16th Road Safety on Four Continents Conference
Beijing, China 15-17 May 2013

USING VARIABLE SPEED LIMITS TO REDUCE REAR-END COLLISION RISKS NEAR RECURRENT BOTTLENECKS

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ABSTRACT

Rear-end collisions would occur if vehicle speeds decrease abruptly when encountering kinematic waves (KWs) emanating from active bottlenecks. This study aims to develop a control strategy in variable speed limits (VSL) to reduce rear-end collision risks near recurrent bottlenecks. Using the crash prediction model developed for rear-end collisions related to risky KWs, the effectiveness of VSL control strategies were evaluated in the cell transmission model (CTM). Several strategies were tested in sequence to determine the best case for risk reduction. Results of this study show that the collision risk can be effectively reduced if the speed limit is lowered in an opportune occasion. The VSL needs to response quickly to the fast changing traffic condition while should simultaneously avoid the potential disturbance to the traffic. According to the simulation results, the following recommendations are made when implementing the VSL to improve safety situation near recurrent bottlenecks: moderate threshold of collision likelihood to active VSL, moderate design speed limit in VSL, fast speed change over time, and small speed difference between consecutive VSLs.

1 INTRODUCTION

Traffic congestion forms repeatedly at the bottleneck area on freeways when traffic demand exceeds capacity. Kinematic waves emanating from an active bottleneck force approaching vehicles to change their traveling speeds frequently and abruptly. Previous studies have demonstrated that the risks of collisions near freeway bottlenecks were highly correlated with the kinematic waves (Yao et al., 2010; Zheng et al., 2010; Chung et al., 2010; Li et al., 2012; Xu et al., 2012; Li et al., 2013).

In recent years, variable speed limit (VSL) control has been increasingly used as an innovative approach to improving traffic safety on freeway mainlines. The VSL control uses variable speed limit signs to dynamically post speed limits according to some control strategies. The central ideal of the VSL control is to make an intervention proactively by adjusting speed limits to help reduce crash risks. Previous studies have reported that the VSL control significantly increased the safety on freeway mainlines, and the reduction in the frequency of crashes varied from 10% to 30% (Abdel-Aty et al., 2004; 2006 a, 2006 b; Abdel-Aty and Dhindsa, 2007; Abdel-Aty et al., 2008; Lee et al., 2004; Lee et al., 2006; Allaby et al., 2007; Park and Yadlapatim, 2003).

The effect of the VSL control on safety is heavily affected by the control strategy. The VSL strategy mainly focuses on addressing the following two questions: (1) when should the VSL control be initiated; and (2) how to adjust the speed limits given traffic and environmental characteristics to reduce the risks of crashes. In some early studies, the VSL control was started by traffic or environmental parameters such as density, vehicle speed, road and weather conditions (Smulders, 1987, Rämä, 2002, Park and Yadlapatim, 2003). Recently, crash risk prediction models developed using real-time loop detector data were used to predict collision risks to assist the development of VSL strategies (Lee et al., 2003; Abdel-Aty et al., 2004; Abdel-Aty et al., 2005; Pande and Abdel-Aty, 2006; Allaby et al., 2007). Microscopic simulation models such as PARAMICS and VISSIM were used to simulate the traffic flow affected by different VSL control strategies. The optimum control strategy was usually selected by considering both the reduction in crash potential and the total travel time.

The results of literature review showed that existing studies had not focused specifically on the control strategies of VSL at freeway recurrent bottlenecks. As mentioned before, the traffic flow characteristics and the mechanism of crash occurrences near recurrent bottlenecks have unique characteristics that are different from those at other freeway sections. The crash risk models and the control strategies developed in previous studies may not be directly used to recurrent bottlenecks where the rear-end collisions caused by kinematic waves constitute the major concern.

The primary objective of this study was to develop control strategies of VSL which specifically focus on reducing the rear-end collisions at recurrent bottlenecks on freeways. A crash risk prediction model which was specifically developed for freeway bottlenecks was used to assess the risks of rear-end collisions given real-time loop detector data. Note that the focus of this study was on rear-end collisions which accounted for more than 75% of total crashes in our dataset. It was assumed by the authors that the rear-end collisions on freeways were most likely to be affected by the VSL control.

2 THE RISKS OF REAR-END COLLISIONS

The surrogate safety measure developed by Li et al. (2012) was used in this study to assess the risks of rear-end crashes in the simulated freeway segment. Assuming that a leading vehicle abruptly reduces its speed when encountering a kinematic wave on a freeway section, a rear-end collision will occur if the following vehicle fails to adjust its speed in a timely way.

