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Assessing Safety Benefits of Variable Speed Limits

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Assessing Safety Benefits of Variable Speed Limits

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The objective of this paper is to suggest a method of evaluating the effectiveness of variable speed limits in reducing freeway crash potential. The real-time crash prediction model that was developed in earlier studies was used to estimate crash potential for different control strategies of variable speed limits. To mimic realistic responses of drivers to changes in speed limits, a microscopic traffic simulation model was used. The simulation results indicate that total crash potential over the entire freeway segment could be significantly reduced under variable speed limit control with a minimal increase in travel time compared to the fixed speed limit. This paper illustrates the methodology of assessing safety benefits of variable speed limits and presents the findings from the experiment using a simple freeway segment.

Variable speed limits have been implemented in a number of locations to provide appropriate speed based on real-time traffic, environment and roadway conditions by means of variable message signs (1). This traffic control strategy has been implemented in real traffic condition in some European countries. Hines (2) reports, based on case studies in Europe, that variable speed limits can stabilize traffic flow in congestion and thereby decrease the probability of crashes. This report presented empirical evidences that variable speed limits can provide many benefits but more in-depth analysis needs to be done to understand the effect of speed limit changes on the safety. In this regard, some studies suggested that as speed limits change (i.e. variable speed limits), individual drivers choose speeds within a different range, they constitute the different aggregate distribution of traffic speeds, and this in turn affects crash probability and crash severity (3). More specifically, Hauer (4) suggested that vehicles with speeds much faster or slower than the median traffic speed – this results in higher speed variance of traffic stream - are likely to encounter more conflicts. Given that there exists a strong relationship between speed limit changes and crash potential, the reduction of crash potential in relation to speed limit changes needs to be quantified as it can be used as an objective measure of effectiveness in assessing safety benefits of different variable speed limit logics.

Thus, this study uses a real-time crash prediction model that was developed earlier (5,6) to identify the link between dynamic speed control and the reduction in crash potential in a quantitative manner. For this task, this study

integrates the crash prediction model into a microscopic traffic simulation model and estimates changes in crash potential as an effect of speed limit changes.

This paper is organized into six sections. The second section discusses the findings from the past studies of variable speed limits based on field experiments and simulation results. The third section describes the real-time crash prediction model and the modification that has been made since the previous study. The fourth section illustrates the traffic simulation model used in this study and the framework of evaluating safety benefits of variable speed limits. The fifth section describes the case study using a simple freeway segment and discusses the results. The sixth section summarizes the findings from the results and recommends future work.

PAST STUDIES OF VARIABLE SPEED LIMITS

There have been only a small number of studies to evaluate the performance of variable speed limits. Most of these have been conducted in Europe and Asia. For example, Van den Hoogen and Smulders (7) performed an experiment with the application of variable speed control on motorways in the Netherlands. Their variable speed control attempts to reduce the difference between the average speed of the traffic stream and the existing speed limit. From the experiment, they found that the differences in volume, speed, and occupancy between and within lanes became smaller and variations also decreased when variable speed control was implemented. Similarly, Rämä (8) investigated the effects of weather-controlled speed limits and signs on driver behavior on a 14-km-long highway in Finland. She observed that when the variable speed limits reduced mean speed and standard deviation of speed, and increased the extent of speed reduction. Ha et al. (9) also found similar results from their field experiment of automated speed enforcement (ASE). They observed that speed, speed variance, and the percentage of short-time headways were significantly reduced a few kilometers ahead of an ASE station where warning signs were posted. They concluded that smaller speed variation eventually resulted in the reduction of crash frequency and fatality based on historical crash records.

However, field evaluations are extremely time consuming, prohibitively expensive and the analyses of before-and-after field observations are hindered by the presence of confounding effects (10). The potentially confounding effects include the effects of other policies undertaken during speed limit changes (e.g. intensive speed enforcement) or the effects of other factors that may have affected the safety (e.g. changes in traffic volume) (3). To overcome the

limitation of field observations, some studies have used simulation models instead of field data. Traffic simulation models are generally classified into macroscopic models and microscopic models.

Macroscopic models consider the movements of individual vehicles as a group behavior whereas microscopic models simulate the movement of each individual vehicle independently. Macroscopic models are advantageous as the theory is clearly defined in mathematical relationships and they do not need to make assumptions as to individual driver's characteristics. The models are used to understand the general relationship between speed limit changes and traffic flow. For example, Sailer et al. (11) formulated the mathematical expression of the speed-density relationship as a function of speed limits. They proved theoretically and empirically that free-flow speeds decrease with speed limits. Their model provides the guideline of predicting the impact of variable speed limits on the distribution of traffic speeds. Alessandri et al. (12) also developed a dynamic macroscopic model to estimate traffic density in real-time and activated speed signaling (variable speed limits) based on the density estimated by the model. They found that the speed signaling can avoid congestion and improve the stability of traffic condition with constant flow and higher average speed. Breton et al. (13) developed a macroscopic traffic simulation model that takes variable speed limits into account, and found that the reduction of speed limits suppressed the upstream traveling shock wave by creating a low-density wave traveling downstream. They concluded that although variable speed limits delay traffic temporarily, they increase the flow by avoiding abrupt variation of speed, and eventually reduce the system travel time. Hegyi et al. (14) further enhanced the performance of variable speed limits, using the same model, through the coordination with ramp metering. Although some underlying assumptions in their model, e.g. 100% driver compliance with variable speed limits, were not realistic, they demonstrated potential benefits of variable speed limits in minimizing total travel time. However, these studies have not attempted to quantify the benefit of variable speed limits in terms of reducing crash potential.

