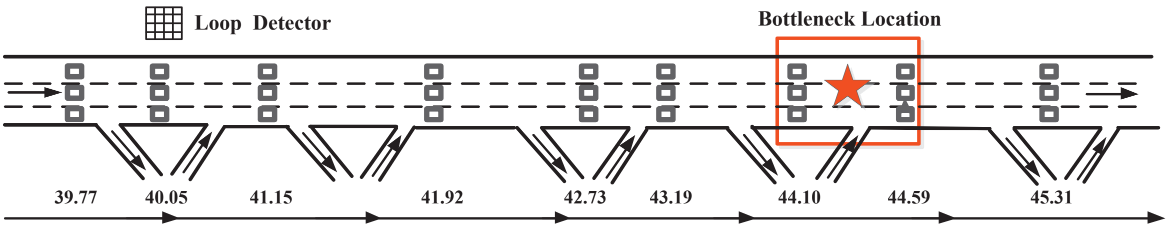

Figure 1. Selected isolated merge bottleneck on the freeway segment

The change of traffic flow parameters at the selected bottleneck area during the selected time period is illustrated in Figure 2. The dark line represents the traffic flow parameters in the upstream area; while the light line represents the traffic flow in the downstream area. The transition from the free flow state to the bottleneck starts at 17:04. The bottleneck forms at 17:08. From the curves in Figure 2, the capacity drop can be easily identified. More specifically, the capacity reduced from 2160 veh/h to 1980 veh/h. The upstream speed began to increase and the downstream discharge rate began to recover from 17:48; and got fully recovered at 17:56.

3. The Simulation Model

A Cell Transmission Model (CTM) was used for the simulation of traffic flow at the freeway bottlenecks affected by the VSL and RM control. The CTM is a macroscopic traffic simulation model proposed by Daganzo based on the kinematic wave theory to reflect the traffic flow characteristics near bottleneck. By dividing the corridor into homogeneous cell sections, the CTM predicts the macroscopic traffic behavior on a given corridor by evaluating the flow and density at finite number of intermediate points every time step. Previous studies have suggested that the CTM captured many important traffic phenomena, such as queue build-up and dissipation and backward propagation of congestion waves (Munoz 2004; Sun 2004). It can also be easily used to calibrate the traffic flow parameters associated with capacity drop. The simplicity and accuracy of the CTM makes it desirable for studying the changes in traffic flow characteristics at recurrent bottlenecks.

In this study, a six-mile four-lane freeway section was developed in the CTM (see figure 3). The model was developed based on a real freeway section from the milepost 39.57 to 45.57 on the I-5 freeway in San Diego County, California, United States. The selected freeway section was divided into ten links which were labeled as L_1 to L_{10} by nine detectors labeled as N_1 to N_9. The isolated bottleneck was located at the merge section in link L_8. There were overall sixty cells in the CTM model, the length of each cell was 0.1 miles.

To realistically reproduce the actual traffic operations near the bottleneck area, the parameters in the CTM were calibrated using the real time detector data. The traffic data were collected from 17:00 to 18:00 pm on July 22, 2009. The research time was divided into 650 clock ticks, each clock tick was corresponding to time interval 5.54 seconds. With prior analysis, this period included the whole bottleneck formation process. The calibrated parameters in the CTM were given in Table 1.The free flow speed in the freeway mainline section was 100 km/h and the capacity of the mainline section was 2160 veh/h/ln. After the occurrence of capacity drop at the merge bottleneck, the discharge flow rate was 1980veh/h/ln. The magnitude of capacity drop was 8.3%. By examining the traffic flow parameters before and after the flow rate reduction, it was found that the capacity drop occurred when the upstream occupancy exceeded 17%, equal to a density of 21.6veh/km/lane, which was considered the threshold for determining capacity drop in the VSL and RM control strategies.

