Quantifying effects of ramp metering on freeway safety◇

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Abstract

This study presents a real-time crash prediction model and uses this model to investigate the effect of the local traffic-responsive ramp metering strategy on freeway safety. Safety benefits of ramp metering are quantified in terms of the reduced crash potential estimated by the real-time crash prediction model. Driver responses to ramp metering and the consequent traffic flow changes were observed using a microscopic traffic simulation model and crash potential was estimated for a 14.8-km section of I-880 in Hayward, California and a hypothetical isolated on-ramp network. The results showed that ramp metering reduced crash potential by 5%-37% compared to the no-control case. It was found that safety benefits of local ramp metering strategy were only restricted to the freeway sections in the vicinity of the ramp, and were highly dependent on the existing traffic conditions and the spatial extent over which the evaluation was conducted. The results provide some insight into how a local ramp metering strategy can be modified to improve safety (by reducing total crash potential) on longer stretch of freeways over a wide range of traffic conditions.

Keywords: Ramp Metering, Crash, Freeway, Safety, Simulation

1. Introduction

The objective of ramp metering is to reduce delay and maintain capacity flow on a freeway by regulating access of ramp traffic to the mainline. Empirical studies have shown that ramp metering reduces turbulence in the merge zone, reduces variance in speed distributions, and thereby improves traffic safety (i.e. reduces sideswipe and rear-end crashes). For example, Piotrowicz and Robinson (1995) reported that ramp metering reduced crash rate by 24%-50% and increased capacity by 17%-25% on the basis of case studies of freeways in major U.S. cities. They also suggested that reductions in crash rate provide a further benefit by reducing crash-induced delay. Other empirical studies have supported the finding that ramp metering reduces

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crash rate (Cambridge Systematics, 2001) and more specifically rear-end and sideswipe crashes in the freeway mainline (Cleavenger and Upchurch, 1999).

Many studies in North America and Europe have assessed the benefits of ramp metering quantitatively through field tests and simulation experiments. For example, Kang and Gillen (1999) considered fuel savings, time savings and the reduction in emission as the benefits of ramp metering. However, whereas most studies focused on the effectiveness of ramp metering in reducing the system travel time and making effective use of capacity, very few studies explicitly considered safety benefits of ramp metering in a quantitative analysis. Although delay savings are associated with the reduction in crashes, it is very difficult to estimate this type of delay savings due to uncertainty with the occurrence of crashes (e.g. frequency) and the characteristics of crashes (e.g. the number of lanes that were blocked and the duration of crashes). In fact, the main reason for the tendency of overlooking the safety improvement associated with ramp metering is that too little is known about the crash reduction mechanism for quantitative modeling (Banks, 2000).

In this regard, some studies have examined the relationship between safety and short-term changes in traffic flow and attempted to estimate crash potential on a real-time basis. These studies mainly related traffic flow data (collected from loop detectors) prior to crash occurrence to crash risk. Oh et al. (2001) found that higher standard deviation of speed within 5 minutes increased the likelihood of crashes. Also, Golob and Recker (2003, 2004) observed that median traffic speed and temporal variations in speed in the left and interior lanes are highly correlated with crash occurrence. However, in spite of statistically significant results in these works, some studies (Davis, 2002; Kockelman and Ma, 2004) pointed out the limitation of using temporally aggregated speed data in estimating individual crash risk. Instead, both works suggested using individual-level data.

To overcome the limitation of aggregated data, some studies have examined the use of microscopic traffic simulation models and estimated individual crash risk. Gettman and Head (2003) collected surrogate measures of safety from a micro-simulation model and use them to evaluate the safety of intersections. They found that the proposed safety measures could reflect the safety level of different intersection designs. They also validated the measures are correlated with actual occurrence of traffic conflicts. Although their approach is somewhat conceptual, it demonstrates that micro-simulation models can be used as an effective tool to investigate a variety of conflict events that may lead to crashes. In Europe, Bonsall et al. (2005) examined safety-related parameters in traffic simulation models and suggested that there exists some limitation of the models in reflecting potential indicators of safety (e.g. unrealistic driver behavior, difficulty with model calibration). However, they claimed that it is possible to overcome the limitation through more accurate calibration of the models using realistic-but-unsafe global parameters (e.g. distribution of aggressiveness).

Some studies have concentrated on quantifying safety benefits of ramp metering or specific vehicle technology using individual vehicle data. For instance, Torday et al. (2003) suggested that safety benefits of ramp metering can be quantified in terms of a safety indicator calculated by speeds and decelerations of leader and follower vehicles. They demonstrated that the simulation models can be used to measure the direct interaction between cars and thereby estimate the chances of crashes. Similarly, Minderhoud and Bovy (2001) used the time to collision for a follower vehicle as a measure of safety assessment for Autonomous Intelligent

Cruise Control (AICC) designs. Although these quantitative measures can directly estimate the probability of crash occurrence between cars, they require a large quantity of microscopic vehicle data that are not readily available in the field. Also, the use of these measures to calculate overall crash risk of many vehicles traversing a section of freeway is computationally intensive.

Thus, it is more practical to describe safety benefits of ramp metering in the form of macroscopic traffic data (collective behavior of a group of vehicles) or consequences (number of crashes). Recently, Thill et al. (2004) defined safety benefits of ramp metering as a decrease in crash frequency at the merging of ramp and freeway lanes from the baseline number of crashes. However, they neither explicitly explained the method of predicting crash frequency nor conducted the analysis to demonstrate that ramp metering can actually reduce crash frequency. However, since crashes are relatively rare events, crash data must be collected over a long period of time after the implementation of ramp metering to have a large enough sample to provide statistically significant conclusions. Thus, the observation of the number of crashes is not practical for evaluating safety benefits of ramp metering. Instead, we need to identify surrogate measures of crash risk associated with short-term variation in traffic flow and observe the changes in these measures as safety impacts of ramp metering.

Fixed-time metering is the simplest ramp metering strategy and has been widely used. However, despite evidence that fixed-time metering can provide safety and congestion reduction benefits (Piotrowicz and Robinson, 1995), other studies identified several significant limitations such as overload of the mainstream flow and underutilization of capacity that result in a net increase in total delay (Hellinga and Van Aerde, 1995; Papageorgiou and Kotsialos, 2002). In an attempt to overcome these limitations, traffic-responsive ramp metering strategies were developed. Many traffic-responsive strategies have been proposed with varying degrees of success in terms of performance (Jacobson et al., 1989; Papageorgiou et al., 1991; O'Brien, 2000).