In spite of superior performance of macroscopic models, they are solely based on the aggregate relationship of traffic flow characteristics. Therefore, they cannot capture the effect of traffic control strategies on the interaction among individual vehicles and the refined changes in traffic flow condition. To tackle this problem, some studies used microscopic simulation models for the analysis of variable speed limits. For example, Park and Yadlapati (15) evaluated a number of variable speed limit control logics at work zones using the VISSIM microscopic simulation model. They used the minimum safety distance equation as a surrogate measure of safety. With varying driver's

compliance rates in the simulation, they found that variable speed limits could be beneficial in improving both mobility and safety at work zones.

CRASH PREDICTION MODEL

In the proposed real-time crash prediction model, crash potential is expressed as a function of crash precursors and a number of external control factors such as road geometry and peak/off-peak periods using a log-linear regression. Crash precursors are those traffic factors that are closely related to turbulence or stability of the traffic flow. In our previous studies (5,6), the following three crash precursor variables were identified: (1) the coefficient of variation of speed (which is equal to the standard deviation of speed divided by the average speed) upstream of a specific location (*CVS*), (2) average density (*D*), and (3) average speed difference between the upstream and downstream of a specific location (*Q*). The details of model structure, the calculation of precursors including the determination of observation time slice duration (time offset), the categorization of precursor variables, and the calibration of parameters using real traffic data are discussed in Lee et al. (5,6).

However, in order to reflect the effect of lane changing behavior on crash potential, the lateral variation of speed between lanes was subsequently included in the model. To restrict the number of cells in the log-linear model from becoming too large (i.e. to avoid too many zero frequencies), the number of categorical variables should be limited. It was found that average density had a weaker influence on crash frequencies than other precursors in spite of its statistical significance. Thus, average density was removed from the model. The new crash precursor represents average cross-sectional (between adjacent lanes) covariance of volume difference between the upstream and downstream of a specific location (*COVV*). The variable is calculated using Equation 1:

$$COVV = \frac{1}{n-1} \sum_{i=1}^{n-1} |\text{cov}(V_i, V_{i+1})| = \frac{1}{n-1} \sum_{i=1}^{n-1} \sum_{t=t^*-\Delta t}^{t^*} [(\Delta v_i(t) - \Delta \bar{v}_i)(\Delta v_{i+1}(t) - \Delta \bar{v}_{i+1})] \quad (1)$$

where,

n = number of lanes;

V_i = time series of $\Delta v_i(t)$ over period Δt (i.e. $V_i = \{\Delta v_i(t_0), \Delta v_i(t_0+1), \dots, \Delta v_i(t_0+\Delta t)\}$);

t^* = actual time of crash occurrence;

Δt = observation time slice duration (seconds);

$\Delta v_i(t)$ = volume difference between upstream and downstream of locations on lane i at time interval t ;

$\Delta \bar{v}_i$ = average volume difference on lane i over period Δt .

In the above equation, lane i and lane $i+1$ are adjacent lanes. With this new crash precursor variable, the modified crash prediction model can be described using Equation 2:

$$\ln(F) = \theta + \lambda_{CVS(i)} + \lambda_{Q(j)} + \lambda_{COVV(k)} + \lambda_{R(l)} + \lambda_{P(m)} + \beta \ln(EXP) \quad (2)$$

where,

F = the expected number of crashes;

θ = constant;

$\lambda_{CVS(i)}$ = effect of the crash precursor variable CVS having i levels;

$\lambda_{Q(j)}$ = effect of the crash precursor Q having j levels;

$\lambda_{COVV(k)}$ = effect of the crash precursor $COVV$ having k levels;

$\lambda_{R(l)}$ = effect of road geometry (control factor) having l levels;

$\lambda_{P(m)}$ = effect of the peak/off-peak traffic pattern (control factor) having m levels.

EXP = the exposure in vehicle-kilometers of travel;

β = the parameter for the exposure.

Crash precursors and control factors are expressed in categorical variables whereas the exposure is expressed in a continuous variable. The model was calibrated using 13-months of crash data and loop detector data collected from the Gardiner Expressway in Toronto, Canada. Since the number of categories and the boundary values for crash precursors are not certain, the model parameters were estimated for different categorizations. When 3 categories (high, intermediate, and low) of crash precursors were used, all the coefficients were statistically significant at a 95% confidence level in all 9 cases as shown in Table 1. The goodness of fit of the log-linear model, as indicated by the log-likelihood ratio χ^2 , was measured by comparing the expected frequencies and the observed

frequencies. Unlike the most types of analyses, a small log-likelihood ratio χ^2 and a large p -value indicate that the distribution of the expected frequencies is *not* significantly different from the distribution of the observed frequencies – i.e. the model fits the data well. Since the values of the log-likelihood ratio χ^2 were found to be low with p -values close to 1 in all cases, the model fit was adequately high at a 95% confidence level ($\alpha = 0.05$). This modified model displayed slightly better performance than the model we developed in the previous study (6). As expected, high-level crash precursors generally contribute to high crash frequency.

Crash potential estimated by this model is used as a surrogate measure of safety to evaluate the potential of the proposed control logic of variable speed limits in reducing crash potential. The calculation method of crash potential using the model is explained in detail in the next section.