A rear-end collision risk index (RCRI) was proposed as a surrogate safety measure of the risks of rear-end collisions. The RCRI is given as (c.f. Li et al., 2012):

$$\mathrm{RCRI} = \frac{(\bar{v}_u(t-\Delta t,t) - \bar{v}_d(t-\Delta t,t)) \cdot \bar{o}_u(t-\Delta t,t)}{1 - \bar{o}_u(t-\Delta t,t)} \tag{1}$$

where $\bar{v}_u(t\text{-}\Delta t, t)$ is the average speed (mph) at the upstream station in the period $[t\text{-}\Delta t, t]$, $\bar{v}_d(t\text{-}\Delta t, t)$ is the average speed (mph) at the downstream station, $\bar{o}_u(t\text{-}\Delta t, t)$ is the average occupancy (%) at the upstream station, and Δt is the time interval for aggregating traffic flow parameters (Δt = 5 min).

A case-control study design was used to identify the factors that affected the risks of rear-end collisions. The traffic before the occurrences of rear-end collisions at freeway bottlenecks were selected as "cases", while the paired traffic data during crash free conditions were used as "controls". With the case-control data, a conditional logistic regression model was developed for predicting the rear-end collision likelihood. The model is given as:

$$P(Y=1) = \frac{\exp(-3.095 + 0.191 \cdot \mathrm{RCRI} + 0.178 \cdot \sigma(O_u) + 0.172 \cdot \sigma(O_u))}{1 + \exp(-3.095 + 0.191 \cdot \mathrm{RCRI} + 0.178 \cdot \sigma(O_u) + 0.172 \cdot \sigma(O_u))} \tag{2}$$

where $\sigma(o_u)$ and $\sigma(o_d)$ are the standard deviation of the occupancy at the upstream and downstream loop detector stations. It was found that the RCRI and the standard deviation of the occupancy at the upstream and downstream loop detector stations significantly affected the risks of rear-end collisions at freeway bottlenecks.

3 THE SIMULATION MODEL

The CTM was used for the simulation of the traffic flow at freeway bottlenecks affected by the VSL control. The CTM is a macroscopic traffic simulation model proposed by Daganzo (1994). The simplicity and accuracy of the CTM makes it very desirable for studying the changes in traffic flow characteristics at recurrent bottlenecks as an effect of the VSL control.

The fundamental diagram of the traffic flow in each cell can be approximated by a triangular shape, as shown in Figure 1 (a). The slopes of the two sides and the apex of the triangle were parameters in the CTM that need to be calibrated. To simulate the traffic flow affected by the VSL control, modifications need to be made to the fundamental diagram.

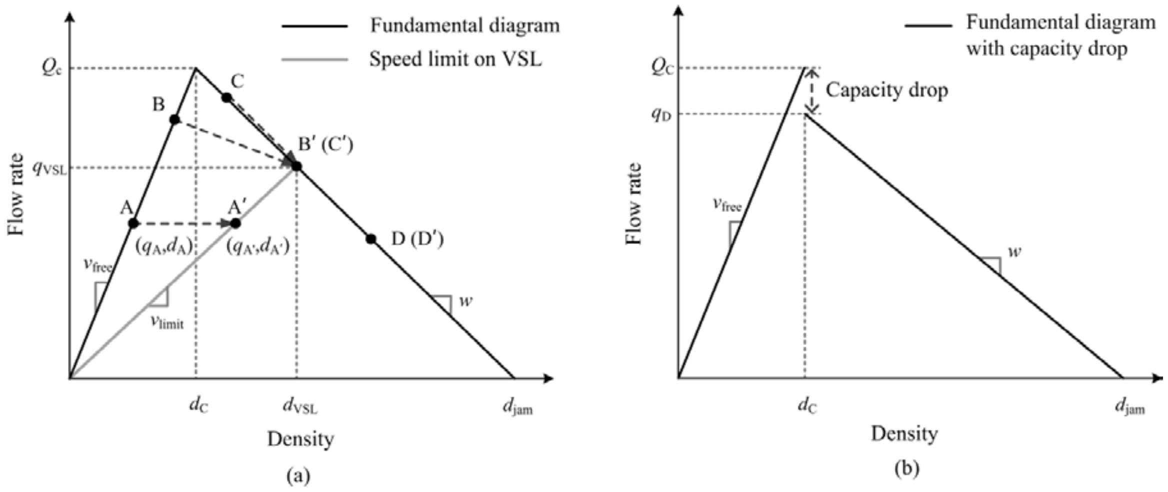

Figure 1: (a) Fundamental diagram in the CTM; (b) Fundamental diagram with capacity drop

Assuming that a cell i is characterized by its triangular shaped fundamental diagram, as shown in Figure 1 (a), the left limb of the triangle represents the sending function and the right limb represents the receiving function. The sending function represents the vehicles that can supply to the downstream cell i+1 with a flow rate of $\sigma_i(k)$, where k is the time step. The receiving function represents the available space in cell i which determines how many vehicles can enter cell i from the upstream cell i-1 with a flow rate of $\delta_i(k)$.