Thus, this study has two objectives: 1) to propose a method of quantifying the effect of a traffic-responsive ramp metering strategy on crash reduction and 2) to evaluate the performance of ramp metering in terms of improving freeway safety under various traffic conditions.

This paper is organized into five sections. The second section introduces the concept of the ALINEA traffic-responsive ramp metering strategy (Papageorgiou et al., 1991), and the method used to estimate freeway crash potential based on change in traffic flow states caused by ramp metering. The third section describes the details of a quantitative analysis for evaluating the effectiveness of ramp metering in reducing crash potential. The fourth section presents the results of the analysis through simulation experiments and discusses the implications of the results. The last section draws conclusions based on the findings and suggests several issues that require future study.

2. Methods

2.1. ALINEA Ramp Metering

ALINEA (Asservissement Linéaire d'Entrée Autoroutière) is a local traffic-responsive ramp metering strategy and has been applied in several European countries (Papageorgiou et al., 1991). It has been found through field tests and simulation experiments that ALINEA can stabilize traffic flow and reduce the risk of flow breakdown while making effective use of freeway capacity. The concept of ALINEA is that the metering rate is determined in real time such that the observed occupancy *downstream* of the merge area matches the pre-specified critical occupancy (occupancy at capacity) as follows:

$$r(k) = r(k-1) + K_R\left[\hat{o} - o_{out}(k)\right] \tag{1}$$

where $r(k)$ is the metering rate at time interval k (veh/hour), $r(k\text{-}1)$ is the metering rate at previous time interval k-1 (veh/hour), K_R is the regulator parameter (veh/hour), $\hat{o}$ is the critical occupancy (%), and $o_{out}(k)$ is the occupancy downstream of the merge area at time interval k (%).

In the above equation, if the occupancy downstream of the merge area during the current time interval exceeds the critical occupancy, ALINEA decreases the metering rate from the value for the previous time interval (i.e. limit the access of ramp traffic to the mainline for longer duration), and vice versa. Ramp metering allows the vehicles on the ramp to enter the mainline only when the traffic signal turns to green. Otherwise (during a red phase), they are required to stop upstream of the signal on the ramp and wait for a green phase. The green-phase duration is determined using the following expression (Papageorgiou et al., 1997):

$$g(k) = g(k-1) + K_R \frac{C}{r_{sat}}\left[\hat{o} - o_{out}(k)\right],\ g_{\min} \le g \le g_{\max} \tag{2}$$

where $g(k)$ is the green-phase duration at time interval k (seconds), $g(k\text{-}1)$ is the green-phase duration at previous time interval k-1 (seconds), C is the fixed signal cycle duration (red phase + green phase) (seconds), r_{sat} is the ramp capacity flow (saturation flow in veh/hour), $g_{\min}$ is the minimum green-phase duration (seconds) ($g_{\min} > 0$), and $g_{\max}$ is the maximum green-phase duration (seconds) ($g_{\max} < C$).

2.2. Real-Time Crash Prediction Model

The real-time crash prediction model first proposed by Lee et al. (2002) was used to estimate crash potential for different traffic conditions. The model imports traffic flow data (speed and volume) from road sensors at the specified time intervals, calculates the values of surrogate measures of traffic turbulence contributing to crash occurrence called "crash precursors", and estimates crash potential based on the categories of these crash precursors. The model is an aggregated categorical model in the functional form of a log-linear model which is capable of describing the general relationship between crash frequency and categorical variables in a broader scope.

Disaggregate models such as a logit model can also estimate the probability of crash occurrence on the basis of individual crash and non-crash cases; however, they cannot objectively determine the relationship due to uncertainty associated with determining the number of non-crash cases for comparison and the exposure measures. On the other hand, the log-linear model considers the distribution of crash frequencies under various combinations of traffic and environment conditions. Thus, exposure can be objectively determined in the form of the long-term frequency of the event for the categorized conditions and the probability of crash occurrence (i.e. crash potential) can be logically determined in the form of crash rate (= crash frequency divided by some function of exposure) as follows:

$$\text{Crash Rate} = \frac{F}{EXP^{\beta}} \tag{3}$$

where F is the expected number of crashes over the given observation time period, EXP is exposure in vehicle-kilometers of travel, and β is a parameter for exposure to be calibrated using the observed crash data. Exposure is described as the products of total traffic volume over the observation time period and the length of each road section. These are split into volume kilometers according to the probabilities of occurrence of traffic factors in daily traffic. The model defines crash potential as a function of crash precursors and external control factors such as road geometry and peak/off-peak period. The following three crash precursors that contribute to the variation of crash potential prior to the crash occurrence were identified and included in the model as independent variables:

1) coefficient of variation of speed (i.e. standard deviation of speed divided by the average speed over some time intervals) upstream of a specific location (*CVS*);

2) average speed difference between the upstream and downstream of a specific location (*Q*);

3) average covariance of volume difference between the upstream and downstream of a specific location between adjacent lanes (*COVV*).

The model was calibrated for actual crash, traffic, and road geometry data collected from a 10-km stretch of the Gardiner Expressway in Toronto, Canada for a 13-month period. For the calibration of the model, incident logs recorded by an operator at the traffic control center were used to locate the time and the sites of 234 "reportable" crashes on the freeway. At each site of crash occurrence, traffic data required for the calculation of crash precursors were retrieved from loop detectors closest to the crash site during the specified time period prior to the estimated time of crashes.

As a result of the calibration, it was found that the model tended to predict high crash potential in high turbulence of traffic flow. These hazardous traffic conditions are reflected by high values of precursors such as high variation of speed over time and frequent lane changing. In particular, the study found that among the three crash precursors, the difference in average speeds between upstream and downstream locations (precursor *Q*) has the most dominant effect on crash potential. Also, it can be anticipated that precursor *Q* is more sensitive to traffic flow control such as ramp metering and variable speed limits than the other precursors. Thus, the effect of precursor on crash risk will be explained mainly in terms of the speed difference. Positive values of *Q* reflect the situation where the upstream speed is higher than the downstream speed (i.e. deceleration) and negative values of *Q* reflect the situation where the upstream speed is lower than the downstream speed (i.e. acceleration). In the model, *Q* is categorized into the following four categories: 1) *acceleration* ($Q \leq -5$ km/hr); 2) *constant speed* (-5 km/hr $< Q \leq 5$ km/hr); 3) *low deceleration* (5 km/hr $< Q \leq 20$ km/hr); and 4) *high deceleration* ($Q > 20$ km/hr).