METHOD OF EVALUATION

This study used the PARAMICS microscopic traffic simulator (16) for modeling variable speed limits. PARAMICS was selected for use primarily because it permits the development of custom control logic through use of an application programming interface. The model permits changes in the posted speed limits on each link during the simulation, and thereby enables the estimation of crash potential profiles in real-time as follows: The model provides instantaneous traffic flow data for individual vehicles and drivers, which can be aggregated to give speed profile and volume of the entire traffic stream. Then, these aggregated data can be used to compute the value of the crash precursor that can in turn be used as input to the log-linear crash prediction model to estimate crash potential.

In PARAMICS, the maximum attainable speed for every vehicle is calculated at every time step based on the vehicle type, car following characteristics, grades, hazards, etc. In this case, a posted speed limit can be externally defined as the maximum attainable speed. However, in order to reflect real-world driver behavior, the simulation model assumes “random” compliance of drivers with speed limit changes. From this randomness, the mean speed of drivers is designed to slightly exceed the speed limit. The speed of each individual driver is determined based on his/her degree of aggressiveness; more aggressive drivers tend to exceed speed limits and less aggressive drivers tend to travel at a speed lower than speed limits. The degree of aggressiveness is expressed as a numerical value (the higher the value, the more aggressive) and it is assumed to follow a normal distribution. The assumption of a normal distribution implies that on average, drivers tend to observe the speed limit. This behavioral distribution has been

validated by the developers of PARAMICS (16). The high compliance with variable speed limits was also supported by the empirical findings in the past studies. For example, Hawkins et al. (17) observed that variable speed limits tended to make drivers more aware and obedient of speed limits due to the correlation of the speeds to actual freeway conditions in real time. However, the detailed investigation of underlying assumptions associated with individual driver behavior in PARAMICS is beyond the scope of this study. A variable speed limit system must include logic that addresses the following three strategy control factors:

- 1) When should speed limits be changed?
- 2) How frequently can speed limits be changed? or How long should speed limit changes be in effect?
- 3) If speed limits should be changed, should they be increased or decreased and by how much?

To perform variable speed limits within PARAMICS, a special purpose software module was developed in C++ using the application programming interface (API). A flow chart illustrating the variable speed limit control logic is shown in Figure 1. At each specified time step, lane-by-lane speed and volume data are imported from loop detectors as input to the real-time crash prediction model. The three crash precursor values are calculated using these data at each time period at each loop detector station. The levels of precursors (high, intermediate, and low) are determined on the basis of the precursor values, and exposures in vehicle-kilometers are calculated. Then coefficients (i.e. relative impact on crash frequency) corresponding to different levels of precursors and external control factors are determined, and crash frequency is calculated. Finally, crash potential is expressed in crash rate (crash frequency divided by exposure). It should be noted that in order to avoid the unrealistic assumption of linear relationship between frequency and exposure, exposure is scaled by the factor β (crash potential = frequency / exposure ^{β}). If the current crash potential exceeds the specified threshold of crash potential, the current speed limits are reduced to a specified reduced speed limit for a specified duration of intervention. Otherwise, current speed limits are maintained.

CASE STUDY

Example Freeway Segment and Control Logics

In this experiment, a 2.5-km stretch of a sample freeway segment is considered. Four loop detectors and three variable message signs (VMSs) are installed as shown in Figure 2. The loop detectors collect the traffic flow information necessary for the calculation of crash potential and VMSs display the associated messages to drivers based on the calculated crash potential. In this case, whenever the current crash potential exceeds the specified threshold of crash potential, VMSs show the message of the reduced speed limit so that drivers reduce their speeds accordingly *before* they pass the location of VMSs. The period from 7 am to 10 am is modeled, however the first hour is used as a warm-up period and no statistics are collected during this time. A total traffic demand in the simulation is 9,600 vehicles, including 2,400 vehicles that enter from the on-ramp. The traffic demand is distributed over 18 ten-minute time intervals according to the specified fraction as shown in Figure 3. The temporal variation in demand, representative of a typical freeway peak period, results in the combined demand from the mainline and the on-ramp exceeding the capacity of the mainline downstream of the on-ramp. This causes the congestion and makes a significant change in speeds during peak period.

In implementing variable speed limits, 1) the threshold of crash potential at which intervention occurs, 2) the duration of intervention, and 3) the extent of intervention (i.e. magnitude of the change in speed limit) must be determined with respect to the three strategy control factors as mentioned in the previous section. To minimize total crash potential, the impacts of these factors on crash potential need to be considered as follows:

Threshold of crash potential:

Two levels of thresholds were considered (Low and High). Due to different ranges of variation of crash potential for different road geometry, different threshold values were set for straight sections and merge/diverge sections. In this study, the Low Threshold was defined as 5 for merge/diverge sections and 1 for straight sections and the High Threshold was defined as 10 for merge/diverge sections and 5 for straight sections.

Duration of intervention:

Four durations of intervention (2, 5, and 10 minutes, and whole simulation time) were considered. The duration of intervention represents the time period in which intervention is in effect. In this study, the time offset for the calculation of crash precursors is set equal to the duration of intervention. In the case of the duration set equal to the whole simulation time, a single speed limit is enforced throughout the simulation.

Control strategies:

In this study, a relatively simple control strategy was assumed in which speed limits posted on VMSs could take on one of two values; either the design speed limit of 90 km/hour (i.e. the speed limit that is in effect when there is no intervention) and a pre-specified reduced speed limit. Six cases of reduced speed limits (80, 70, 60, 55, 50 and 40 km/hour) were considered.

