Estimating the Effect of Freeway Ramp Metering on Safety

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ABSTRACT

This paper presents a method evaluating benefits of ramp metering strategies on freeway safety. Based on the traffic and the accident data collected on a 4.2 km (2.6 mile) section of Interstate highway 35-West in Minneapolis, U.S.A., the relationship between traffic variables and safety measures is investigated. An aggregate specification that could be used to predict accident frequencies on freeways is proposed as a multiple regression form. The specification includes 15 minutes volume and occupancy data, which are commonly available from surveillance and control systems. The primary variables that appear to affect the frequencies of freeway accident are: vehicle-miles of travel, entrance ramp volumes and the dynamic effect of queue building. A simulation method evaluating the dynamic effect of control strategies on safety is proposed next. The potential benefits of freeway ramp metering on freeway safety are finally investigated via a proposed method.

1. INTRODUCTION

Many urban freeways are characterized by non-homogeneous geometries which disturb traffic flow. An operational problem service in freeway system is caused by congestion which in turn is caused by geometric bottlenecks. Operational problems may lead drivers to making erratic maneuvers, and such maneuvers may results in accidents. These operational problems could be relieved by some kind of control over traffic with the objective of avoiding unnecessary congestion and improving freeway safety.

Freeway Traffic Management Systems (FTMS) seek to improve efficient management of traffic on freeways using traffic monitoring, communications, and freeway management systems. Among the available management tools in FTMS, ramp metering has proven to be most widely used form of traffic control. Ramp metering aims to maintain uninterrupted, non-congested flow on the freeway by regulating the number of vehicles entering the freeway. While ramp metering systems are designed to improve operation at the merge point to improve mainline speed and capacity, field experience has demonstrated a significant reduction in accident rate. Ramp metering systems reduce accidents primarily by limiting the conflict of traffic streams between mainline and entrance ramp. Further it reduces the rear-end collisions resulting from freeway congestion. Owing to the interrelationships between ramp metering action and traffic system response, a successful evaluation of the effect of ramp metering on freeway safety requires a safety prediction method which takes into account system responses such as changes in volume and lane occupancy. However, research to clarify the mechanism between ramp metering and safety is still inconclusive. Addressing this need, the major objective of this study is to propose a method evaluating the dynamic effect of ramp metering strategies on urban freeway safety.

This paper begins with a review of literature on highway safety evaluation. Then, based on data collected on a 4.2 km "high-hazard" section of Interstate 35W, the identification of the operational variables which affects on urban freeway safety is performed. An aggregate specification for accident prediction, incorporating operational variables (volume and lane occupancy) is proposed. Finally, the proposed simulation method is tested on a test section.

2. OPERATIONAL VARIABLES AFFECT ON FREEWAY SAFETY

2.1 Ramp Metering and Freeway Safety

Freeway traffic control addresses the problems of congestion and safety. As many literatures show, well designed and maintained ramp metering systems have proven to be an effective tool in reducing not only congestion but accident rates. According to Minnesota DOT accident rates on I-35W in Minneapolis before FTMS were 421 per year and are now 308 per year (a 27% reduction). A survey of traffic management centers in North America using ramp metering reported that accidents on freeway systems under freeway management are reduced between 15% and 50% (FHWA, 1995).

The question is, how ramp metering systems improve the safety of freeways? First, it can improve merging safety, particularly at entrance ramps with inadequate sight distances. The primary merging safety problem involves rear-end and lane-changing collisions caused by platoons of vehicles on the ramp competing for gaps in the freeway traffic stream. Metering breaks up these platoons and facilitates single-vehicle entry. Second, ramp metering can also reduce rear-end collisions at mainlines by maintaining uninterrupted, non-congested flow. Once the mainline traffic slows or stops to allow ramp vehicles to enter the freeway under high density conditions, shock-wave forms in the freeway flow and move upstream which can lead to rear-end accidents and major traffic congestion. These suggest that the dynamic operation of freeway traffic contribute to collisions. This claim can be supported by the study of Sullivan(1990) who showed that, in the presence of queuing, the average accident rate is about two to three times higher than in no-queuing situations.

2.2 Safety Model

Since the 1950s a large number of studies have been carried out on the relationships between highway geometric design elements, traffic characteristics, and road safety. Attempts to predict road safety from geometric and environmental factors led to the development of macro models that relate accident rates to such factors. Regression models for safety from geometric and environmental factors led to the development of macroscopic models that relate accident rates to such factors. Regression models for safety analysis can be divided into three categories; 1) accident rate vs. geometric factors, 2) accident frequency vs. traffic flow, and 3) accident frequency vs. volume and geometric factors.