As expected, a different crash potential is associated with each of these four categories. Crash potential is expressed as the expected number of crashes per million vehicles-km over 13 months at the selected road section. The order of crash potential estimated by the model from the highest to the lowest (while all other variables remain constant) is crash potential during high deceleration (Category 4), low deceleration (Category 3), acceleration (Category 1), and constant speed (Category 2). For instance, crash potential for different categories of Q on two types of road geometry is shown in Figure 1. The figure shows that the model outputs agree with our prior expectation that reducing speed abruptly is more likely to lead to a crash than increasing speed or traveling at almost constant speed. The figure also shows that the likelihood of crash occurrence is higher on merging/diverging road section where lane changing occurs more frequently than straight road sections.

2.3. Traffic Simulation Model

To estimate the impact of ramp metering on crash potential, traffic flow changes as a result of ramp metering control must be observed as these are primary inputs to calculate crash precursors and crash potential. For this purpose, this study used the PARAMICS microscopic traffic simulator (Quadstone Ltd., 2002). PARAMICS can describe individual vehicle movements and thereby capture the effect of refined traffic characteristics on the performance of ramp metering (e.g. delay in merging on acceleration lane).

The simulation model was calibrated by comparing flow, density and travel time between the actual condition and simulations. The comparisons were made using the two “fitness functions”. The first function calculates the sum of absolute errors in 1-minute average flow and density in each lane at each detector station during each time interval. The second function calculates the sum of squares of errors in travel time for selected routes during each time period. As a result of the calibration, these relative errors were found to be less than 5%.

In this study, the above crash prediction modeling logic was incorporated into PARAMICS through the application programming interface (API). An additional API, that adjusts the rate of releasing vehicles from the origin in order to reflect the actual variation in the number of vehicle counts observed at detector stations, was also used (Ozbay et al., 2004). Finally, the “plans” file in PARAMICS was used to specify signal timing plan on the exit point of the ramp as described in Equation 2.

3. Analysis

This study analyzes the effects of the ALINEA ramp metering strategy on crash reduction for the two types of freeway network: the real freeway sections of I-880 (Application 1) and the hypothetical freeway sections (Application 2).

3.1. Application 1: I-880

This application considers a 14.8-km (9.2-mile) section of I-880 in Hayward, California as shown Figure 2. The simulation was run for morning peak period (7:45–11:00 am); however, statistics were collected only for an hour from 9 to 10 am while statistics during the first 1 hour 15 minutes warm-up period and the last 1-hour cool-down period were not used in the analysis. There are six loop detector stations with an average spacing of 550 meters. An additional detector station (Station #0) was modeled in the simulation to permit estimation of crash potential upstream of the ramp (i.e. Section 1). Crash potential was computed every 10-minute period for six road sections (Sections 1~6 in Figure 2) each bounded by a pair of successive detector stations. The total crash potential was calculated as the sum of crash potential at six road sections for six 10-minute periods from 9 to 10 am.

The on-ramp from A-Street was metered using the ALINEA control algorithm. Metering rate (r) was calculated every 0.5 second (k = 0.5) using Equation 1. Regulator parameter (K_R) was set to 59 veh/hour that showed the best performance (Ozbay et al., 2004). Critical occupancy ($\hat{o}$) was set to 0.17 which is slightly less than the observed critical value of 0.18. The slightly undercritical value of occupancy must be chosen because if the algorithm attempts to match downstream flow to an exact value of freeway capacity, the flow is more likely to exceed the capacity and this leads to the over-saturation of flow. The occupancy downstream of the merge area (o_{out}) was calculated as a volume-weighted average occupancy across all lanes at each time step interval.

The green-phase duration (g) was calculated using Equation 2. To prevent a ramp queue from reaching back to the surface street junction, the green-phase duration was set to a maximum value ($g_{\max}$) when the number of vehicles on the ramp exceeded the threshold of 45 vehicles. The fixed signal cycle duration (C) was assumed to be 17 seconds in order to avoid large fluctuation of the green-phase duration resulting from a long ramp queue and a queue override strategy (Ozbay et al., 2004). Ramp capacity flow (r_{sat}) may be fixed or estimated in real time on the basis of ramp traffic volume over some past cycles. This can be considered saturation flow (maximum flow) that can be released from the ramp given the current traffic characteristics. The value of r_{sat} was set to 730 veh/hour as a result of trial-and-error process using the simulation, not based on field data (Ozbay et al., 2004). Minimum and maximum values of the green-phase duration ($g_{\min}$ and $g_{\max}$) were set to 2 and 15 seconds, respectively.

3.2. Application 2: Hypothetical Isolated On-ramp Network

One of the characteristics of the I-880 network described in previous section is the presence of a capacity bottleneck, in the form of a lane reduction, downstream of the metered on-ramp at A-Street. Examination of field data (Petty et al., 1996) indicated that this bottleneck causes the formation of recurrent congestion that spills upstream and interacts with the on-ramp influence. In an effort to examine the effects of isolated ramp metering without downstream bottleneck effects, a hypothetical freeway network was modeled. This network, illustrated in Figure 3, is generally based on the portion of I-880 illustrated in Figure 2 upstream of Section 6.

The number of lanes on the mainline was reduced from 5 to 4 and the traffic demand adjusted to produce recurrent congestion in the ramp merge area. While this network scenario does not represent any specific real-world freeway section, it can be considered to reflect typical characteristics associated with an isolated on-ramp. The simulation was run to model the morning peak period from 7:45-11:00 am and only the period from 9-10 am was analyzed similar to Application 1. All ramp control parameters were kept the same as for Application 1. For this application, traffic data were collected from 6 modeled loop stations and these data were imported by the crash prediction model to estimate crash potential on each of the 5 sections every 10 minutes.