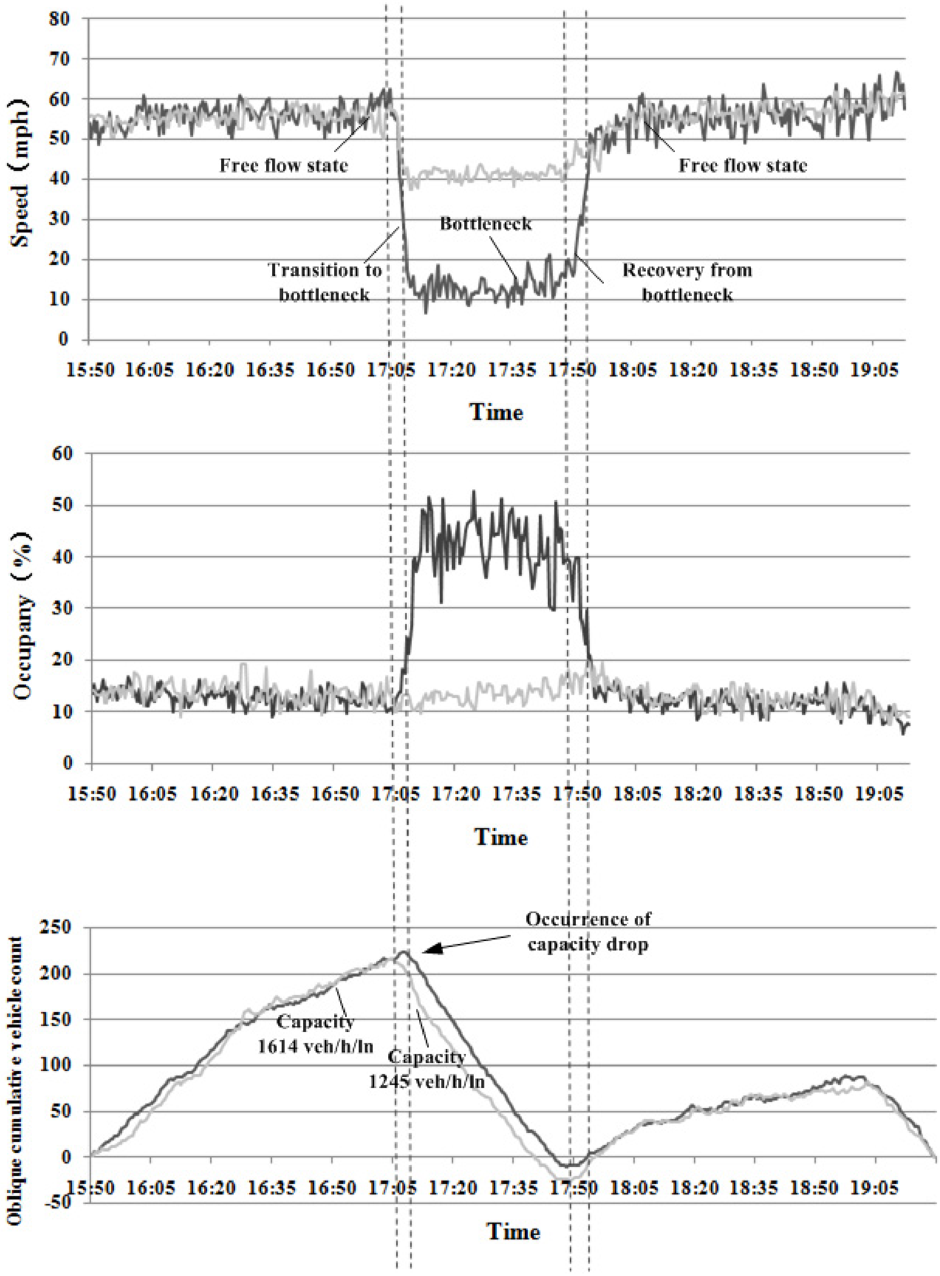

Figure 2. Variation of upstream and downstream traffic parameters at capacity drop isolated merging bottleneck