The sending and the receiving functions for a cell i affected by the VSL control can be determined by:

$$\sigma_i(k)=\min\{\min\{v_{\text{free}},v_{\text{limit}}(k)\}\cdot d_i(k)\cdot n_i,\ Q_{\text{VSL}}\} \quad (3)$$

$$\delta_i(k)=\min\{w_i\cdot(d_{i,\text{jam}}-d_i(k))\cdot n_i,\ Q_{\text{VSL}}\} \quad (4)$$

where $\sigma_i(k)$ is the sending flow rate (veh/h) at time k, $\delta_i(k)$ is the receiving flow rate (veh/h), v_{free} is the free-flow speed (mph), $v_{\text{limit}}(k)$ is the speed limit (mph) posted on the variable speed limit sign at time k, $d_i(k)$ is the density (veh/mile/ln), n_i is the number of lanes, Q_{VSL} is the maximum flow rate (veh/h) under current speed limit, w_i is the speed of the kinematic wave (mph), and $d_{i,\text{jam}}$ is the jam density (veh/mile/ln).

To simulate the capacity drop phenomenon at the bottleneck, we assumed that the bottleneck cell i was characterized by an inverse λ-shaped fundamental diagram, as shown in Figure 1 (b). The sending and the receiving functions for cell i with capacity drop being considered can be determined by:

$$\sigma_i(k)=v_{\text{free}}\cdot d_i(k)\cdot n_i \qquad \text{If } d_i(k)\le d_C \quad (5)$$

$$\sigma_i(k)=q_D \qquad \text{If } d_i(k)>d_C \quad (6)$$

$$\delta_i(k)=w_i\cdot(d_{i,\text{jam}}-d_i(k))\cdot n_i \qquad \text{If } d_i(k)\le d_C \quad (7)$$

$$\delta_i(k)=Q_C \qquad \text{If } d_i(k)>d_C \quad (8)$$

where Q_C is the capacity (veh/h) q_D is the maximum discharge flow rate (veh/h) after capacity drop, and d_C is the critical density. The flow rate in a cell i can be determined by the sending and the receiving functions, as it was given as follows:

$$q_i(k)=\min\{\sigma_{i-1}(k),\ \delta_i(k)\} \quad (9)$$

The density evolution in cell i can be determined by the following equation:

$$d_i(k+1)=d_i(k)+\Delta T/(L_i \cdot n_i)\cdot(q_{i-1}(k)-q_i(k)) \quad (10)$$

where ΔT is the length of the time step during simulation which equals the time with which a vehicle passes a link at free-flow speed, and L_i is the length (mile) of link i. The speed within each cell i can be determined according to the current density and speed limit with the following equation:

$$v_i(k)=\begin{cases}\min\{v_{\text{free}}, v_{\text{limit}}(k-1)\} & \text{if } d_i(k)\le d_{\text{VSL}} \\ (d_{i,jam}(k)-d_i(k))\cdot w_i / d_i(k) & \text{if } d_i(k) > d_{\text{VSL}}\end{cases} \quad (11)$$

where d_{VSL} is the density (veh/mile/ln) associated with the maximum flow rate Q_{VSL}.

As shown in Figure 1 (a), traffic state changes in accordance with the speed limit posted on the variable speed limit sign in the link. Assuming that traffic is in a free flow state A, if the flow rate q_A is smaller than the maximum flow rate Q_{VSL} with the speed limit v_{limit}, the state A will transfer to state A' with a higher density ($d_A<d_{A'}$). If the flow rate in the current state is larger than Q_{VSL}, such as the state B or C in Figure 1 (a), the traffic state will transfer to state B' or C' with a lower flow rate and a higher density with the impacts of the VSL control. For the heavily congested state D in which the flow rate is smaller than Q_{VSL}, the speed limits posted on variable speed limit signs will not change the traffic state (D=D').

