APPLICATION OF VARIABLE SPEED LIMITS AND RAMP METERING TO IMPROVE SAFETY AND EFFICIENCY OF FREEWAYS

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ABSTRACT
Research recently conducted at the University of Central Florida involving crashes on Interstate-4 (I-4) freeway in Orlando, Florida led to the creation of new statistical and neural networks models that are capable of determining rear-end and lane-change crash risks along the freeway in real-time. For determining the rear-end crash risk, it was found that rear-end crashes occur within one of two distinct traffic regimes: regime 1 (congested conditions) or regime 2 (uncongested conditions). The lane-change crash risk was mainly based on a single neural network model. Based on these models, the safety and travel time effects of two Intelligent Transportation Systems (ITS) strategies, ramp metering and variable speed limits (VSL), for reducing rear-end and lane-change crash risks along I-4, were evaluated. Using the PARAMICS micro-simulation package, a 36.25 miles of I-4 was simulated. For applying VSL, the idea of homogeneous speed zones was introduced to determine the distance over which VSL should be implemented from the station of interest. Two ramp metering strategies were tested on this simulated network, the uncoordinated ALINEA algorithm and the coordinated Zone algorithm. Two implementation methods of these algorithms were examined, the traffic-cycle (TC) realization and the one-car-per-cycle (OCPC) realization. Moreover, the potential of combining both ITS strategies (ramp metering and VSL) along the same simulated network was also tested. Two combination methods used, implementing ramp metering everywhere (through the whole network) in conjunction with VSL everywhere, as well as implementing ramp metering downtown (in downtown areas only) in conjunction with VSL everywhere.

It was concluded that VSL is an effective crash prevention strategy when the freeway is operating at uncongested conditions. At free-flow conditions (60 percent loading scenario) and conditions approaching congestion (80 percent loading scenario), VSL can be used to reduce crash risk and prevent crash occurrence, in addition to reducing travel time, especially at free-flow conditions. The highest decrease in travel time is found to be around 0.8%. Moreover, VSL was not found to effectively reduce crash risk at congested situations (90 percent loading scenario).

The study indicated that both ramp metering algorithms successfully reduce real-time crash risk along I-4. The traffic-cycle realization provides better safety and operational benefits when applied with the ALINEA algorithm. The ALINEA algorithm works best with shorter cycle lengths, while the Zone algorithm performs best with longer cycle lengths. The ALINEA algorithm proves to be superior to the Zone algorithm at reducing the crash risk as it is more restrictive. In spite of the fact that the ALINEA
algorithm provides better overall results, the Zone algorithm is much better in terms of the overall network travel time (measure of efficiency), where the Zone algorithm yielded smaller travel times than the ALINEA algorithm.

For examining the combination of both ITS strategies, applying ramp metering alone was more beneficial at congested situations, while applying VSL alone was more beneficial at free-flow conditions. At conditions approaching congestion, the combination of ramp metering and VSL produced the best benefits. These results illustrate the significant potential of ITS strategies to improve the safety and efficiency of urban freeways.

**Keywords:** Ramp Metering, ALINEA Algorithm, Zone Algorithm, Variable Speed Limits, VSL, Combining Ramp Metering and Variable Speed Limits, ITS

**INTRODUCTION**

Recently, at the University of Central Florida, research is conducted to examine crashes occurring on typical urban freeways such as the Interstate roadway system. This research uses statistical models that determine the crash risk along I-4. These models use data mining techniques to identify the crash potential along the freeway (1, 2, 3, 4). Two ITS strategies were tested on a simulated section of the freeway to determine the safety effect (in terms of real-time rear-end and lane-change crash risks) and efficiency effect (in terms of total travel time). These two ITS strategies include ramp metering and variable speed limits (VSL). In this study, the safety and efficiency effect of using VSL separately, ramp metering separately, as well as combining ramp metering and VSL strategies were simulated along a 36.25 miles of I-4 at three percent loading scenarios (60, 80 and 90 percent loadings) using the PARAMICS micro-simulation package. PARAMICS was chosen due to its demonstrated reliability on urban freeways and its use in previous research examining ramp metering and VSL strategies (5, 6, 7, 8).