In addition to this simple control strategy, the speed limit reduction that accounts for the current average speed of the traffic stream was also considered. This strategy attempts to reduce the difference between the current speed and the speed limit, and thereby avoids the situation where vehicles are required to reduce speeds by a large amount. In this strategy, when crash potential exceeds the threshold, the speed limit is determined from the following criteria:

- If average speed ≤ 60 km/hr, the current speed limit is reduced to 50 km/hr.
- If average speed > 60 km/hr and ≤ 70 km/hr, the current speed limit is reduced to 60 km/hr.
- If average speed > 70 km/hr and ≤ 80 km/hr, the current speed limit is reduced to 70 km/hr.
- If average speed > 80 km/hr, the current speed limit is reduced to 80 km/hr.

To eliminate the random effect of the results, ten simulations were conducted for each combination of strategy control factors and the average crash potential was computed from these 10 simulation runs. For each run, average total crash potential at the three detector stations and total travel time in vehicle-hours were calculated. Average total crash potential is defined as sum of cumulative crash potential at the three stations over entire simulation time divided by frequency of “intervention check” (i.e. total simulation time divided by the duration of intervention). For example, if cumulative crash potential at the three stations are all 10 and the duration of intervention is 5 minutes,

then average total crash potential is 1.25 ($= (10 + 10 + 10) / (120 \text{ minutes} / 5 \text{ minutes})$). This measure synchronizes the effect of different duration of intervention on the calculation of total crash potential. In order to assess the impact of variable speed limits, each scenario is compared with the “do-nothing” case in which no intervention is undertaken.

RESULTS AND DISCUSSIONS

The results obtained provide some insight into the impact that three strategy control factors have on crash potential of the freeway segment. The effects of each factor on average total crash potential and total travel time are discussed as follows:

Effect of threshold of crash potential:

As shown in Table 2, average total crash potential was generally low and the reduction in crash potential from the do-nothing case was high when the *Low Threshold* for crash potential was used instead of the *High Threshold*. This is because when the threshold is lower, speed limit reduction occurs more conservatively and this contributes to the stabilization of traffic condition. However, the use of the *Lower Threshold* also results in the increased total travel time due to more frequent speed limit reduction as shown in Table 3.

Effect of duration of intervention:

As shown in Table 2, average total crash potential was significantly low at 5-minute intervals compared to 2-minute intervals. This result indicates that too short duration of speed limit reduction does not help reduce crash potential and may, in fact, increase crash potential due to unnecessarily frequent changes in speed limits. On the contrary, there was not a significant difference in average total crash potential between 5-minute and 10-minute intervals. This implies that 5-minute and 10-minute intervals are a reasonable amount of time that traffic is stabilized after speed limit changes and the speed limit reduction is in effect. It is possible that the small difference in results obtained for the 5-minute and 10-minute durations is influenced by the scale of the freeway segment examined, however this was not tested within this study. On the other hand, total travel time was higher at shorter duration of

intervention as shown in Table 3. This may be because short duration of speed limit reduction causes more turbulence of traffic flow and increases the delay.

When the duration of intervention is whole simulation time, we essentially examine the effect of different “fixed” speed limits on crash potential. As shown in Figure 4, as fixed speed limits decrease, average total crash potential also tends to decrease but total travel time dramatically increases. In particular, we found that total travel time of fixed speed limits was significantly higher than that of variable speed limits. This result indicates that lower speed limits are desirable from a safety perspective, however, there is an associated penalty in terms of increase in travel time. Thus, marginal benefit of speed limit reduction (i.e. reduction in crash potential) must be compared with the additional cost of speed limit reduction (i.e. increase in travel time) to find a cost-effective region of enforcing speed limits.

Effect of control strategies:

As shown in Table 2, lower speed limits (i.e. high speed limit reduction) generally reduced total crash potential. This means that traffic conditions are more stabilized under low speed limits and the three crash precursors reflected this condition. From the result, we can also see that high speed variation, abrupt speed reduction due to queue formation, and frequent lane changes are less likely to occur when speed limits are low. However, it should be noted that speed limit reduction does not always guarantee the reduction in average total crash potential relative to the do-nothing case. For example, speed limits of 80, 70 and 60 km/hour yielded higher crash potential than the do-nothing case. For 5-minute intervals, speed limits of 55, 50 and 40 km/hour significantly reduced crash potential from the do-nothing case by 20%, 28% and 27%, respectively when using the *Low Threshold*, and 7%, 25%, and 25%, respectively when using the *High Threshold*. Similar results were obtained for 10-minute intervals (27%, 45%, and 30% for when using the *Low Threshold* and 12 %, 18%, and 29% for when using the *High Threshold*).

Contrary to expectation, the last control strategy, in which the magnitude of speed reduction was made based on the current average speed, did not provide safety benefits. This result seems to indicate that speed limit changes to non-fixed levels are possibly more detrimental for smoothing traffic flow than speed limit changes to a fixed level. Also, from a driver’s point of view, too many different speed limits along the road are confusing.

It appears that 50 and 40 km/hour are optimal speed reductions if the duration of intervention is 5 or 10 minutes. However, total travel time significantly increased from the do-nothing case by 9 to 19% in the case of 40 km/hour

reduction compared to an increase by only 2 to 8% in the case of 50 km/hr reduction. It is clear that the penalty or cost associated with reducing crash potential is an increase in system travel time. Since the strategy of variable speed limits at 50 km/hr and 40 km/hr provide similar safety benefits, but the increase in travel time is much greater for variable speed limits of 40 km/hr, it can be concluded that the use of a speed reduction to 50 km/hr is optimal for the freeway segment and traffic conditions examined.