4 SIMULATION NETWORK

As shown in Figure 2, a six-mile four-lane freeway section was developed in the CTM. The section was divided into eleven links which were labeled as L_1 to L_{11}. Each link was 0.5 miles long which contained five cells (0.1 miles for each cell). The section contained 12 loop detectors which were labeled as N_1 to N_{12}. Ten variable speed limit signs were implemented with ten loop detector stations located upstream of the bottleneck. The isolated bottleneck was located at the merge section in link L_{10}.

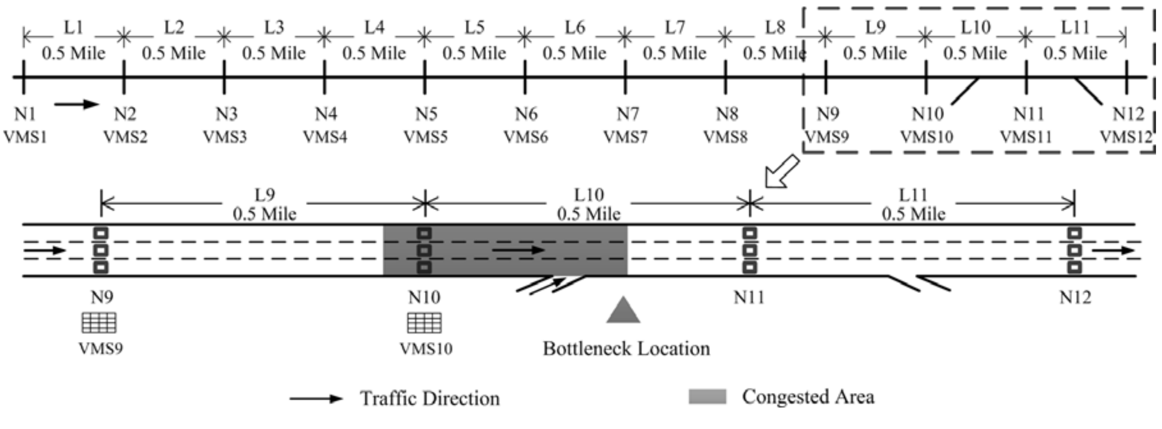

Figure 2: Study segment for simulation in CTM

To realistically reproduce the actual traffic features near the bottleneck area, the parameters in the CTM was calibrated using traffic data collected from a recurrent bottleneck on the northbound stretch of the I-880 highway in California. The capacity of the freeway mainline before capacity drop (Q_C) was found to be 2340 veh/h/ln and the maximum discharge flow rate after capacity drop (q_D) was 2040 veh/h/ln. The magnitude of capacity drop was found to be 12.8%. The free flow speed is 65 mph. By examining the travel time of kinematic waves between two consecutive loop detectors, the speed of the kinematic wave was estimated to be 12 mph.

5 EVALUATION OF VSL STRATEGIES

5.1 Procedure for determining VSL strategy

The decision logic considered in this study was to gradually reduce the speed limits posted on upstream variable speed limit signs until a target speed limit was achieved, when the crash potential at the influence area of a freeway bottleneck exceeded a pre-specified threshold. The speed limits would be recovered after the crash potential dropped below the threshold. The following control factors were considered for determining the optimum control strategy: (1) the threshold of collision likelihood; (2) the target speed limit; (3) the rate at which the speed limit was changed; and (4) the coordination between variable speed limit signs. The procedure for determining the optimum VSL strategy is shown in Figure 3.