When compared to previous studies, this study is unique in that it uses a wider network for implementing both ramp metering and variable speed limit strategies than other networks in previous research. So, it is expected that more accurate results can be obtained from this simulated network.

**RAMP METERING**

Ramp meters are traffic signals placed on the ramp to control when and how many vehicles can enter the freeway (9). Nowadays, ramp metering has become an increasingly well-known method of reducing congestion on freeways. The main objective of ramp metering is to reduce delay and maintain capacity flow on a freeway by regulating access of ramp traffic to the mainline (10).

Originally, the signals that controlled ramp metering were pre-timed signals that allowed vehicles into the freeway at a fixed rate (9). Now actuated signals are used that take into account conditions on the freeway when determining how much green time to be allotted to the meter.
RAMP METERING ALGORITHMS

ALINEA RAMP METERING ALGORITHM
The first ramp metering algorithm used in this study is the ALINEA algorithm, which is developed by Papageorgiou et al. (11). It is an uncoordinated (local) strategy that is based on the Proportional Integral (PI) feed-back control law. Local ramp metering takes into account traffic conditions only near the ramp that is being metered. This algorithm is also a feed-back algorithm that considers the previous metering rate when determining the current metering rate.

ZONE RAMP METERING ALGORITHM
The second ramp metering algorithm used in this study is the Zone algorithm. It is a coordinated strategy, and its main purpose is to balance the number of vehicles entering a freeway zone with the number of vehicles leaving. Coordinated ramp metering requires that the metering rate of a particular ramp to be based on traffic data from various locations within the freeway.

VARIABLE SPEED LIMITS
Variable speed limits are variable signs posted on the freeway. While somewhat different than a typical variable message signs (VMS) display, VSL still requires the same reaction by a road user. The user should clearly read, understand and react to the message. The main purpose of VSL is to reduce speed in some areas across the freeway to overcome rear-end and lane-change crash risks, and hence, to increase safety benefits.

VSL is used in microscopic simulation studies and have been implemented all over the world (12). There are so many reasons for using VSL. In terms of safety, VSL has sometimes been used during inclement weather to state a reduced safe speed limit for drivers (13). Speed limits can be reduced when visibility decreases, when heavy precipitation approaches and when high speed winds are present (14). VSL has also been used to increase safety in work zones (15).

VARIABLE SPEED LIMITS FACTORS

SPEED DIFFERENCE
The speed difference is defined as the difference between the 5-minute average speed at the station upstream and the 5-minute average speed at the station of interest (12). The equation for estimating the speed difference is described in Equation (1).

\[
\text{Speed Difference} (F) = \text{Average Speed}_E - \text{Average Speed}_F
\]

where:
“F” is the station of interest; and
“E” is the station upstream of the station of interest.

In this study, when the speed difference is greater than or equal to 7 mph, VSL is implemented. This is based on the study done by Cunningham (12). This was concluded because it was noted that there is an abrupt increase in the average rear-end crash risk after a speed difference of 7 mph. This 7 mph speed difference is shown to be the critical speed difference. This critical speed difference is the best point at which VSL should be implemented to overcome the sudden increase in crash risk. Thus, this cutoff speed
difference value (7 mph) was used to implement VSL strategy across the entire network alone, as well as in conjunction with ramp metering strategy.

**CONCEPT OF HOMOGENEOUS SPEED ZONES**
Due to the dynamic and stochastic characteristic of traffic flows, the dynamic VSL strategy was introduced. Thus, in order to apply a dynamic applicable distance for the VSL strategy, the concept of homogeneous speed zones was introduced (12). According to Cunningham (12), a homogeneous speed zone is the collection of similar, contiguous segments of highway into homogeneous groups, based on average speed, and distinguished from other homogeneous groups.

The process of defining homogeneous speed zones involves taking the difference of the 5-minute average speeds at each station of interest and the station just upstream of it. This measure - as previously indicated - is known as the speed difference. If the speed difference at a given station is less than the speed zone threshold, then the current station of interest is considered part of the same homogeneous speed zone as the station upstream of it. If the speed difference at the stations of interest is greater than or equal to the speed zone threshold, then the station of interest is the first station in a new speed zone.