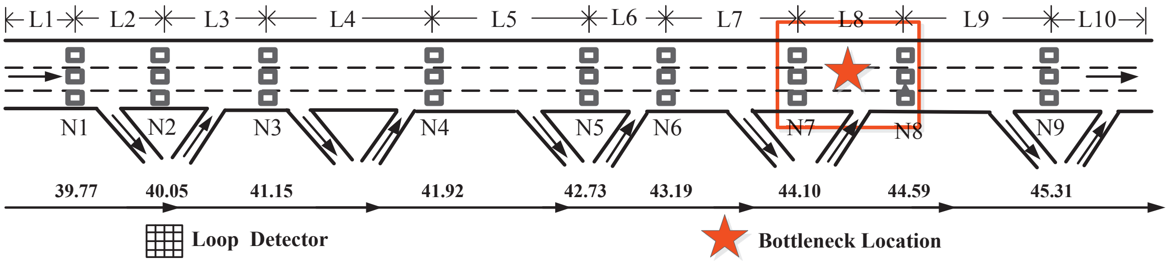

Figure 3. Study segment for simulation in the CTM

Table 1. Traffic flow parameters for model calibration

Traffic Parameter	Value
Free-flow speed(km/h)	100
Maximum flow(veh/h/ln)	2160
Critical density (veh/km/ln)	21.6
Discharge flow after capacity drop (veh/h/ln)	1980
Percentage of dropped capacity (%)	8.3%

4. Control Strategies

4.1. VSL Control Strategy

A control strategy of VSL that aimed at preventing capacity drop at freeway bottlenecks was proposed. Assuming that the real-time traffic flow at a bottleneck area is monitored, the traffic flow parameters such as density or occupancy can be used as indicators to help identifying the occurrence of capacity drop.

The VSL control strategy which aims at improving traffic operations at freeway bottlenecks is shown in Figure 4. The VSL control starts to intervene when the traffic flow parameters reach the predetermined threshold. The proposed control strategy starts from eliminating the queue that has formed at the bottleneck area. The speed limit in the VSL control section is reduced to restrict the flow rate that goes into the bottleneck. When the queue at the bottleneck fully dissipates, the speed limit in the VSL control section is adjusted to keep the traffic flow roughly the capacity of the bottleneck. The VSL intervention stops when the traffic demand decreases and the queue at the VSL-induced bottleneck fully dissipates.

Specifically, we construct a VSL control section at upstream cell C_{33}-C_{37} (in Link 6).When merge bottleneck cell C_{46} (in Link 8) occupancy achieves the critical threshold 17%, corresponding to critical density 21.6 veh/miles/lane, we start the variable speed limit so as to reduce the flow rate that goes into the bottleneck. The speed limit in this stage should be sufficiently low so that the outflow rate is lower than the discharge flow rate to ensure the queue formed at bottleneck dissipate quickly .The target speed limit value is I=30 km/h. When C_{46} occupancy is under the critical threshold, but C_{37} occupancy is higher than its corresponding critical threshold, start the target speed limit value II=70 km/h. In this stage, the speed limit in VSL is higher than that in the first stage to generate an outflow rate that is close to the bottleneck capacity to let the queue in the control section dissipate .When both the occupancies are lower than its critical thresholds. The speed limit recovers to the value prior to the speed limit control, namely the free flow speed III=100km/h. There is also an acceleration section from cell C_{38} to C_{45} (in Link 7). Its purpose is to let vehicles from the VSL control section accelerate to free flow speed sufficiently. In addition ,considering the safety and degree of driver acceptances, we set the change of every cell speed limit and adjacent cell speed limit value in every 10 mph for every time step.