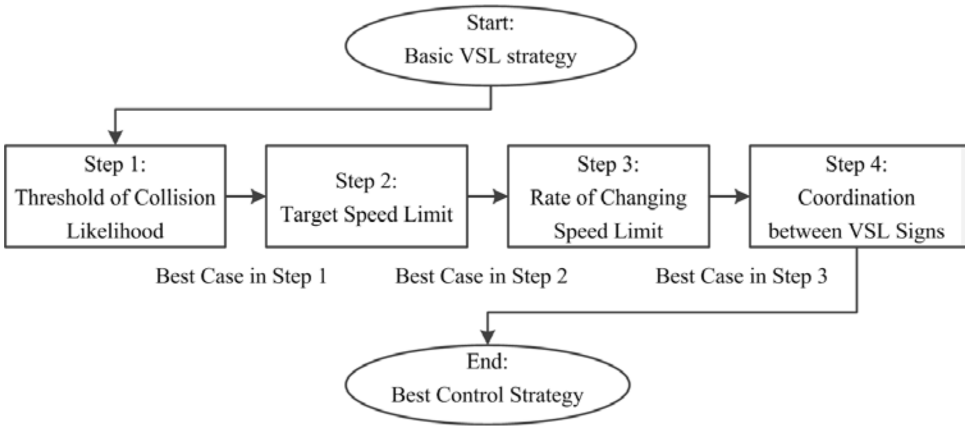

Figure 3: Algorithm for determining best control strategy

The procedure started from testing a basic VSL in which the speed limit posted on variable speed limit signs was determined by reducing the free-flow speed by 15 mph. The VSL control would start when the collision likelihood in the link reached 50% of the maximum collision likelihood. The speed limit in each link would change abruptly over time, and the coordination between variable speed limit signs was not considered. The evaluation was then moved forward step by step to find out the optimum control factors. In each step, several options for a control factor were evaluated; and the control factor which reduced the collision likelihood without significantly increasing the travel time was considered the optimum. The optimum control factor was then used in the following steps to determine other control factors. The best control strategy was determined when all the control factors were optimized

A 1.5-h simulation with a 10-min warm-up period was conducted to evaluate the safety effects of the VSL control. The mainline and the on-ramp flow rates were specified to produce traffic congestion at the bottleneck during peak periods. Congestion propagated towards upstream and dissipated when traffic demand decreased.

5.2 Simulation results for the basic VSL strategy

The simulation results for the basic control strategy showed a similar pattern for different links regarding the safety impacts, as it was illustrated in Figure 4. The curves showed that using the basic control strategy the VSL control did not always reduce the likelihood of rear-end collisions. It was found that by abruptly changing the speed limits the disturbance in the traffic flow and the speed differences between adjacent links were increased temporarily, which increased the collision likelihood before and after the arrival of the kinematic wave.

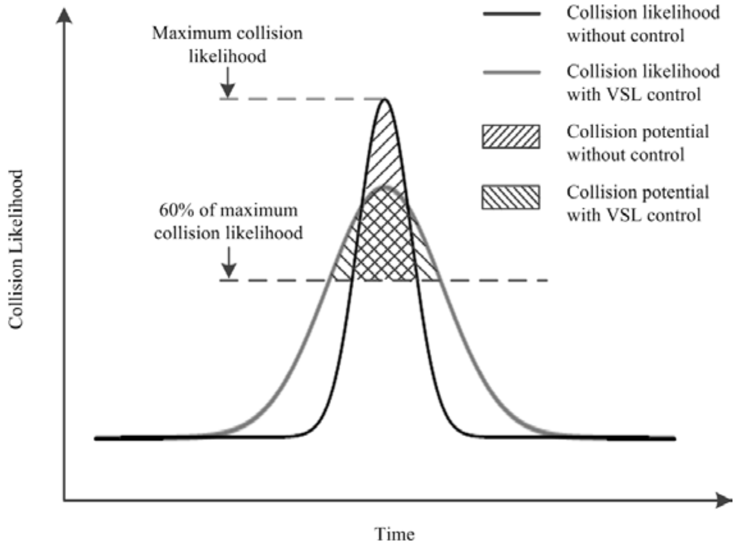

Figure 4: Impacts of VSL on Collision Likelihoods

The simulation results for the basic control strategy also suggested that the average collision likelihood was not an appropriate measure for evaluating the safety effects of the VSL control. Instead, we were actually more interested in the reduction in the collision likelihood which was greater than a specific level. The assumption was that the collision likelihood below a certain level was not a good indicator for crash potential, and accordingly, should not be considered in evaluating the safety impacts of VSL control. For example, if we only consider the collision likelihood that is greater than the 60% of the maximum collision likelihood, the safety impacts of the VSL control on crash potential should be evaluated by the difference in the areas bounded by the two collision likelihood curves (with and without VSL control) and the line which represented the 60% of the maximum collision likelihood, as shown in Figure 4. The safety measure can be estimated as:

$$P(L) = \begin{cases} \sum_{t=1}^{T} (L(t) - L) \cdot \Delta t & \text{if } L(t) > L \\ 0 & \text{if } L(t) \leq L \end{cases} \tag{12}$$

$$\Delta P_L = \frac{P_{\text{VSL}}(L) - P_{\text{No-VSL}}(L)}{P_{\text{No-VSL}}(L)} \times 100 \tag{13}$$

where $P(L)$ is the crash potential, $L(t)$ is the collision likelihood at time t which can be estimated using Eq. (2) given simulated traffic flow data, L is the minimum collision likelihood for consideration which equals a certain percentage of the maximum collision likelihood, T is the duration of the simulation period, Δt is the duration of the time step, ΔP_L is the percentage of the reduction in crash potential due to the VSL control, P_{VSL} is the crash potential with the VSL control, $P_{\mathrm{No\text{-}VSL}}$ is the crash potential without the VSL control.