**SPATIAL AND TEMPORAL EXTENT OF VSL IMPLEMENTATION**
The spatial extent over which VSL is applied is directly related to the length of the homogenous speed zone in which that speed limit falls (12). This is what is called the speed multiplier. This multiplier is a fraction of the speed zone or the entire speed zone. The spatial extent is considered dynamic because the homogeneous speed zones are redefined every 5 minutes in the simulation. Therefore, the spatial extent is dynamic both in its location and in its point in time.

The final important factor that was considered was the temporal extent of the VSL implementation. Most previous studies included fixed time periods of application such as: 2 min, 5 min, 10 min, 15 min and 30 min. In this study, 5, 10, 20 and 30 minutes were used to apply VSL on the simulated network. Lee et al. (10) found that the use of 5-min and 10-min time periods were the most effective. When the network requires the change of speed limits, speed limits will be changed to the target speed limit for the given time period and then returned to normal speed limits afterwards. However, if the network still requires VSL at the end of the time period, VSL can be immediately reapplied.

**STUDY AREA AND SIMULATION PERIOD**
The study area used in this research is a portion of the Interstate-4 freeway that runs through Orlando, Florida. I-4 generally runs in an east-west direction from Daytona Beach, Florida to Tampa, Florida, bisecting Orlando, Florida in its way. The specific area that was modeled for this study was the 36.25 mile stretch that runs through the downtown Orlando metropolitan area. This segment runs north-south through the heart of the downtown area starting at S.R. 192 in the southwest and ending just north of Lake Mary Blvd in the northeast. Throughout the downtown area, the freeway varies between 6 and 8 lanes with 12 ft lane width and a speed limit of 50 mph. The segment of the modeled freeway is fitted with dual inductance loop detectors at 0.5 mile intervals, giving measures of the speed, lane occupancy, and volume on each lane at 30 second intervals.
In this study, there were 63 stations (from station 4 to station 66). The spacing between each two successive stations is 0.5 mile.

In PARAMICS, each simulation run starts at 15:45, and ends at 19:00. So, each run simulates 3 hours of vehicular traffic flow on I-4 (the first 15 minutes is just a warm-up period). This 3-hour period represents the peak pm period on I-4, which is the best time to simulate the 90 percent loading scenarios. This is the worst time period on I-4, in which it suffers much congestion. This allows to capture the worst traffic behavior on I-4.

METHODOLOGY

SURROGATE MEASURES OF SAFETY

Traffic crashes are complex events that involve numerous human and environmental factors in addition to traffic and roadway conditions. For this reason, micro-simulation software cannot be directly used to measure crashes or traffic safety. Therefore, a surrogate measure should be used to measure traffic safety. A surrogate measure of safety is a measurable variable that has a known relationship with traffic crashes. Typical surrogate measures of safety include speed, speed variance, time to collision, and post encroachment time (16). There are some studies that developed statistical models to measure the risk of a crash on a roadway. One example are the models created by Abdel-Aty et al. (2) which describe the risk of a crash occurring on an urban freeway using logistic regression and real-time loop detector data. These models were created using loop data taken from the same study area (I-4) used in this study.

Other models used in this study are those newer models created by Pande and Abdel-Aty (3, 4) using neural networks. These models include factors to account for the location and geometry along the freeway and yield separate values for the rear-end and lane-change crash risk. These models have been published in peer-reviewed journals and have been proven to be a reasonable surrogate measure of crash risk. Using these models, a better picture of the crash risk across the length of the freeway corridor can be obtained. These models use the 30-second loop data that has been aggregated over 5-minute intervals in order to reduce the variation within the data. The real-time measures that are considered are average speed, coefficient of variation of speed (the standard deviation divided by the average), standard deviation of speed, average occupancy, standard deviation of occupancy, average volume, and standard deviation of volume all taken either at the station of interest or at locations up to 1 mile upstream or downstream of the station of interest. These values are all calculated for a time period of 5 to 10 minutes before the time of interest which means that if the models are implemented in real-time, they will become predictive and give the crash risk for a time period 5 to 10 minutes in the future. This will allow for the implementation of a crash prevention strategy in real-time to help reduce the crash risk before a crash occurs.