The third category of research attempt to interpret the accident frequency as an additional information to the road geometry. Thomas and Gallon(1998) claimed that the geometric variables(hillness and bendness) by themselves have little direct influence on the occurrence of accidents. However, when combined with the traffic flow, they formed an integral part of a fairly strong relationship with accidents. Cedar(1982) introduced hourly volume as an independent variables in order to predict accident frequencies. However, hourly volume was too long to explain the effect of traffic operation variables on safety. Sullivan(1990) quantified relationships between accident frequency and congestion on a California urban freeway assuming that the principal effect of urban freeway congestion on accidents takes place at the entry point of queues, where accidents occur because drivers cannot decelerate quickly enough or because of lane-changing. The data showed that in the presence of queuing, the average accident rate is about two to three times higher than in no-queuing situations. Despite extensive research in freeway safety analysis, the relationships between traffic operation variables and urban freeway safety have not comprehensively been identified. Nor has the interaction of these variables been sufficiently explored.

3. EFFECT OF TRAFFIC OPERATION VARIABLES ON FREEWAY SAFETY

3.1 Data

This study concentrates on a 4.2-km(2.6-mile) segment of Interstate I-35W from 46-st to 61-st in Minneapolis, Minnesota, U.S.A.. This segment includes on interchange "commons" area with state highway 62. Figure 1 show the schematic diagram of study section along with detector stations. This specific section of I-35W was chosen since it is heavily traveled, has a high accident frequency, and has a variety of geometry. Accident data for 1991 and 1992 were obtained from the Minnesota Department of Transportation (Mn/DOT), along with five minute volume and lane occupancy data. In the two-year period, 258 accidents were recorded on the selected 4.2-km segment.

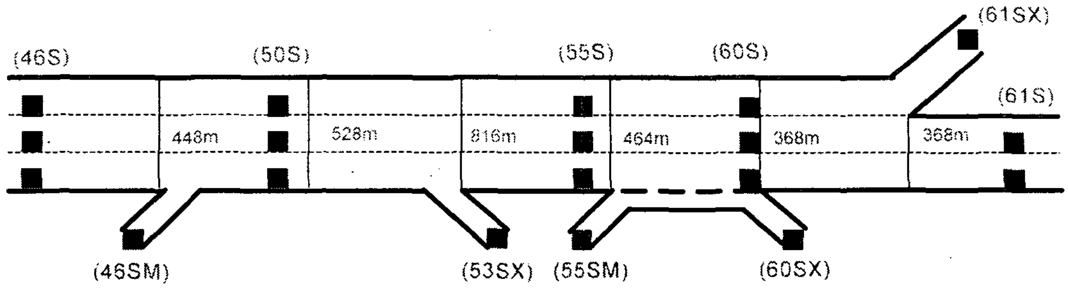


Figure 1. Geometries of Study Section (I-35W, Southbound, Minneapolis)

Figure 2 shows the distribution of accident rate per million vehicle miles by one-tenth of a mile increments through the study section. The most pronounced accident pattern is through mile point 12.2-11.7 (the direction of traffic flow is from mile point 14, downstream of detector station 61S, to mile point 10, upstream of detector station 46S depicted in Figure 1). This is a congested section with a great deal of weaving traffic just upstream from where the freeway splits into two sections. The left side of the split leads to eastbound Highway 62, while the right side of the split leads to westbound Highway 62 and the continuation of I-35W southbound. The left side of the split is a low speed curve continuing into a "commons" shared by Highway 62 and I-35W. In addition, the section is also the culmination of lane drops squeezing traffic from three lanes into two lanes. The complex operation of this sections resulted an extreme spike in the number of accidents for this section of road (see in Figure 2).

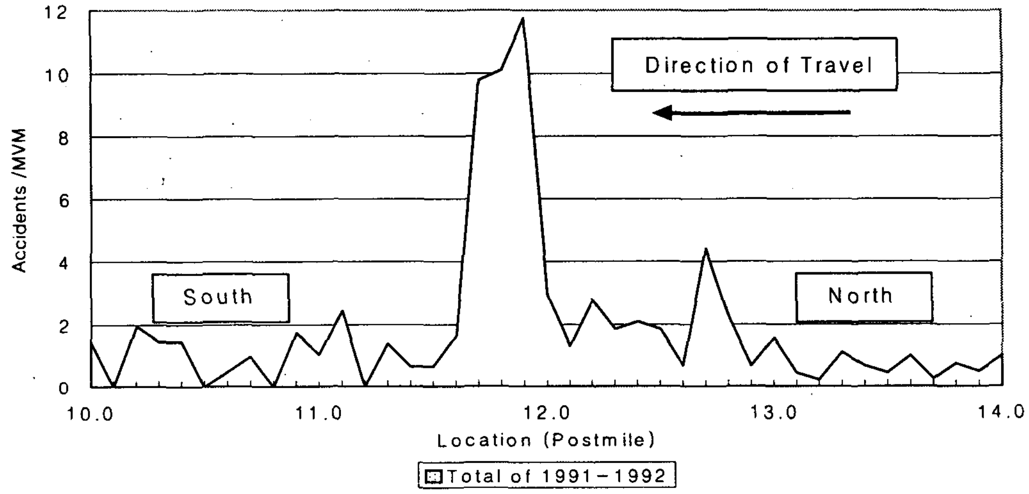


Figure 2. Accident Rate Distribution (I-35W Southbound: 10-14 Mile Point)