The average reduction in crash potential across different links during the simulation period was used in this study to evaluate the safety performance of different VSL strategies. Considering the fact that the selection of the minimum collision likelihood for consideration was quite subjective, two collision likelihood which represented the 60% and the 30% of the maximum collision likelihood were considered in this study for the evaluation of VSL strategy. The safety measures using these two minimum collision likelihood levels were denoted as $\Delta P_{30\%}$ and $\Delta P_{60\%}$ for the rest part of the paper. Using the basic control strategy, the average collision potential was reduced by 7.28% ($\Delta P_{30\%}$) to 14.11% ($\Delta P_{60\%}$).

5.3 Determination of critical control factors

5.3.1. Threshold of collision likelihood

The threshold of collision likelihood determines when the VSL control should be initiated or terminated. Results of preliminary simulation tests showed that the safety effects of the VSL control did not change significantly when the threshold of collision likelihood was above 35% or below 15% of the maximum collision likelihood. Three levels of the thresholds of collision likelihood were further evaluated in greater details, including the threshold level 1 to 3 (35%, 25% and 15% of the maximum collision likelihood). The speed contours for the traffic flow with and without the VSL control for three start-up thresholds were compared in Figure 5.

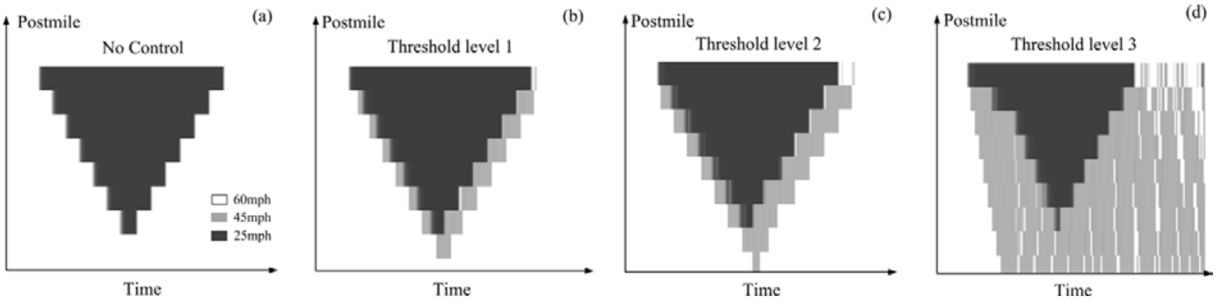

Figure 5: Speed contours with and without the VSL control for different start-up thresholds

The simulation results showed that using the threshold level 1 the VSL control provided the least reduction in the potential of rear-end collisions. In this condition the VSL control did not have sufficient time to respond to the kinematic waves. It was also found that using the threshold level 3 the VSL control resulted in the largest reduction in collision potential. However, the speed counter in Figure 5 (d) showed that traffic in this condition became quite unstable because of the frequent intervention of the VSL control, which introduced disturbances to the traffic.

The moderate threshold level (level 2) which equaled the 25% of the maximum collision likelihood was found to be the optimum start-up threshold. Using the moderate start-up threshold the VSL control reduced the average crash potential by 12.46% to 29.62%. It was also found that the VSL control did not introduce large disturbances to the traffic flow and the increase in the total travel time was small (0.54%).

5.3.2. Target speed limit

The simulation results showed that the speed in congested traffic was approximately 25 mph. The safety effects of four speed reduction strategies were then, including reducing the free-flow speed by 15 to 30 mph. The safety effects of the VSL control with different levels of speed reduction were shown in Figure 6.