In the research by Pande and Abdel-Aty (4), rear-end crashes were determined to occur within one of two distinct traffic regimes: regime 1 (congestion conditions) or regime 2 (uncongested conditions). Separate models were created to determine the crash risk for each of the traffic regimes. For the lane-change crash risk (3), only a single neural network model is required. The main factors affecting the lane-change crash risk are the average speeds upstream and downstream of the station of interest as well as the difference in the lane occupancies across each individual lane on the freeway.
MEASURES OF EFFECTIVENESS
There are two measures of effectiveness (MOE) used in this study. These are safety and efficiency. The first and primary MOE is safety. Safety in this study is given in terms of two crash risk measures. The first measure is the rear-end crash risk, which is stated in terms of the Overall Rear-End Risk Change Index (ORERCI). The second measure is the lane-change crash risk, which is stated in terms of the Overall Lane-Change Risk Change Index (OLCRCI). So, it is required in this study to reduce the rear-end and the lane-change crash risks as much as possible to increase safety benefits across the simulated network. A plot of the average crash risk value vs. location is created for the base case (no ramp metering or VSL) and the test case. The area between the two rear-end crash risk curves represents the ORERCI, while the area between the lane-change crash risk curves is the OLRCRI. A negative value of the ORERCI (or OLRCRI) indicates that the overall change across the network is an increase in the crash risk, while a positive value shows a decrease in the crash risk (i.e., improved safety conditions).

The second MOE is efficiency. Efficiency is given in terms of the total travel time or the overall network travel time. It is to be noted that PARAMICS reports the overall travel time of the network in total vehicle-hours traveled (VHT) through the whole simulation period (3 hours). This value is calculated by summing the travel time of each vehicle over the entire network and over the whole simulation time. It is also required in this study to reduce the travel time through the network.

EXPERIMENTAL DESIGN
The experimental design described will mainly focus on that used for combining ramp metering with VSL. As for implementing ramp metering only and VSL only, the results will only be shown and discussed.

IMPLEMENTATION OF RAMP METERING EVERYWHERE AND VSL EVERYWHERE
As previously indicated, implementing ramp metering and VSL everywhere means implementing both of them in conjunction with each other over the entire network. The used experimental design for implementing VSL strategy over the entire network involves 4 different factors. The first factor is the speed change implementation, which is decreasing the speed limit by 5 mph upstream the station of interest, and increasing the speed limit by 5 mph downstream the station of interest. The second factor is the speed zone definition, and it involves two values, 2.5 and 5 mph. The third factor is the speed change distance, and it involves implementing the VSL strategy over half the distance of each speed zone (value of “0.5”), and also over the full distance of each speed zone (value of “1”). The last factor is the speed change time (the minimum time period over which VSL is applied), and it involves two values, 5 and 10 minutes.

The used experimental design for implementing ramp metering strategy over the entire network involves using the ALINEA algorithm in non downtown areas and the Zone algorithm in downtown areas. The ALINEA algorithm cycle length is 30 seconds, and the critical occupancy is 0.17, while the Zone algorithm cycle length is 60 seconds. This means that there 8 possible test cases, labeled from 1 to 8. These 8 test cases were implemented at the 60, 80 and 90 percent loadings.
IMPLEMENTATION OF RAMP METERING DOWNTOWN AND VSL EVERYWHERE
The experimental design used for implementing ramp metering downtown and VSL everywhere is very similar to that for implementing ramp metering everywhere. The only difference is using the Zone algorithm in downtown areas only, and the used cycle length is 60 seconds.

RESULTS FOR IMPLEMENTING VSL ONLY
In the free-flow condition (60% loading), the best treatment involved the more liberal threshold for homogeneous speed zones (5 mph) and the more liberal implementation distance (the entire speed zone) for a minimum time period of 10 minutes. Moreover, for the best treatment, positive results were observed when the downstream speed limits were increased and the upstream speed limits were decreased simultaneously by 5 mph. Travel time analysis was also performed for the best treatment, and it was found that it reduced the network travel time by 0.8%. It is worth mentioning that the best treatment was captured so that it has the highest cumulative positive ORERCI and OLCRCI values over the positively and negatively affected sections (12).

In conditions approaching congestion (80% loading), the best treatment involved the more liberal threshold for homogeneous speed zones (5 mph), yet the more conservative implementation distance (half the speed zone) and the minimum time period of 5 minutes. Moreover, for the best treatment, positive results were observed when the downstream speed limits were increased and the upstream speed limits were decreased simultaneously by 5 mph. This treatment was found to increase the network travel time by less than 0.4%, which is deemed acceptable for the beneficial trade-off with safety.