When crash potential at different locations (loop detector stations) was compared, we found that crash potential was always reduced from the do-nothing case at Detector 2 that is located immediately downstream of the on-ramp. On the other hand, crash potential at other loop detector stations increased or decreased according to strategy control factors. This result implies that safety benefits of variable speed limits are the highest downstream of merging locations where the vehicles on the mainline conflict with the vehicles entering from the on-ramp. Consequently, we can expect that crash potential increases near merging locations when traffic entering from on-ramps is heavy. However, when the messages of speed limit reduction are displayed in VMSs *upstream* of merging locations (in this example, Detector 1), vehicles upstream of VMSs are forced to slow down to observe the required speed limit reduction before they reach merging locations. This allows sufficient gaps for the vehicles entering from the on-ramp and is likely to reduce the crashes with vehicles on the mainline.

CONCLUSIONS AND RECOMMENDATIONS

This study shows the potential safety benefits of variable speed limits using a real-time crash prediction model integrated with a microscopic traffic simulation model. The study found that variable speed limits can reduce average total crash potential by approximately 25% by temporarily reducing speed limits during risky traffic conditions. The findings from this study are summarized as follows:

- 1) Lower threshold of crash potential yields more reduction of crash potential. More conservative countermeasures are desirable but this will increase the cost of intervention in terms of increases in total travel time.
- 2) Short duration intervention (i.e. 2 minutes) results in increased crash potential due to the more frequent speed limit changes. An intervention duration of 5 to 10 minutes was found to maximize safety benefits for the freeway segment examined in this study.

- 3) Reductions in speed limits (whether fixed or variable speed limits) appear to provide safety benefits in terms of reduced crash potential. However, reductions in speed limits also increase system travel time. Therefore, there is a quantifiable trade-off between reduction in risk (crash potential) and increase in system travel time.
- 4) The reduction in crash potential is the greatest at the location of high traffic turbulence such as downstream of merging locations. Advanced warning to drivers who are approaching these merging locations is likely to be very effective in reducing crash potential.

From this study, we could verify that as speed limits are reduced, the speed deviance of individual vehicles decreases. The decrease in the speed deviance will reduce the variation of speed on each lane (*CVS*). Also, as the speed reduction remains in effect for a defined time period, the speed difference between upstream and downstream detectors (*Q*) will also be reduced. The reduction of speed limits will also decrease the variation of speed between lanes and will reduce the number of lane changes reflected by the precursor variable *COVV*. With these changes in crash precursors, the reduction of speed limits is likely to reduce crash potential.

The results of our experiment showed that variable speed limits could be used on a real-time basis to provide significant safety benefits. However, in spite of promising results in this paper, the analysis did not use real traffic data and we could not speculate whether the results are realistic. Thus, it is required to calibrate and validate the PARAMICS model using real traffic data to ensure that the simulation reflects the actual traffic condition in real world. In calibration process, we need to make sure that the temporal variation of traffic characteristics such as speed, volume and density in the simulation is reasonably close to the variation of the observed traffic characteristics. These traffic characteristics are fundamental input to the calculation of crash precursor values and crash potential.

Clearly, many assumptions in the PARAMICS simulation model have not been empirically validated and the results may be valid only for the limited conditions examined in this study. One of the important limitations of PARAMICS in the application to variable speed limits is that PARAMICS assumes the driver's response to changes in speed limits follows a unique distribution regardless of different traffic and environmental factors such as weather, congestion, composition of vehicles, etc. This may lead to relatively high compliance with variable speed

limits in the simulation and may overestimate the reduction in crash potential. More work is needed to overcome this limitation.

To understand more fully the general relationship between crash potential and variable speed limits, the work described in this paper should be expanded to consider a much broader range of traffic flow conditions, road geometry, and variable speed limits control strategies. Also, in order to effectively reduce overall crash potential at the network-level, we need to develop a spatially coordinated control of variable speed limits on freeways. Finally, we also need to examine safety benefits of other real-time traffic control strategies such as ramp metering and lane signal control.

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TABLE 2. Effect of Control Factors on Average Total Crash Potential