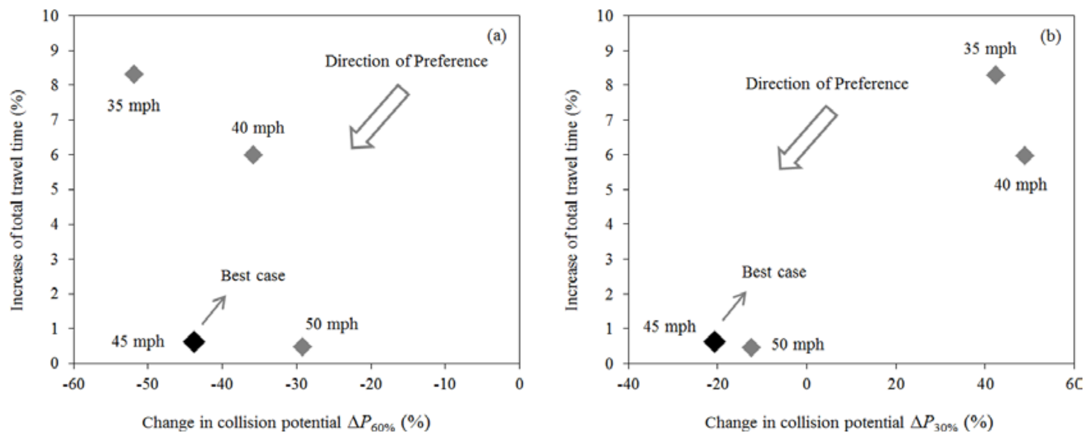

Figure 6: Results with and without the VSL control for different target speed limit

By making a small reduction in the free-flow speed the VSL control was not so effective in reducing collision potential because the VSL control failed to reduce vehicle speeds to a safe value before they reached the kinematic waves. Using a large speed reduction strategies the VSL control was effective in reducing crash potential. But the simulation results also showed that using the large speed reduction strategy the VSL control introduced large disturbances to the traffic and increased the speed differences between adjacent links. The total travel time was increased by 8.32% when the largest speed reduction strategy was used. Thus, the moderate speed reduction strategy, i.e., to reduce the free-flow speed by 20 mph was selected. The target speed limit was set to 45 mph. In this condition, the crash potential was reduced by 20.66% to 43.81%, and the increase in total travel time was small (0.62%).

5.3.3. Rate at which the speed limit was changed

To avoid the disturbances introduced into the traffic flow, the speed limits should be gradually reduced until the target speed limit was achieved. In this study, four levels of speed change rates were tested, including the rate of changing speed limits by 10 mph per 5 min, by 10 mph per 2 min, and by 10 mph per 1 min.

It was found that if the speed limit was reduced by 10 mph per 5 min the VSL control provided the least reduction in collision potential. The optimum speed change rate was to reduce the speed limit by 10 mph per 1 min. In this condition, the VSL control produced the greatest reduction in collision potential by 26.04% to 53.83%. The findings imply that because the kinematic waves could move fast along freeways sections, the VSL control need to response quickly to the traffic condition by reducing the speed limit at a fast rate to ensure the effectiveness of VSL control on safety improvement.

5.3.4. Coordination between variable speed limit signs

The coordination between variable speed limit signs should be considered to avoid creating large speed differences between consecutive links. In this study, the speed limits in other links were determined from downstream to upstream according to the pre-specified maximum difference in speed limit between adjacent links. Three levels of speed differences between adjacent links including 5 mph, 10 mph, and 15 mph were tested.

In general, a more gradual reduction of speed limit over space has a better performance in reducing collision potential. The coordinating VSL control using the 5 mph as the maximum speed difference achieved the best safety benefits than the other cases. The result is consistent to intuition since a gradual reduction of speed limit over space could reduce the speed of vehicles smoothly. Moreover, a gradual speed reduction is more acceptable for drivers.

5.3.5. The best control strategy

The best control strategy of VSL was determined according to the optimal control factors determined in above sections. In the optimal strategy, the start-up threshold of collision likelihood is the 25% of the maximum collision likelihood, and the target speed limit in each link is 45mph. The speed limit in each link would change at a rate of 10 mph per 1 min, and the coordination of variable speed limit signs restricts the maximum difference of speed limit between adjacent links within 5 mph.

The results of VSL control strategy in each step were shown in Table 1. It can be found that the effects of VSL on reducing collision risk were improved when more critical factors were optimized. Using the best strategy of VSL, the collision potential was reduced by 70.14% and 40.35%, depends on the minimum collision likelihood for consideration. The total travel time in the case of optimal control strategy was increased slightly by 0.96% than the case without control. The best control strategy effectively reduced the collision potential without significantly increasing the total travel time.

Table 1. Simulation results of VSL control strategies in the first iteration

Scenario	$\Delta R_{60\%}$ (%)	$\Delta R_{30\%}$ (%)	ΔT (%)
Basic control strategy of VSL	14.11	7.28	-0.67
Best case in step 1	33.62	16.46	-0.64
Best case in step 2	43.81	20.66	-0.62
Best case in step 3	53.83	26.04	-0.95
Best control strategy of VSL	70.18	40.35	-0.96

The simulation results of no control and control with optimal strategy were compared in Figure 7. As shown in Figure 7 (a), without VSL control, the vehicle speed drops abruptly from free-flow speed to the speed in congestion. There are high rear-end collision potential associated with the large speed decrease as shown in Figure 7 (b). Using the optimal control strategy of VSL determined in this study, the vehicle speeds are gradually reduced by variable speed limit signs in upstream links as shown in Figure 7 (c). Consequently, due to the gradual reduction of speed limits prior to the reach of risky kinematic wave, the high rear-end collision potential were obviously reduced as shown in Figure 7 (d).