In the congested scenario, no treatment was found to have a positive ORERCI or OLCRCI in the rear-end and lane-change crash risk analysis, respectively. This is due to the nature of the traffic flow in the 90% loading scenario. In congested situations, the speeds of vehicles are mostly determined by the traffic conditions as opposed to the speed limit. Varying the speed limit, therefore, will not have the desired effect, since the vehicles are subject more to the congestion than to the speed limit. These findings concur with past studies on variable speed limits in congested situations, such as Abdel-Aty et al. (6).

RESULTS FOR IMPLEMENTING RAMP METERING ONLY
This study has shown that ramp metering can be applied to a congested freeway to successfully reduce both the rear-end and lane-change crash risk along the freeway in real-time. The general findings of this study are that both the Zone and ALINEA ramp metering algorithms are successful at reducing the real-time crash risk measures. The ALINEA ramp metering algorithm is more restrictive due to its localized nature and, therefore, tends to reduce the overall crash risk along the network more than the coordinated Zone algorithm. The best implementation method for the ramp metering algorithm has been found to be the traffic-cycle realization (TC) which allows vehicles to enter the freeway in platoons. This implementation method provides increased safety benefits over the one-car-per-cycle (OCPC) realization and also improved operation as the average network travel times are smaller when the traffic-cycle realization is applied. For the ALINEA algorithm, shorter cycle times are preferred since this allows one or two vehicles to enter the freeway at a time but at an increased frequency.
For the travel time analysis (efficiency MOE), it was found that the average network travel times for the Zone algorithm are smaller than those experienced when the ALINEA metering algorithm is used. The coordination of the Zone metering algorithm, which increases the metering rate at saturated ramps to compensate for reduced flows at other ramps, helps to decrease the average delay for all vehicles on the on-ramps. This, in turn, reduces the average travel time along the entire network. Similar travel time decreases have been concluded from other studies that used the Zone algorithm to improve traffic operations (17).

RESULTS FOR COMBINING RAMP METERING AND VSL

60 PERCENT LOADING

IMPLEMENTATION OF RAMP METERING EVERYWHERE AND VSL EVERYWHERE

After performing 10 runs for cases 1 to 8, it was found that stations 28 to 43 have the highest safety benefit for the rear-end crash risk (this was clear in the much lower average rear-end crash risk profile than the base case). A magnified look at the average rear-end crash risk profile vs. location for stations 28 to 43 is shown in Figure 1.

![Figure 1: Average Rear-End Crash Risk vs. Location (Stations 28 to 43) for Cases 1 to 8 (18)](image)

The best test case was captured so that it has the highest positive cumulative ORERCI or OLCRCI. The cumulative ORERCI (or OLCRCI) is calculated by summing up the average difference between the base case (no ramp metering or VSL) and each test case for all the number of runs, through the whole simulation period (3 hours) and through all the positively affected stations (those having safety benefit). The cumulative OLCRCI over the positively affected locations is shown in Table 1. It is to be noted that the 2 best cases are highlighted.

| Table 1: Cumulative OLCRCI for Cases 1 to 8 over the Positively Affected Locations (18) |
|-----------------|-----------------|-----------------|-----------------|-----------------|-----------------|-----------------|-----------------|-----------------|
|                 | Base            | Case 1          | Case 2          | Case 3          | Case 4          | Case 5          | Case 6          | Case 7          | Case 8          |
It is to be noted that the highest OLCRCI values are for cases 2 and 5, and thus, they were considered the 2 best cases. For the 3rd MOE, which is the efficiency (stated in terms of the total travel time), it was noted that both cases reduced the travel time. Case 2 significantly reduced the travel time by 0.42%, while case 5 insignificantly reduced the travel time by 0.22%. Thus, case 2 is deemed the best case out of the 8 cases that significantly reduced the crash risk (the lane-change crash risk) in some areas across the network as well as significantly decreased the total travel time. Case 2 involved using a homogeneous speed zone threshold of 2.5 mph, a speed change distance of half speed zone and a speed change time of 5 minutes in conjunction with a 60 seconds cycle length for the Zone algorithm, a critical occupancy of 0.17 and a 30 seconds cycle length for the ALINEA algorithm. Case 5 is similar to case 2, except for using a homogeneous speed zone threshold of 5 mph and a speed change time of 10 minutes.