TABLE 3. Effect of Control Factors on Total Travel Time

FIGURE 1. Flow chart of variable speed limit control logics

FIGURE 2. Schematic drawing of a sample freeway section

FIGURE 3. Temporal variation of 10-minute traffic demand

FIGURE 4. Effect of fixed speed limits on crash potential and travel time

TABLE 1 Estimated Parameter of a Log-linear Model

Parameter	Assumed Proportions of Crash Precursors (%Low/%Intermediate/%High)								
	20/60/20	20/50/30	30/50/20	33/33/33	40/40/20	40/30/30	50/30/20	50/20/30	60/20/20
θ	3.0419	3.015	2.9617	0.9916	2.8264	1.9481	2.7676	2.8595	2.9421
$\lambda_{CVS=1}$	-4.9024	-4.3035	-3.1951	-3.0426	-2.9778	-3.3609	-2.8891	-2.9906	-2.3989
$\lambda_{CVS=2}$	-1.3487	-2.4957	-1.7137	-1.8775	-1.8471	-2.014	-1.5684	-2.0835	-1.6492
$\lambda_{CVS=3}^*$	0	0	0	0	0	0	0	0	0
$\lambda_{Q=1}$	-2.6106	-2.213	-2.1881	-2.1249	-2.2656	-2.6161	-2.5314	-2.3886	-1.9224
$\lambda_{Q=2}$	-1.0012	-2.3939	-1.3546	-1.9922	-1.5974	-2.1198	-1.4096	-2.2411	-1.3618
$\lambda_{Q=3}^*$	0	0	0	0	0	0	0	0	0
$\lambda_{COVV=1}$	-2.6068	-2.3352	-2.0468	-1.8741	-2.0444	-2.4909	-2.1808	-2.1899	-1.5409
$\lambda_{COVV=2}$	-0.6217	-1.63	-0.9512	-1.2487	-1.1645	-1.1901	-0.9915	-1.2023	-1.0144
$\lambda_{COVV=3}^*$	0	0	0	0	0	0	0	0	0
$\lambda_{R=0}$	-0.4469	-0.6068	-0.4399	-0.9719	-0.4937	-0.8044	-0.5109	-0.5816	-0.4766
$\lambda_{R=1}^*$	0	0	0	0	0	0	0	0	0
$\lambda_{P=0}$	-0.3817	-0.9831	-0.5395	-2.3746	-0.7922	-1.7261	-0.8158	-0.9453	-0.5783
$\lambda_{P=1}^*$	0	0	0	0	0	0	0	0	0
β (Exposure in 10^9 veh- km)	0.0073	0.0427	0.0318	0.1309	0.0709	0.1119	0.0787	0.0481	0.0344
Likelihood Ratio χ^2	65.5	28.9	61.2	20.2	49.7	23.3	47.8	33.6	68.7
p -value ($\alpha=0.05$)	1.00**	1.00**	1.00**	1.00**	1.00**	1.00**	1.00**	1.00**	0.99

* Aliased cell. This cell serves as the basis against which log-linear parameters are applied to obtain crash frequency for any combination of crash precursors.

** The p -values are close to 1, not exactly equal to 1.

Description of Parameters:

θ : Constant;

$\lambda_{CVS=1}, \lambda_{CVS=2}, \lambda_{CVS=3}$: Effect of CVS (=1 (low), =2 (intermediate), =3 (high));

$\lambda_{Q=1}, \lambda_{Q=2}, \lambda_{Q=3}$: Effect of Q (=1 (low), =2 (intermediate), =3 (high));

$\lambda_{COVV=1}, \lambda_{COVV=2}, \lambda_{COVV=3}$: Effect of $COVV$ (=1 (low), =2 (intermediate), =3 (high));

$\lambda_{R=0}, \lambda_{R=1}$: Effect of road geometry (=0 (straight section), =1 (merge/diverge section));

$\lambda_{P=0}, \lambda_{P=1}$: Effect of time of day (=0 (off-peak), =1 (peak));

β : Coefficient for exposure.

TABLE 2 Effect of Control Factors on Average Total Crash Potential

Threshold Type	Duration Strategies	Average total crash potential*			Change in crash potential from do-nothing case**		
		2 min.	5 min.	10 min.	2 min.	5 min.	10 min.
High Threshold	Do nothing	20.41	18.71	16.50	-	-	-
	VSL = 80 km/hr	24.62	18.13	17.94	4.21	-0.58	1.44
	VSL = 70 km/hr	29.06	21.55	18.83	8.65	2.84	2.33
	VSL = 60 km/hr	28.18	18.90	18.85	7.76	0.19	2.35
	VSL = 55 km/hr	23.04	17.48	14.51	2.62	-1.23	-1.99
	VSL = 50 km/hr	25.36	14.11	13.53	4.95	-4.60	-2.97
	VSL = 40 km/hr	20.35	13.99	11.71	-0.07	-4.72	-4.79
	VSL = Avg. Speed	26.90	17.79	18.79	6.48	-0.92	2.29
	Average change in crash potential				4.94	-1.29	-0.19
Low Threshold	Do nothing	20.41	18.71	16.50	-	-	-
	VSL = 80 km/hr	23.91	19.94	20.90	3.50	1.22	4.40
	VSL = 70 km/hr	27.12	20.22	17.78	6.71	1.51	1.28
	VSL = 60 km/hr	24.05	19.27	16.26	3.64	0.56	-0.24
	VSL = 55 km/hr	21.39	14.88	11.98	0.98	-3.83	-4.52
	VSL = 50 km/hr	20.71	13.46	9.14	0.30	-5.26	-7.36
	VSL = 40 km/hr	19.46	13.67	11.48	-0.95	-5.05	-5.02
	VSL = Avg. Speed	28.20	20.31	17.71	7.78	1.60	1.21
	Average change in crash potential				3.14	-1.32	-1.46

* Average of 10 simulation runs.

** Negative value implies that crash potential of the given control strategy is lower than crash potential of the do-nothing case, and vice versa. Thus, the lower the value, the more the safety benefits of the strategy.