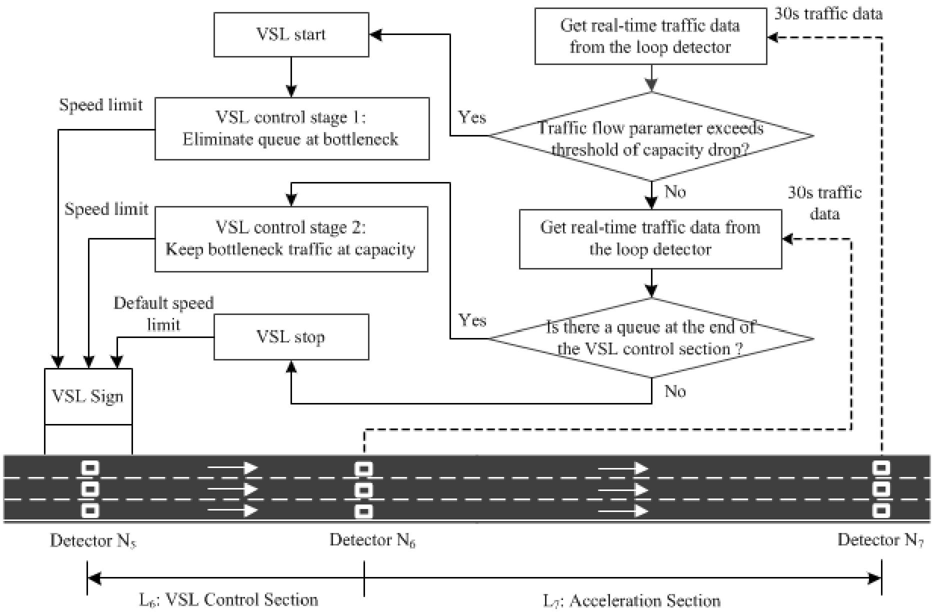

Figure 4. Control strategy of VSL for improving traffic operations

4.2.RM Control Strategy

Our RM strategy is based on real-time upstream occupancy to adjust and control traffic flow from the on-ramp metering to the mainline. By controlling the upstream occupancy under the critical threshold, the vehicle could pass through the bottleneck with capacity so that to improve the efficiency.

Identically , C_{46} is the bottleneck cell, C_{45} and R_{45} are the cell and on-ramp cell just upstream to the bottleneck. y_{ri} represents the number of vehicles that can flow from the on-ramp cell *i*. $C_{\text{i}}.Sending$ and $R_{\text{i}}.Sending$ represent the capacity flow into cell *i+1* from cell *i* and on-ramp cell *i*. $C_{\text{i}}.Receiving$ represents the amount of empty space in cell *i*.

(1) When the ramp queue reaches its geometric capacity, whatever the mainline condition is, in order to avoid the negative effect of ramp overflow to the adjacent lanes, we release ramp traffic in accordance with the peak flow. $y_{r45}=R_{45}.Sending$;

(2) When the ramp vehicle number is under its capacity, the upstream occupancy exceeds the critical threshold, to avoid the capacity drop caused by the increasing occupancy, we maintain the bottleneck flow near the capacity. $y_{r45}=0$;

(3) Besides the two special circumstances above. When ramp have capacity surplus and the bottleneck occupancy do not reach the critical threshold, If the merge area downstream cells are capable of receiving traffic flow greater than the sum of upstream on-ramp and mainline cells receiving, the ramp could release according to its peak flow, $y_{r45}=R_{45}.Sending$;

(4) If only the upstream cell sending flow is greater than downstream receiving flow, namely $C_{45}.Sending>C_{46}.Receiving$, it is unavoidable of the mainline accumulation. To avoid the capacity drop, The passage must be completely given to the mainline cell, the accumulated vehicles transfer to the ramp, $y_{r45}=0$;

(5) When above conditions are not established, $C_{45}.Sending<C_{46}.Receiving$ and $C_{45}.Sending+R_{45}.Sending>C_{46}.Receiving$. We set priority to release mainline flow and control on-ramp flow rate to make the sum number at the bottleneck area near its capacity. $y_{r45}=Min\{ R_{45}.Sending , C_{46}.Receiving - C_{45}.Sending \}$;

Previous studies have developed numerous VSL control strategies which focus on improving the traffic operations at freeway bottlenecks. However, most of the control strategies contain parameters that need to be calculated using on-line optimization algorithms. These parameters are hard to calibrate using real-world data. The parameters in the proposed control strategies are all traffic flow variables that can be easily obtained from loop detectors. The proposed control strategy does not require large on-line optimization workloads and can be easily used in practical engineering applications.

5. Evaluation of the Proposed Control Strategies

The simulation results (see Figure 5 to Figure 7) for the freeway section with no control strategy, VSL strategy and RM strategy were compared in this section. First, with occupancy space-time diagram, we observed the difference in the process of the congestion formation, propagation and dissipation. Then, we compared the variation of traffic characteristics under different strategies. At last, with three evaluating indexes, which were total outflow, total travel time and total delay, we analyzed the effects of local RM and VSL in improving traffic efficiency.