Comparing these results with Cunningham (12) who only used the VSL strategy for the same network, it is found that implementing the VSL strategy only at the 60% loading is the best effective solution to reduce both crash risks (rear-end and lane-change) as well as to decrease the total travel time, as implementing VSL only yielded higher ORERCI and OLCRCI values.

IMPLEMENTATION OF RAMP METERING DOWNTOWN AND VSL EVERYWHERE
After performing 10 runs, the best case involved using a homogeneous speed zone threshold of 2.5 mph, a speed change distance of half speed zone and a speed change time of 10 minutes in conjunction with a 60 seconds cycle length for the Zone algorithm. Moreover, this best case significantly reduced the total travel time by 0.41%.

Comparing these results with Cunningham (12), it is found that implementing the VSL strategy only at the 60% loading is the best effective solution to reduce both crash risks (rear-end and lane-change) as well as to decrease the total travel time.

Thus, as a general result for the 60 percent loading, the best effective strategy to reduce both crash risks (rear-end and lane-change) as well as to decrease the total travel time is to implement the VSL strategy only.

80 PERCENT LOADING
For the 80% loading, adjustments were applied to some variables in the experimental design, as unfavorable results were obtained. These adjustments include changing the speed change implementation as well as changing the speed change time. After performing various trials, it was found that the best results were for implementing VSL strategy for 30 minutes.

IMPLEMENTATION OF RAMP METERING EVERYWHERE AND VSL EVERYWHERE
After performing 10 runs, the best case involved using a homogeneous speed zone threshold of 5 mph, a speed change distance of half speed zone and a speed change time of 30 minutes in conjunction with a 60 seconds cycle length for the Zone algorithm, a critical occupancy of 0.17 and a 30 seconds cycle length for the ALINEA algorithm. Moreover, this best case insignificantly increased travel time by 0.2%.

Comparing these results with Cunningham (12), it is found that implementing ramp metering strategy everywhere in conjunction with VSL strategy everywhere at the
80 percent loading yields better results and is more effective than implementing the VSL strategy only over the simulated network.

**IMPLEMENTATION OF RAMP METERING DOWNTOWN AND VSL EVERYWHERE**

After performing 10 runs, the best case involved using a homogeneous speed zone threshold of 5 mph, a speed change distance of half speed zone and a speed change time of 30 minutes in conjunction with a 60 seconds cycle length for the Zone algorithm. Moreover, this best case insignificantly increased the total travel time by a very small percentage (0.93%).

Comparing these results with Cunningham (12), it is found that implementing ramp metering strategy downtown in conjunction with VSL strategy everywhere at the 80 percent loading yields better results and is more effective than implementing the VSL strategy only over the simulated network.

Thus, as a general result for the 80 percent loading, implementing ramp metering strategy in conjunction with VSL strategy is the best effective solution to reduce both crash risks (rear-end and lane-change).

**INDEPTH INVESTIGATION**

Since it was recommended to use a combination of both ramp metering and VSL strategies for the 80 percent loading, an indepth investigation was performed to improve the plot of the average crash risk vs. time step, as it was noted that the plot of the average lane-change crash risk vs. time step had some successive fluctuations and variations, which is not favorable in terms of safety benefits. Successive fluctuations mean that there is a reduction in the crash risk, followed by an increase in the crash risk at two successive time steps. For this study, there were 36 time steps, and each time step represents 5 minutes of the whole 180-minute (3-hour) simulation period.

Thus, by thoroughly investigating the reason of this fluctuation, it was noted that this fluctuation in the crash risk vs. time step was attributed to applying VSL in consecutive zones. It is known in this study that VSL is implemented when the speed difference between any two consecutive stations along the entire network is greater than or equal to 7 mph. So, applying VSL at two consecutive zones along the whole network might deteriorate the VSL strategy, and thereby can cause these fluctuations in the plot of the average crash risk vs. time step. Thus, the concept of not implementing VSL strategy at any 2 consecutive zones was introduced, and much better results were gained.