The simulation was conducted using PARAMICS for the no-control case (where ramp metering was not implemented) and the ALINEA ramp metering case in each application. Total crash potential is calculated as the sum of the crash potential for all road sections over the one-hour simulation time (9-10 am). The effects of the ALINEA ramp metering strategy on the crash potential reduction were investigated by comparing total crash potential between the no- control case and the ALINEA ramp metering case.

4. Results and discussions

Ten simulations were conducted to eliminate the random effect of the results and the average crash potential over ten simulation runs was computed. The results of the simulation experiments are summarized and discussed below:

4.1. Application 1: I-880

When a queue formed on the most downstream road section due to the lane reduction, it propagated upstream and spilled back over the road section upstream of the on-ramp and largely reduced the speed on the ramp section (Section 2 between Station #20 and #10) in the no-control case. Although there exists an off-ramp upstream of the on-ramp, the number of vehicles exiting via the off-ramp is much smaller than the mainline volume and thus the effect of diverging traffic on traffic flow is minimal. For the purpose of demonstration, Figure 4 shows the spatial variation of average speed, precursor Q, and crash potential only for one 10-minute period (9:10-9:20 am) in one of the ten simulation runs. However, it should be noted that crash potential was computed over all six 10-minute periods during 9-10 am and added to estimate the total crash potential. The abrupt drop in speed on Section 2 is illustrated in Figure 4(a). This resulted in the value of precursor Q being categorized "high deceleration" and in turn caused high crash potential on Section 2 as shown in Figures 4(b) and (c). It should be noted that the 95% confidence intervals shown in Figure 4(c) (dashed lines) were calculated based on crash potential at this specific 10-minute period in 10 simulation runs. On the other hand, the speed started to increase on the road sections downstream of the ramp (Section 4, 5, and 6) after vehicles have passed the merging point and crash potential decreased. Similar trends of high deceleration upstream of the ramp and acceleration downstream of the ramp were observed for all other 10-minute time periods during the simulation time.

In the ALINEA ramp metering case, the abrupt speed drop did not occur upstream of the ramp and crash potential was consequently reduced on Section 1 and 2 compared to the no-control case. The results indicate that the ALINEA ramp metering strategy avoids the congestion upstream of the ramp by reducing the length of a queue (i.e. it prevents a queue from spilling back over the sections upstream of the ramp). However, the use of ramp metering resulted in the increased crash potential on the two road sections downstream of the ramp (Section 3 and 4). While ramp metering can eliminate the congestion in and upstream of the ramp merge area, it cannot prevent the recurrent congestion that forms as a result of the lane drop downstream of the ramp. Clearly, ramp metering has no effect on reducing crash potential downstream of the ramp when the congestion forms downstream of the ramp. Consequently, in the metering case, vehicles must still decelerate as they join the tail of a queue, but they do so on Sections 2, 3, and 4 rather than Sections 1, 2, and 3 for the no-control case. Thus, the crash potential reduction on the road sections upstream of the ramp was offset by the increased crash potential on the road sections downstream of the ramp where a queue exists. For this reason, overall safety benefit of ramp metering (average of 10 simulation runs) was only a 5% reduction in total crash potential as shown in Table 1. As the results of *t*-test indicated that total crash potential in the ramp metering case is not different from the crash potential in the no-control case at a 95% confidence level, this reduction is not considered to be statistically significant. This is also indicated by an overlap of the 95% confidence intervals between the no-control case (230.9~259.5) and the ramp metering case (221.6~246.3). However, in the ramp metering case, the reduction in crash potential on Sections 1 and 2, and the increase in crash potential on Section 3 and 4 are statistically significant.

Examination of the results in Table 1 clearly shows that ramp metering provides significant benefits in the immediate vicinity of the ramp, but in the specific scenario modeled, these benefits are negated by increases in crash risk in downstream sections. To observe the pure effect of ramp metering, the confounding factor (i.e. lane drop in this case) must be avoided. This can be done through adjusting road geometry as described in the next section.

4.2. Application 2: Hypothetical Isolated On-ramp Network

In this application, a queue formed upstream of the ramp merge area due to excessive ramp traffic volume that enters the mainline. Unlike Application 1, there is no downstream bottleneck. Figure 5 shows the results at one 10-minute time period (9:10-9:20 am) for one of the ten simulation runs. As shown in Figure 5(a), an abrupt drop in speed occurred immediately upstream of the ramp in the no-control case (high deceleration on Section 1 in Figure 5(b)) whereas the speed was nearly constant along the road sections when ramp metering was implemented. This difference in speed profiles caused a large reduction in crash potential for the ramp metering case as shown in Figure 5(c). The results indicate that ramp metering helped avoid the congestion at the merge area and consequently reduced crash potential upstream of the ramp. Table 2 shows that ramp metering reduced total crash potential by 37%, on average, from the no-control case. This reduction is statistically significant at a 95% confidence level as indicated by *t*-statistics higher than the critical value of *t*. It can be also seen that the confidence interval for the no-control case (138.2~156.2) is clearly separated from the confidence intervals for the ramp metering case (83.4~102.8). It was also found that the reduction in crash potential is significant on the road sections upstream of the ramp (Sections 1 and 2), but not significant on the sections downstream of the ramp (Sections 3 and 4). Unexpectedly, the reduction is significant on the most downstream section (Section 5); however, the difference in means between the no-control case and the metering case on this section is relatively smaller than the differences on Sections 1 and 2. The variation of crash potential over the ten simulation runs on this section (standard deviation = 1.71 for the metering case) is also smaller. Thus, the impact of crash potential on Section 5 on total crash potential is considered to be minimal.

In comparison with Application 1, the crash potential reduction in Application 2 is much greater. Similar to the results in Table 1, the results in Table 2 also show some spatial variation in safety benefits. These findings appear to suggest that safety benefits of local ramp metering strategies are restricted to the freeway in the vicinity of the ramp merge area. Furthermore, safety benefits of ramp metering appear to be highly dependent on the existing traffic conditions, ramp metering control strategy, and the spatial extent over which the evaluation is conducted.