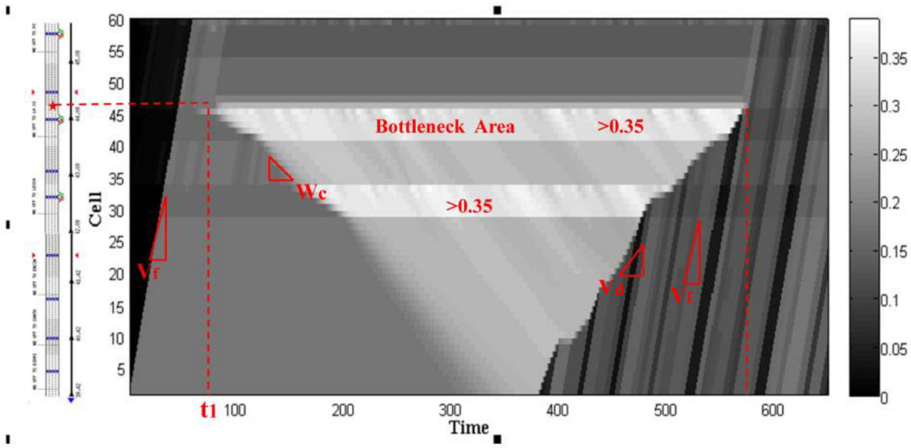

Figure 5. Occupancy Space-time diagram with no control strategy

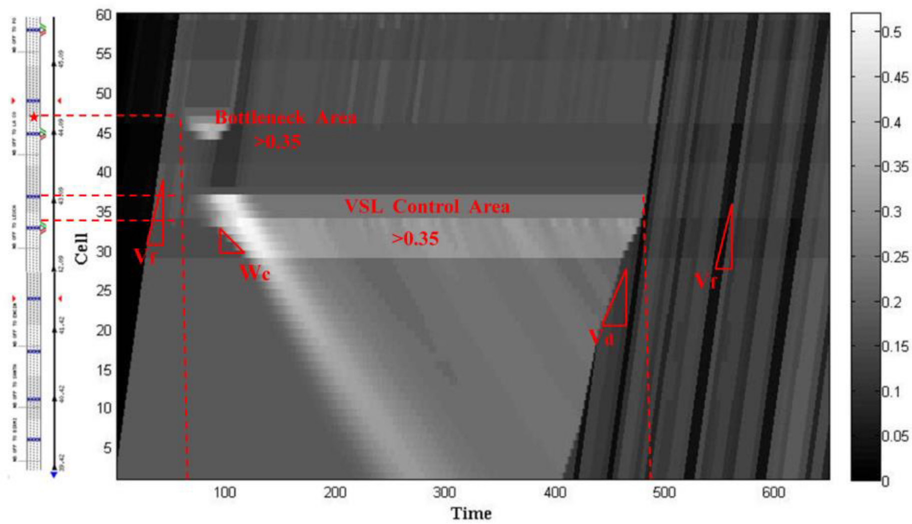

Figure 6. Occupancy Space-time diagram with VSL control

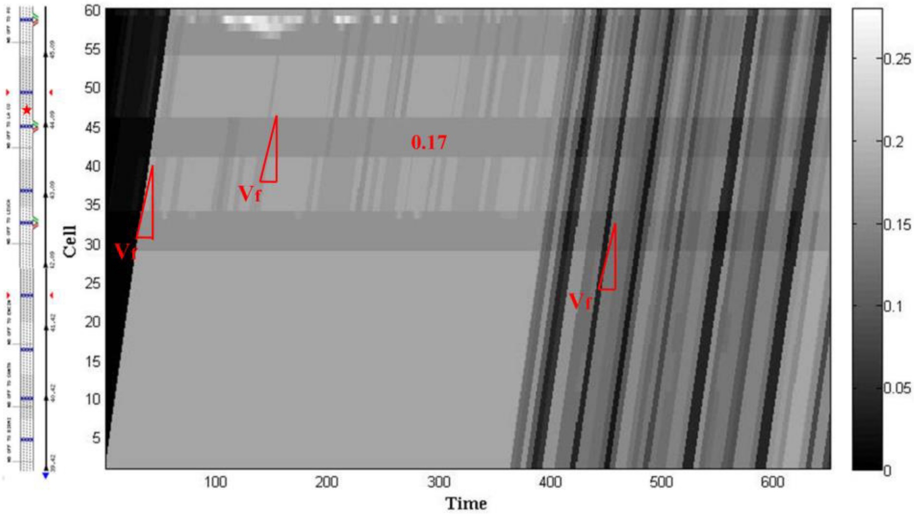

Figure 7. Occupancy Space-time diagram with RM control

We use occupancy as an indicator to represent the traffic state. When occupancy exceeds the critical threshold 17%, it means the traffic is in congestion. When occupancy is below the critical threshold 17%,it means the traffic is in free flow condition. According to the diagram, with no control strategy, a queue starts to form first at the bottleneck at t_1=81th time step and propagated towards upstream at speed *Wc* causing another entrance ramp area form congestion. Complicated traffic flow merging and diverging makes the two positions the most serious congested. After t_3=370th time step, freeway traffic demand drops to a lower level and congestion starts to dissipate. Congestion fully dissipates at t_4=570th time step. With VSL control, when queue starts to form at t_1=81th step, the upstream VSL control start immediately to make the queue in the bottleneck dissipate soon by reducing the flow rate into the bottleneck through lower posted speed limits. However, a new bottleneck is created in the VSL control section with the reduced outflow. In order to control the vehicle to bottleneck, variable speed control area has accumulated more vehicles, so even if the mainline demand at the 370th time step was down to below capacity, the VSL control congestion do not dissipate until t_3=405th time step. Congestion fully dissipates at t_4=480th step. Although the VSL control increases vehicle delay in the upstream area, the total traffic delay is reduced (it is proved in the next section). Different from no control and VSL control, ramp metering control can quickly respond to the bottleneck. So capacity drop do not happen at the bottleneck area. Occupancy stabilizes nearby 17%.

5.1.Traffic Characteristics