The optimal control strategy of VSL in this study was compared to those in previous studies. Consistent findings were shown in several control factors in VSL strategy such as that both our study and previous ones (Park and Yadlapatim, 2003; Allaby et al., 2007; Lee et al., 2006; Abdel-Aty et al., 2006a; Lee et al., 2008) recommended using a moderate reduction of speed limit from free-flow speed as the target speed limit posed in VSL signs. But for some other control factors, different findings were reported. For example, a fast rate at which the speed limit is changed is recommended in this study which is by 10 mph per 30 s, while in previous studies a rate of changing speed limit every 5 to 10 min commonly recommended (Lee et al., 2004; Abdel-Aty et al., 2006 a; Abdel-Aty et al., 2008). The kinematic wave propagates along freeway sections at a high speed that requires a fast rate of changing speed limit in VSL control to reduce vehicle speeds proactively. The control strategies in previous studies could be less effective in reducing collision potential. The rear-end collisions related to kinematic waves near recurrent bottleneck was not the major consideration in previous studies. This study made a contribution to propose dynamic control measures to address the safety issue near recurrent bottlenecks on freeways.

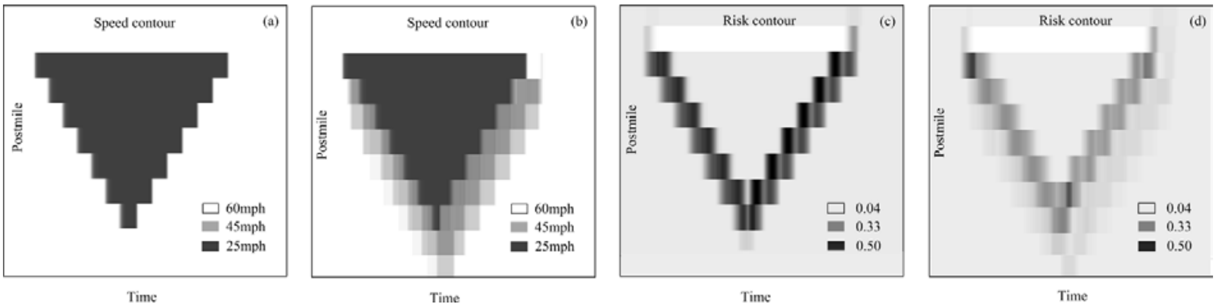

Figure 7: (a) Speed contour for the no control case; (b) Speed contour for the optimal control strategy of VSL; (c) Collision likelihood contour for the no control case; (d) Collision likelihood contour for the optimal control strategy of VSL.

6 CONCLUSION AND RECOMMENDATION

This study developed the control strategies in VSL to reduce rear-end collision risks near recurrent bottlenecks. Using the crash prediction model to predict the rear-end collisions during the propagation of KWs upstream of an active bottleneck, the effectiveness of these strategies were evaluated in the CTM integrated with VSL control algorithm. Critical factors in the VSL were tested in several steps via simulation to determine the best control strategy for preventing traffic collisions.

The results of analysis showed that the collision risk can be effectively reduced if the speed limit is lowered in an opportune occasion. The VSL needs to response quickly to the fast changing traffic condition while should simultaneously avoid the potential disturbance to the traffic. According to the simulation results, the following recommendations were made when implementing the VSL to improve safety situation near recurrent bottlenecks: moderate threshold of collision likelihood to active VSL intervention, moderate design speed limit in VSL, fast speed change over time, and small speed difference between consecutive VSLs.

Our research team also calculated the travel time during the simulation, since some previous studies have reported that the total travel time is reduced by VSL simultaneously with the increases of safety. However, the decrease of travel time was not observed in our simulations. The reason was that our VSL strategies did not eliminate the queue at bottleneck area and prevent the capacity drop phenomenon, which were the critical factors to improve traffic efficiency at bottleneck area (Carlson et al., 2010; Carlson et al., 2011). The VSL strategy that aims at improving both safety and efficiency will be developed in our next step of research. Moreover, this study did not distinguish the VSL strategies for various traffic states, i.e. free flow state, and congested state, in which the strategies were expected to be different. The authors recommended further researches would focus on these issues.

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