In spite of a remarkable reduction of the congestion at the merge area by limiting the access of ramp traffic, the length of a queue on the ramp became longer in this application. If the travel time of vehicles on the ramp is considered in the analysis, the long delay in ramp traffic is considered as a trade-off to the crash potential reduction. On the other hand, this transfer of delay from the mainline to the ramp may have a positive effect on improving safety (Cassidy, 2003). Thus, it is worth to consider the impacts of the ramp queue on the safety in the future work.

5. Conclusions and recommendations

This study investigated the potential of using a log-linear crash prediction model to quantify safety benefits of ramp metering. The model estimates crash potential in real time as a quantitative measure of freeway safety, based on short-term variation in traffic flow. The model was applied to a section of I-880 as well as a hypothetical freeway sections. The results demonstrated that the ALINEA ramp metering strategy can reduce total crash potential by 5-37% compared to the no-control case. In particular, the crash potential reduction was the most noticeable under the traffic condition when congestion was caused by high ramp traffic volume in the absence of a queue downstream of the ramp. The study found that if a queue already exists downstream of the ramp, the ability of ramp metering to make significant safety benefits is severely limited. In fact, the results confirm our intuition that large speed drop that occurs immediately upstream of the on-ramp causes high crash potential. However, the main contribution of this study is that it attempts to "quantify" the increase in crash potential due to speed drop and also the reduction in crash potential by smoothing speeds with an aid of ramp metering. The quantification of crash potential reduction is particularly important in evaluating the safety benefits of traffic operation strategies.

Although this study demonstrates that ramp metering potentially improves freeway safety, care must be taken when evaluating safety using microscopic traffic simulation models.

First, the simulation models should be calibrated for the real freeway sections not only in terms of aggregated flows and speeds, but also individual vehicle movements such as merge/diverge, lane changing, and car-following, that are the basis of the proposed safety measures – aggregated speed and volume at the selected locations.

Second, it should be noted that car-following models ensure that follower vehicles always maintain safe headways and consequently, crashes do not take place in the simulation models. To avoid this idealistic and unrealistic driver behavior, it has been proposed that the simulation models must allow the levels of driver perception to vary to a greater extent so that drivers can make errors leading to crashes (Archer, 2000).

Third, the simulation results tend to be demand specific and they may change for different demand levels on the mainline and the ramp. Thus, the sensitivity of the results in terms of both congestion and crash potential to various demand levels needs to be analyzed. However, the verification and the functional evaluation of the PARAMICS simulation model are beyond the scope of this study.

The above limitations of using microscopic simulation models in safety evaluation are presented in order to suggest how the simulation models can be improved to reflect driver behavior in the real world, not to criticize the use of models in safety evaluation. Safety benefits of ramp metering found in the study (i.e. the value of reduction in crash potential) may not be accurate due to these limitations, we can at least logically explain how ramp metering can reduce crash potential using simulation models.

The findings from this research raise several questions that warrant further research.

First, additional ramp metering strategies should be evaluated. In particular, strategies that provide coordinated control rather than only local control should be evaluated to determine if they provide more consistent safety benefits over a wide range of traffic conditions.

Second, it appears that there is the potential to achieve a more robust traffic management capability by ramp metering through the coordination with variable speed limits. Effort should be made to investigate suitable control strategies and to quantify the safety benefits of these systems.

Third, it should be noted that crash potential estimated using the proposed log-linear crash prediction model is sensitive to the selected boundary values of the categories of precursor Q. For instance, although there should be little difference in crash potential between Q = 20 km/hour and Q = 21 km/hour, these values of Q fall into different categories of Q (former is low deceleration and latter is high deceleration) and consequently the difference in estimated crash potential is quite large. This characteristic is a limitation of categorical models such as the log-linear model. We have attempted to incorporate the non-linear effect of the rate and sign of Q on crash potential within the log-linear model (e.g. defining Q as a continuous variable or increasing the number of categories for Q). However, we were unable to identify a statistically valid relationship due to the limited size of the sample crash data used for the calibration of the model. Consequently, it is recommended that a larger calibration data set be compiled and a model structure be adapted to provide a more continuous relationship between crash potential and precursor Q.

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Table 1. Comparison of crash potential for Application 1: I-880

Runs	Strategy	Crash potential on each road section (← Direction of Traffic)						
		Section 6	Section 5	Section 4	Section 3	Section 2	Section 1	Total
1	No-Control	25.9	16.6	12.2	55.7	108.3	44.9	263.6
	ALINEA	22.1	12.4	34.2	60.9	76.8	8.9	215.2
	% Change[a]	-15%	-25%	180%	9%	-29%	-80%	-18%
2	No-Control	24.2	16.6	15.5	33.8	102.6	62.0	254.7
	ALINEA	22.1	13.5	28.8	60.9	97.0	16.9	239.1
	% Change	-9%	-19%	86%	80%	-6%	-73%	-6%
3	No-Control	22.1	13.5	11.0	43.8	95.3	45.4	231.1
	ALINEA	22.8	10.9	41.3	60.9	81.6	10.1	227.5
	% Change	3%	-20%	274%	39%	-14%	-78%	-2%
4	No-Control	18.9	14.6	11.3	41.3	78.6	62.0	226.7
	ALINEA	25.9	12.4	35.0	69.2	91.3	10.1	244.0
	% Change	37%	-15%	209%	68%	16%	-84%	8%
5	No-Control	17.3	14.1	12.4	37.1	89.7	44.1	214.6
	ALINEA	25.9	13.3	36.1	65.6	85.7	16.3	242.9
	% Change	50%	-6%	191%	77%	-4%	-63%	13%
6	No-Control	25.9	16.6	13.3	39.7	108.3	54.8	258.6
	ALINEA	22.1	10.1	34.7	50.6	67.8	10.1	195.4
	% Change	-15%	-39%	161%	27%	-37%	-82%	-24%
7	No-Control	25.9	16.6	12.2	55.7	108.3	51.1	269.9
	ALINEA	25.9	13.3	42.4	69.2	80.0	15.1	245.9
	% Change	0%	-20%	246%	24%	-26%	-70%	-9%
8	No-Control	25.9	16.6	13.3	52.1	108.3	48.5	264.7
	ALINEA	22.8	8.7	41.3	65.6	78.3	16.3	233.0
	% Change	-12%	-48%	210%	26%	-28%	-66%	-12%
9	No-Control	22.1	14.6	12.1	30.4	92.2	49.1	220.4
	ALINEA	25.9	12.2	41.3	65.6	85.7	10.1	240.8
	% Change	17%	-16%	241%	116%	-7%	-79%	9%
10	No-Control	22.1	14.6	11.3	48.5	108.3	42.8	247.6
	ALINEA	25.9	14.4	42.4	65.6	91.3	16.3	255.9
	% Change	17%	-1%	274%	35%	-16%	-62%	3%
Average	No-Control (Std. dev.)[c]	23.0±2.2[d] (3.12)	15.4±0.9 (1.25)	12.5±0.9 (1.31)	43.8±6.3 (8.96)	100.0±7.4 (10.54)	50.5±5.0 (7.03)	245.2±14.3 (20.26)
	ALINEA (Std. dev.)	24.1±1.3 (1.89)	12.1±1.2 (1.75)	37.8±3.3 (4.62)	63.4±3.9 (5.46)	83.6±6.0 (8.48)	13.0±2.4 (3.39)	234.0±12.3 (17.51)
	% Change	**5%**	**-21%**[b]	**203%**[b]	**45%**[b]	**-16%**[b]	**-74%**[b]	**-5%**