This section shows traffic characteristics under different control strategies at bottleneck during the simulation time. Figure 8 to Figure 12 represent the change of upstream occupancy, mainline discharge flow rate ,re-scaled cumulative flow and upstream speed and on-ramp total number of vehicles.

With no control strategy, bottleneck upstream occupancy exceeded 27% at the 81th time step. At the same time, downstream dissipation rate dropped from 11.34 to 9.92 veh/5.54s, upstream speed was from 65 to 40 mph. The slope of bottleneck downstream accumulative vehicle number curve also changed at this time. This series of changes meant the happening of capacity drop. Until the 570th time step, occupancy began to decline, and the speed, the dissipation rate gradually increased, the capacity began to recover. While under VSL control, the difference is that VSL began to work after capacity drop happened at 81th time step. From the 119th time step, the series of traffic characteristic value and capacity began to recover. At 135th time step, the bottleneck had fully recovered to free flow state. It was worthy to mention that, after the 119th time step, there was a time when the dissipate flow rate is untraditionally low, it was not due to the capacity drop, it was because VSL decreased flow rate reaching the bottleneck. While under RM control, the occupancy stabilized nearby 17%, upstream speed stabilized at the free flow speed of 65 mph. Bottleneck dissipate rate and capacity did not occur remarkable change. Bottleneck region downstream of the accumulative total dissipation vehicle number and dissipation rate also did not happen capacity declined landmark change. This suggested that ramp metering control makes the bottleneck area to release at capacity, effectively eliminate the occurrence of the capacity drop. Different from the first two kinds of control mode, vehicle numbers of on-ramp traffic had an obvious increase with the implement of ramp metering control .But even in the worst case, ramp flow rate was 14 veh/5.54 s, still far less than its geometric capacity 80 veh/5.54 s.