**90 PERCENT LOADING**

For the 90% loading, it was found that there was safety benefit (for both the rear-end crash risk and the lane-change crash risk) in some areas across the network for implementing ramp metering everywhere in conjunction with VSL everywhere (cases 1 to 8) only, but for implementing ramp metering downtown in conjunction with VSL everywhere, there was no safety benefit at all through the entire network, and thus, this combination strategy was excluded. Once more, adjustments were introduced that include changing the speed change implementation as well as changing the speed change time. After performing various trials, it was found that the best results were for implementing VSL strategy for 20 minutes.
IMPLEMENTATION OF RAMP METERING EVERYWHERE AND VSL EVERYWHERE

After performing 10 runs, the best case involved using a homogeneous speed zone threshold of 2.5 mph, a speed change distance of the entire speed zone and a speed change time of 20 minutes in conjunction with a 60 seconds cycle length for the Zone algorithm, a critical occupancy of 0.17 and a 30 seconds cycle length for the ALINEA algorithm. Moreover, this best case significantly decreased the total travel time by 1.62%.

Comparing these results with Gayah (9), it is found that implementing ramp metering only everywhere (Zone algorithm in downtown areas, and ALINEA algorithm in non downtown areas) is more beneficial and more effective to the simulated network in terms of safety benefits than implementing ramp metering and VSL strategies in conjunction with each other, as implementing ramp metering only yielded higher ORERCI and OLCRCI values. It is to be noted that Cunningham (12) found that there is no safety benefit at all for implementing the VSL strategy at the 90 percent loading.

CONCLUSIONS

This study has examined the potential of applying VSL strategy only, applying ramp metering strategy only, as well as combining ramp metering and VSL strategies to be used as a real-time crash prevention technique. First, this study found that the implementation of VSL successfully reduces the rear-end and lane-change crash risks at low-volume traffic conditions (60% and 80% loading conditions). Moreover, no treatment was found to successfully reduce the rear-end and lane-change crash risks in the congested traffic condition (90% loading). These conclusions concur with Abdel-Aty et al. (6).

Secondly, this study has shown that ramp metering can be applied to a congested freeway to successfully reduce both the rear-end and lane-change crash risk along the freeway in real-time. The general findings of this study are that both the Zone and ALINEA ramp metering algorithms are successful at reducing the real-time crash risk measures. The ALINEA ramp metering algorithm tends to reduce the overall crash risk along the network more than the coordinated Zone algorithm. The best implementation method for the ramp metering algorithm has been found to be the traffic-cycle realization which allows vehicles to enter the freeway in platoons. This implementation method provides increased safety benefits over the one-car-per-cycle realization and also improved operation as the average network travel times are smaller when the traffic-cycle realization is applied. For the ALINEA algorithm, shorter cycle times are preferred. Moreover, the Zone algorithm is much better in terms of the overall network travel time (measure of efficiency), where the Zone algorithm yielded smaller travel times than the ALINEA algorithm.

Thirdly, for implementing ramp metering in conjunction with VSL for the 60 percent loading, it was concluded that implementing VSL strategy only was more beneficial to the network than either implementing ramp metering everywhere in conjunction with VSL everywhere or implementing ramp metering downtown in conjunction with VSL everywhere. However, either implementing ramp metering everywhere or downtown in conjunction with VSL everywhere showed safety benefits across the simulated network as well as a reduction in the total travel time.

For the 80 percent loading, it was concluded that either implementing ramp metering everywhere in conjunction with VSL everywhere or implementing ramp
metering downtown in conjunction with VSL everywhere was more beneficial to the network than implementing VSL strategy only. Also, both of them increased slightly the total travel time, but this was deemed acceptable. Moreover, the idea of not implementing VSL at consecutive zones (using either a gap of one zone or more) was introduced. This idea perfectly succeeded in removing these fluctuations and variations in the average crash risk which is a very useful outcome.

For the 90 percent loading, it was concluded that implementing ramp metering strategy only (Zone algorithm in downtown areas, and ALINEA algorithm in non downtown areas) was more beneficial to the network than implementing ramp metering everywhere in conjunction with VSL everywhere. Moreover, implementing ramp metering downtown in conjunction with VSL everywhere did not show any safety benefits across the simulated network.

REFERENCES