TABLE 3 Effect of Control Factors on Total Travel Time

Threshold Type	Duration Strategies	Total travel time (vehicles-hours)*			Change in total travel time from do-nothing case**		
		2 min.	5 min.	10 min.	2 min.	5 min.	10 min.
High Threshold	Do nothing	224.00	224.50	224.00	-	-	-
	VSL = 80 km/hr	225.65	224.10	224.14	1.66	-0.40	0.14
	VSL = 70 km/hr	227.68	222.04	224.95	3.69	-2.46	0.95
	VSL = 60 km/hr	239.05	229.59	224.51	15.06	5.09	0.51
	VSL = 55 km/hr	238.38	235.16	232.42	14.38	10.66	8.43
	VSL = 50 km/hr	250.52	232.41	229.42	26.52	7.91	5.42
	VSL = 40 km/hr	283.01	245.79	237.12	59.01	21.29	13.13
	VSL = Avg. Speed	240.25	227.75	223.54	16.25	3.24	-0.45
	Average change in total travel time				19.51	6.47	4.02
Low Threshold	Do nothing	224.00	224.50	224.00	-	-	-
	VSL = 80 km/hr	223.32	221.40	225.48	-0.67	-3.10	1.49
	VSL = 70 km/hr	231.60	227.14	226.94	7.60	2.64	2.95
	VSL = 60 km/hr	238.93	237.07	227.88	14.93	12.57	3.88
	VSL = 55 km/hr	248.30	237.95	234.65	24.30	13.45	10.65
	VSL = 50 km/hr	256.45	241.56	234.87	32.46	17.06	10.88
	VSL = 40 km/hr	292.51	268.27	256.65	68.51	43.77	32.66
	VSL = Avg. Speed	238.84	237.24	230.42	14.84	12.74	6.42
	Average change in total travel time				23.14	14.16	9.85

* Average of 10 simulation runs.

** Positive value implies that total travel time of the given control strategy is higher than total travel time of the do-nothing case, and vice versa. Thus the higher the value, the more the cost (travel time) of the strategy.

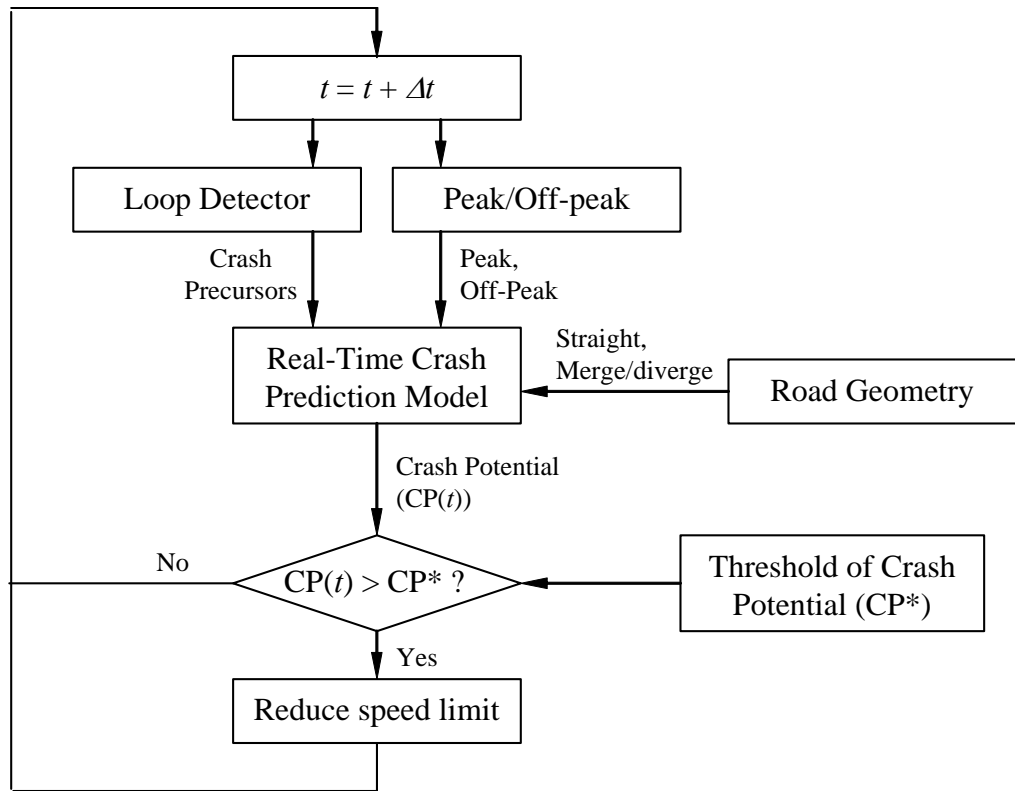


FIGURE 1 Flow chart of variable speed limit control logics.

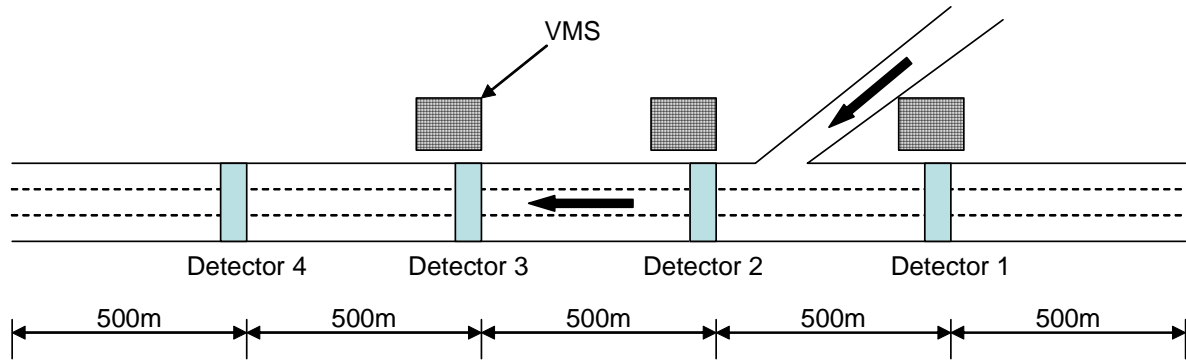


FIGURE 2 Schematic drawing of a sample freeway section.