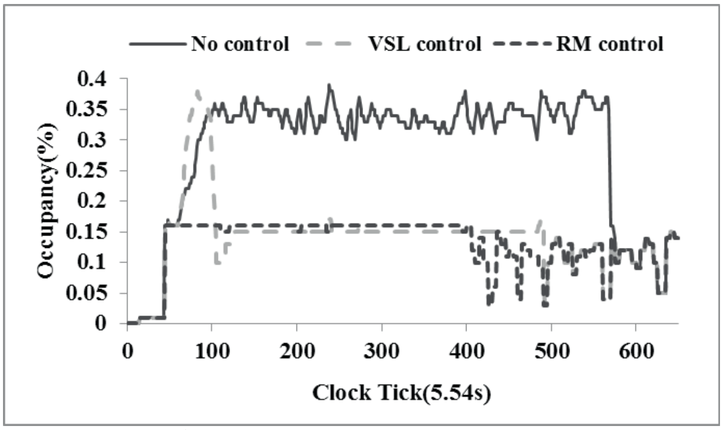

Figure 8. bottleneck upstream occupancy

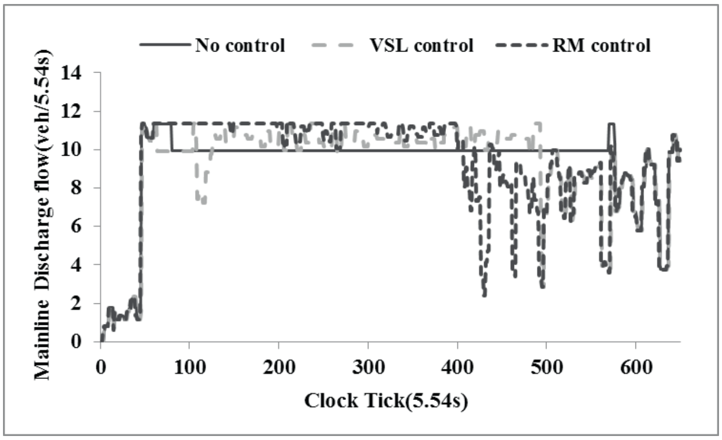

Figure 9. mainline discharge flow rate

5.2. Operational Effects of Proposed Control Strategies

With three traffic efficiency evaluating indicators, the simulation results under different control strategies were shown in Table 2. The effects of VSL and RM compared with no control were summarized in Table 3. Both the VSL and RM control have a positive effect on the traffic efficiency. In our simulation section, RM performs better than VSL in improving traffic efficiency. This is mainly because the real on-ramp traffic demand data used in simulation is low, when controlling the on-ramp flow, no ramp vehicle overflow to neighboring lane. At the same time, it ensures the upstream mainline with a higher flow rate. When off-ramp percentage is constant, there will be a higher outflow. This is also because that in VSL control, considering the safety and degree of driver acceptances, we set the change of every link speed limit and adjacent link speed limit value in every 10 mph for every time step. These additional requirements reduce the effectiveness of variable speed limit in some extent.

Therefore, for isolated merging bottleneck with few on-ramp traffic demands, the single ramp metering control is more effective in improving the efficiency than the variable speed limit. When on-ramp flow is in great demand, single point ramp metering control could not meet the requirements, this time a combination of two control might achieve a better effect.