[a] The percentage change in crash potential for the ALINEA ramp metering case compared to the no-control case.

[b] The change in crash potential is statistically significant at a 95% confidence level.

[c] The numbers in brackets denote the standard deviation of crash potential values over the 10 simulation runs.

[d] The average crash potential with the 95% confidence interval.

Table 2. Comparison of crash potential for Application 2: Hypothetical isolated on-ramp network

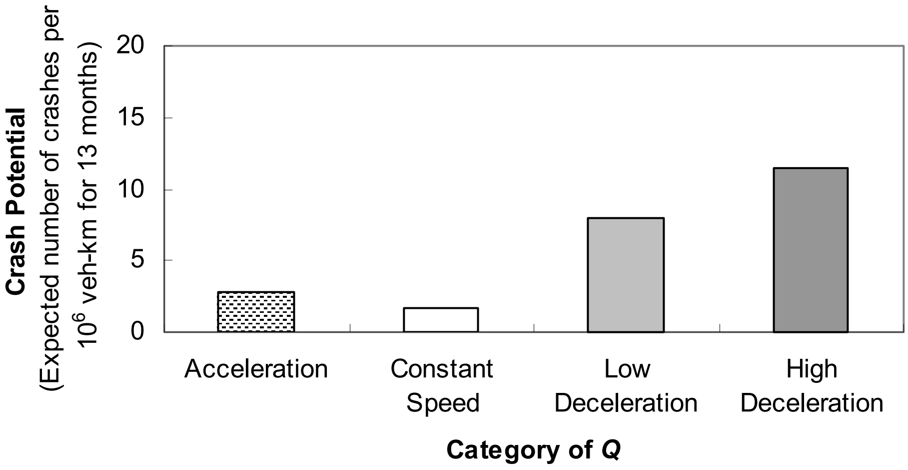
Runs	Strategy	Crash potential on each road section (← Direction of Traffic)					
		Section 5	Section 4	Section 3	Section 2	Section 1	Total
1	No-Control	14.4	20.6	14.4	24.2	69.2	142.9
	ALINEA	13.9	18.1	22.0	14.4	35.0	103.5
	% Change[a]	-4%	-12%	53%	-40%	-49%	-28%
2	No-Control	14.4	11.2	15.5	24.2	69.2	134.4
	ALINEA	14.4	37.3	16.0	16.6	29.8	114.0
	% Change	0%	234%	3%	-31%	-57%	-15%
3	No-Control	13.0	15.8	13.3	24.2	69.2	135.5
	ALINEA	14.4	13.5	14.4	19.1	28.8	90.2
	% Change	11%	-15%	8%	-21%	-58%	-33%
4	No-Control	15.5	12.2	21.7	25.9	69.2	144.5
	ALINEA	14.4	18.4	6.3	28.2	35.0	102.3
	% Change	-7%	50%	-71%	9%	-49%	-29%
5	No-Control	15.5	18.5	15.5	22.5	69.2	141.2
	ALINEA	12.2	29.6	5.2	9.8	26.2	83.1
	% Change	-21%	60%	-66%	-56%	-62%	-41%
6	No-Control	16.6	37.1	16.6	34.0	65.6	169.8
	ALINEA	13.3	14.3	6.4	17.9	22.6	74.5
	% Change	-20%	-62%	-61%	-47%	-66%	-56%
7	No-Control	12.9	31.0	16.6	40.4	69.2	170.0
	ALINEA	11.7	21.5	23.2	16.6	26.2	99.1
	% Change	-10%	-31%	40%	-59%	-62%	-42%
8	No-Control	15.5	18.5	13.3	22.5	69.2	139.0
	ALINEA	14.4	34.4	15.3	10.1	32.4	106.6
	% Change	-7%	86%	15%	-55%	-53%	-23%
9	No-Control	16.6	18.5	14.4	25.9	69.2	144.5
	ALINEA	9.5	6.6	14.2	19.6	28.8	78.7
	% Change	-42%	-64%	-2%	-24%	-58%	-46%
10	No-Control	14.4	19.6	16.6	30.6	69.2	150.3
	ALINEA	11.2	24.9	11.8	8.5	22.6	78.9
	% Change	-22%	27%	-29%	-72%	-67%	-48%
Average	No-Control	14.9±0.9[d]	20.3±5.6	15.8±1.7	27.4±4.1	68.8±0.8	147.2±9.0
	(Std. dev.)[c]	(1.28)	(8.00)	(2.43)	(5.81)	(1.14)	(12.81)
	ALINEA	12.9±1.2	21.9±6.8	13.5±4.4	16.1±4.1	28.7±3.2	93.1±9.7
	(Std. dev.)	(1.71)	(9.72)	(6.24)	(5.83)	(4.52)	(13.79)
	% Change	**-13%**[b]	**8%**	**-15%**	**-41%**[b]	**-58%**[b]	**-37%**[b]

[a] The percent change in crash potential for the ALINEA ramp metering case compared to the no-control case.