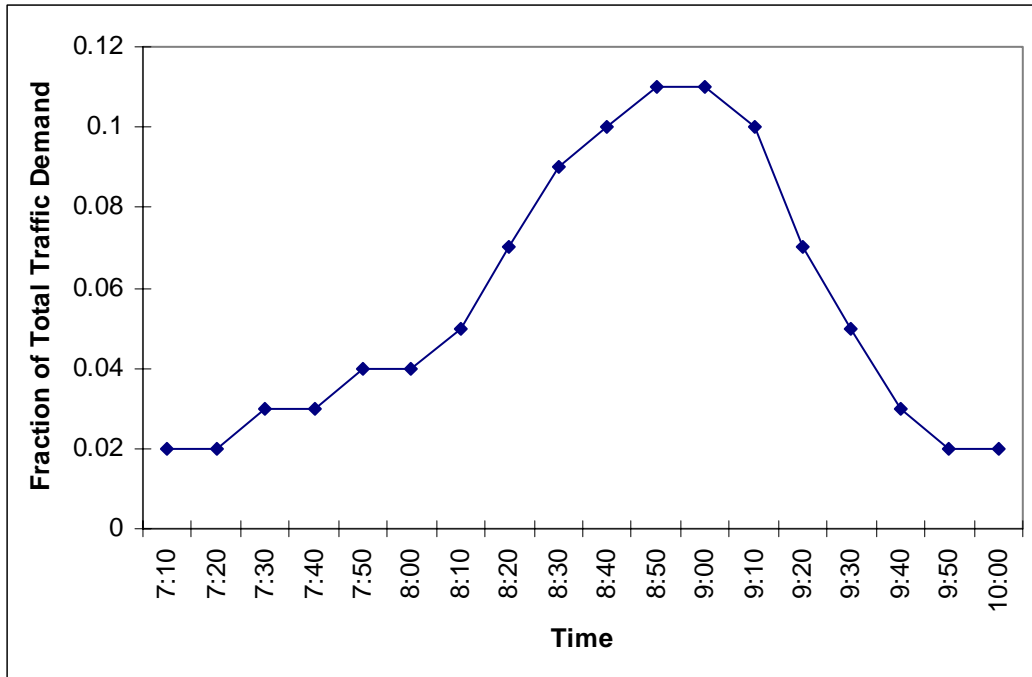


FIGURE 3 Temporal variation of 10-minute traffic demand.

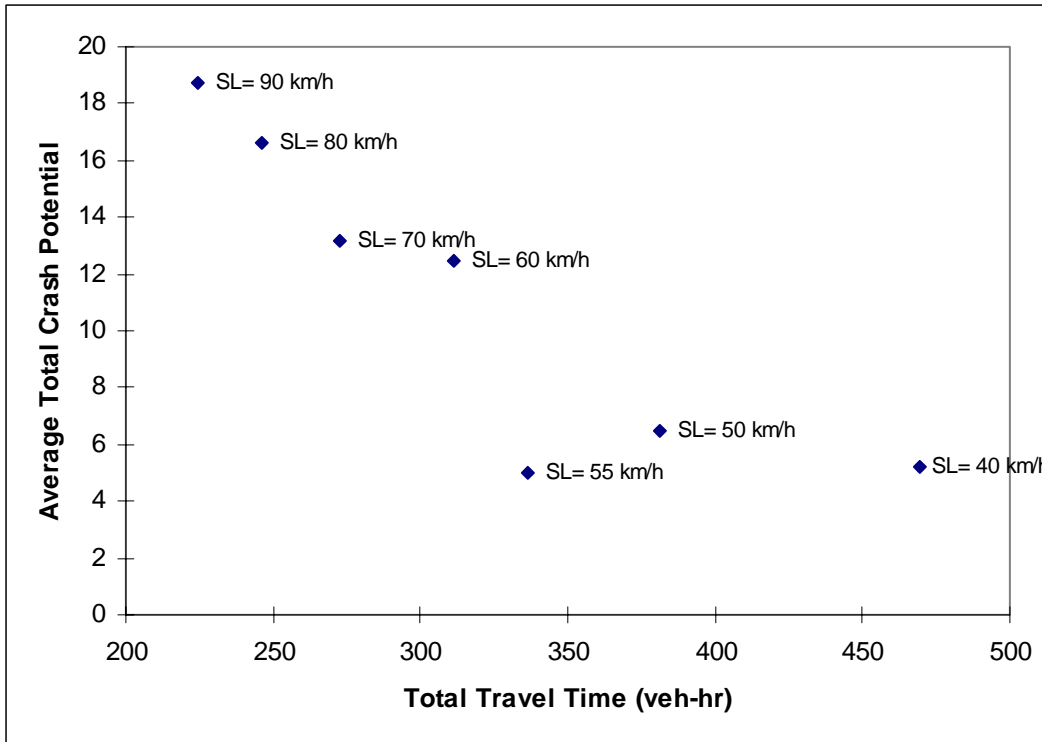


FIGURE 4 Effect of fixed speed limits on crash potential and travel time.