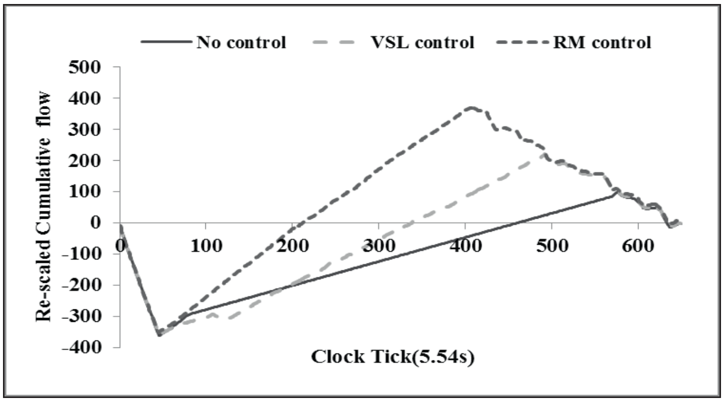

Figure 10. re-scaled cumulative flow rate

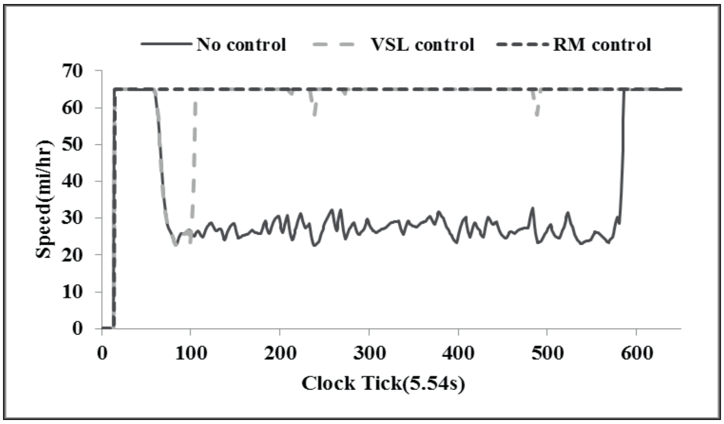

Figure 11. bottleneck upstream speed

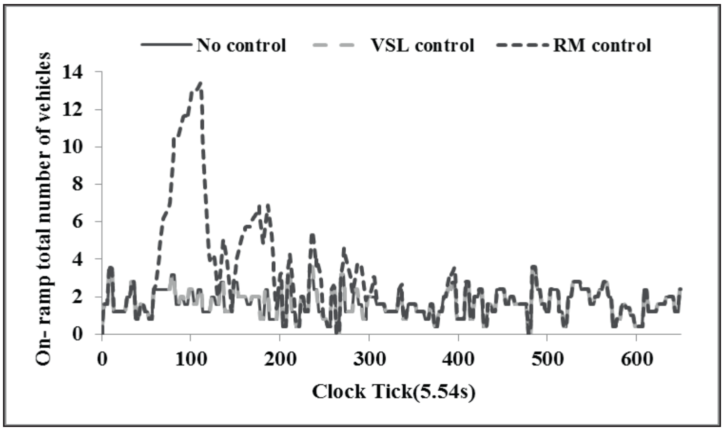

Figure 12. bottleneck on-ramp total number of vehicles.

Table 2. Simulation results under different control strategies

Measurement		No control	VSL control	RM control
Total Outflow(vehicle)	Mainline	3612.50	3772.68	4010.54
	Offramp	903.48	928.66	979.27
	Sum	4515.98	4701.34	4989.81
Total Travel Time(h)	Mainline	48.72	44.03	35.75
	Onramp	11.11	11.11	11.11
	Sum	59.83	55.14	46.86
Total Delay(vehicle*h)	Mainline	108.63	81.88	3.05
	Onramp	3	3	4.16
	Sum	111.63	84.88	7.66

Table 3. Effects of VSL and RM control in Comparison with no control

Measurement	VSL control	RM control
Increasing Total Outflow	4.1%	10.49%
Reducing Total Travel Time	7.84%	21.68%
Reducing Total Delay	23.96%	93.13%

6. Discussion and Recommendation

In this study, we proposed VSL and RM control strategies to improve the traffic operations at freeway isolated merge bottlenecks. The proposed control strategies specifically focused on preventing capacity drop at the bottleneck area. A CTM was developed to evaluate the effects of the proposed control strategies on traffic operations. The CTM was adjusted and calibrated using real-world traffic data to accurately capture the capacity drop phenomenon. With space-time diagrams and traffic characteristic diagrams, the occurrence mechanism of traffic congestion at the bottleneck under different control strategies was compared. The simulation results showed that total travel time and vehicle delay were reduced under the proposed control strategies. It was found that the VSL control and RM control were effective in improving traffic operations at freeway isolated merge bottlenecks. In addition, the RM control outperformed the VSL control in reducing traffic congestion when the on-ramp flow rate was low.

As compared to the control strategies proposed in previous studies which require large on-line optimization workloads, the control strategies proposed in this study is easier to be used in practical engineering applications. Following the present study, additional research efforts are needed to evaluate the effects of the proposed control strategies under different traffic conditions. In addition, drivers in the real world may not completely comply with the speed limits posted on VSL signs. The effects of drivers' compliance with the posted speed limit should be considered when evaluating the effects of VSL control strategy. The authors recommend that future studies may focus on this issue.

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