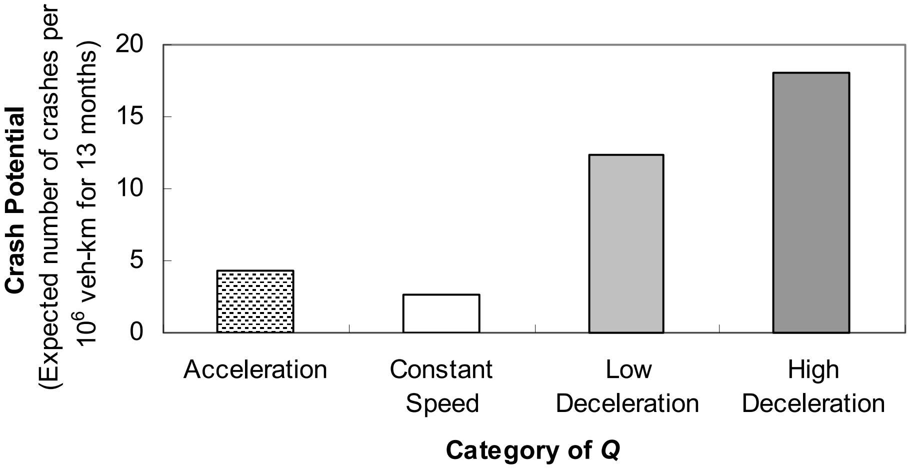
[b] The change in crash potential is statistically significant at a 95% confidence level.

[c] The numbers in brackets denote the standard deviation of crash potential values over the 10 simulation runs.

[d] The average crash potential with the 95% confidence interval.



(a) Straight road sections



(b) Merging/Diverging road sections

Figure 1. Comparison of crash potential at different categories of precursor *Q*

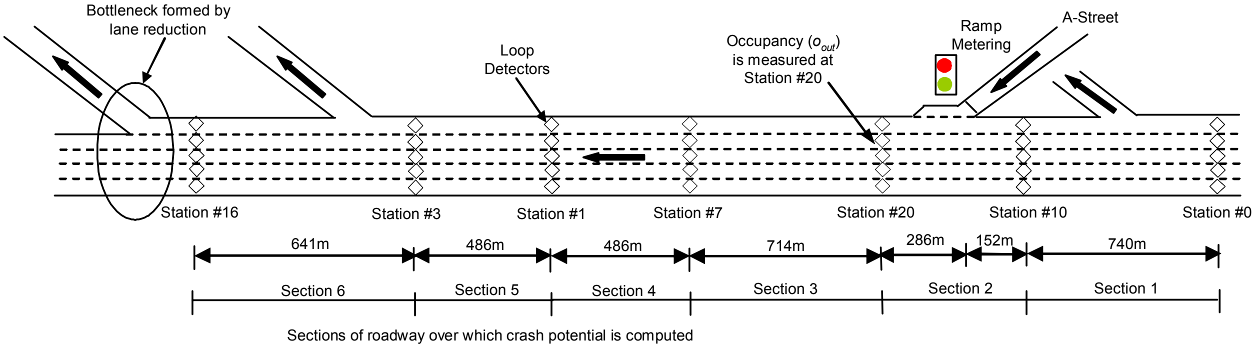


Figure 2. Schematic drawing of study section of I-880, Hayward, California

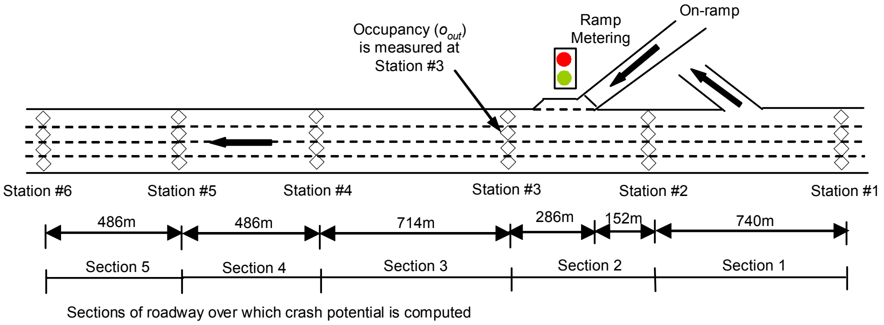
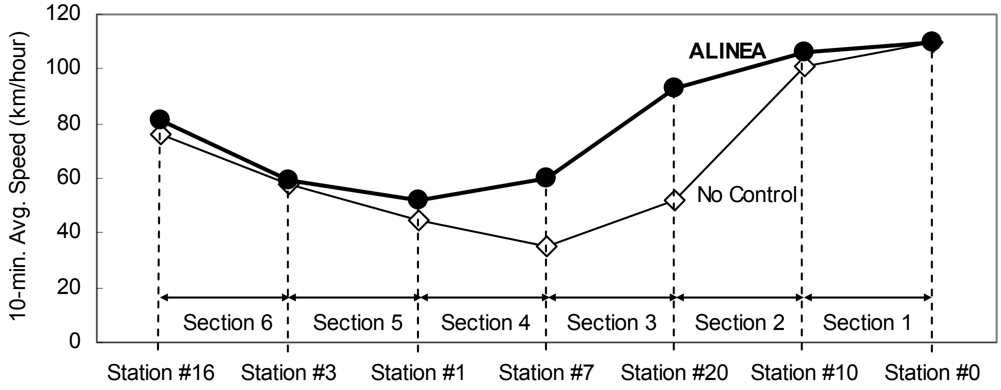
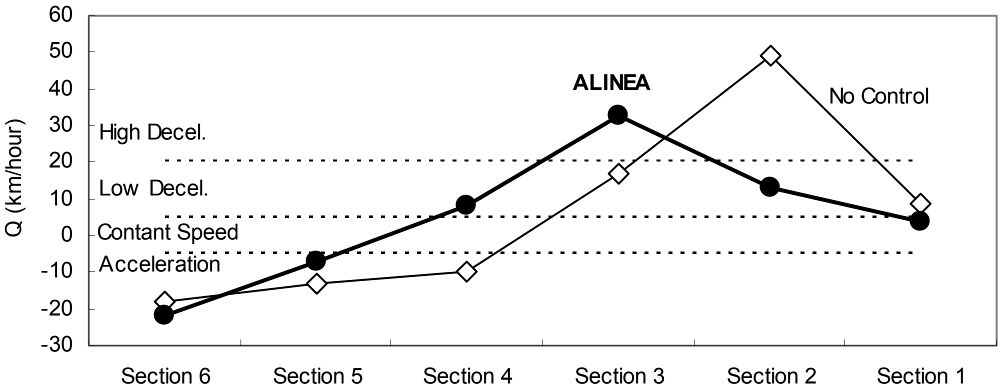


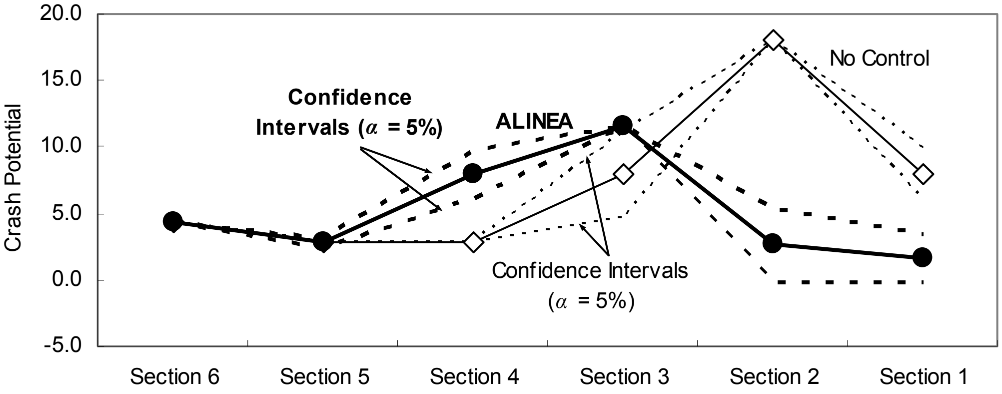
Figure 3. Schematic drawing of hypothetical isolated on-ramp network



(a) 10-minutes average speed (9:10 ~ 9:20 am)

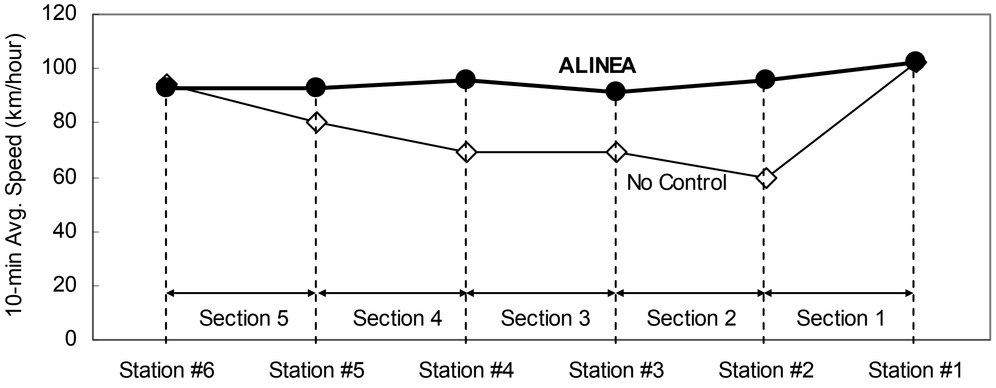


(b) Values and categories of precursor *Q* (9:10 ~ 9:20 am)

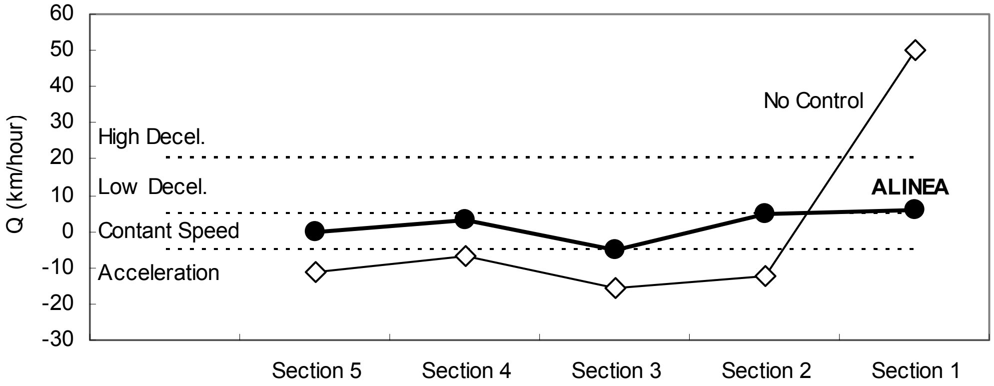


(c) Crash potential (9:10 ~ 9:20 am)

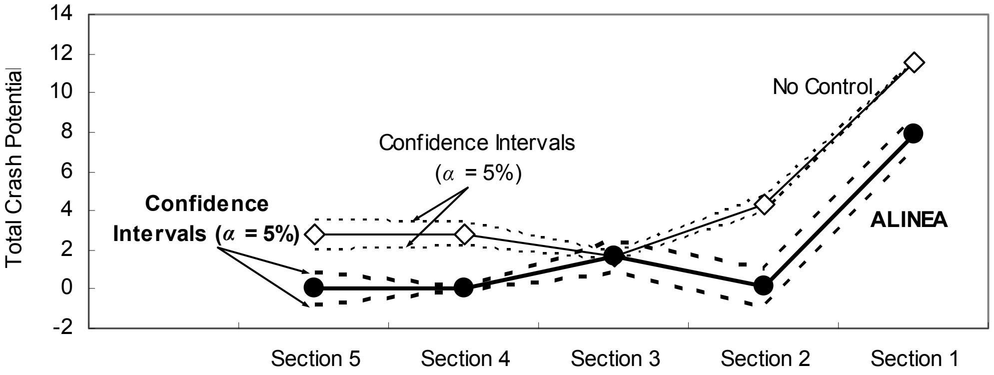
Figure 4. Effects of ramp metering control in Application 1: I-880



(a) 10-minutes average speed (9:10 ~ 9:20 am)



(b) Values and categories of precursor *Q* (9:10 ~ 9:20 am)



(c) Crash potential (9:10 ~ 9:20 am)

Figure 5. Effects of ramp metering control in Application 2: Hypothetical isolated on-ramp network