The time distribution of accident rates, normalized by vehicle-miles, along with the average volume and lane occupancy of five detectors in the corresponding section is shown in Figure 3. The rates of accidents increase markedly during both the AM and PM peak periods. The AM pattern is shorter in duration, which is closely related with the volume and lane occupancy distributions, but higher in accident rate. It should be noted that the volume distribution is closely correlated with the lane occupancy distribution. An examination of Figure 3 shows an interesting pattern emerging. Accident rates are higher when lane occupancy is higher. This seems reasonable because headway is shorter at higher occupancies. It should be noted that accident rates are rather stable when traffic conditions are stable (9-12 a.m. and 5-6 p.m.). Another interesting point is that accident rates are highest when lane occupancy is increasing (queue building). This indicates that the chance of accident is higher when queues are building. As it turns out the accident rate on a congested freeway is about twice the rate on a freeway with freely flowing traffic (Sullivan, 1990). This suggests that incorporation of congestion related variables may improve the accuracy of safety prediction on freeways.

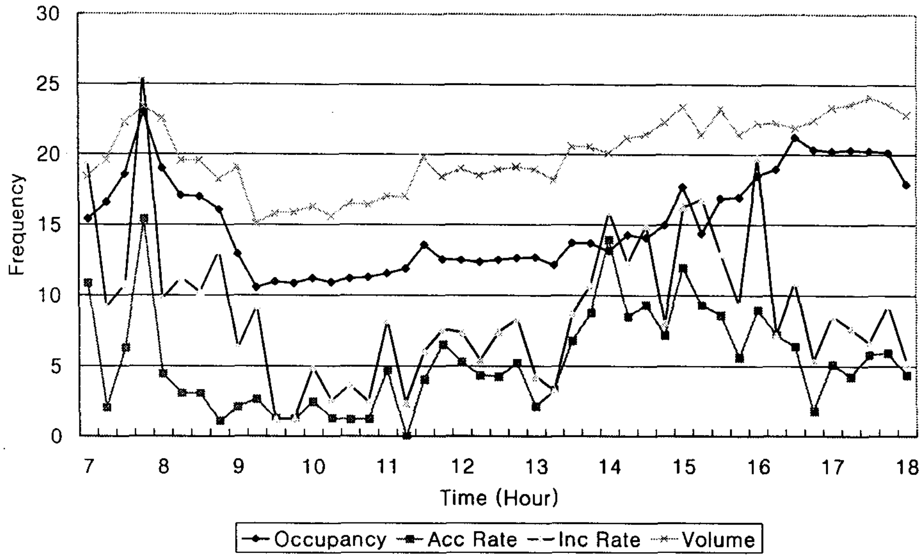


Figure 3. Simulated Flow Distribution (Non-Control vs. Ramp-Control)

3.2 Variables Affecting on Freeway Safety

The object of this section is to identify independent variables that significantly affect the level of freeway safety, as expressed by the number of accidents. The highway, traffic, and accident data for the study section were used to select the variables that show correlation with accidents. The definition of the initially selected variables are summarized as follows:

ACC: Accident frequency for 15 minutes during 2 years
MNVM: Mainline Vehicle-Miles
ONV: Total entrance ramp Volume
OFFV: Total Exit Volume
MNVO: $\sum_N$[$MNVM_t$*$Occupancy_t$]
ONVO: $\sum_N$[On-Ramp $Volume_t$*Mainline $Occupancy_t$]
OFFVO: $\sum_N$[Off-Ramp $Volume_t$*Mainline $Occupancy_t$]
MNVODF: $\sum_N$[Mainline $Volume_t$*(OCC_t-OCC_{t-1})], if OCC_t>OCC_{t-1}; zero, otherwise

Note:
1) N= Number of Detectors = 5 (46S, 50S, 55S, 60S, 61S)
2) t = time interval (15 minute)

The variables MNVO, ONVO, OFFVO were created in order to give weight to shorter headways. The variable MNVODIF was created to include the queue building effect. The first step of this analysis between safety measures and the independent variables led to the construction of the correlation matrix, where correlations between the safety measures and the interaction variables MNVO, OFFV, ONVODIF are evident. There also were some collinearity among some independent variables.

4. EVALUATION OF RAMP METERING ON FREEWAY SAFETY

4.1 Suggested Procedures

Step 1: collect accident and traffic operation data;

Step 2: formulation of accident prediction model using operation variables as independent variables;

Step 3: simulate the test site with/without ramp metering strategies(*** using the Control Emulation Program(CEP)***). This step produces the prediction of operational variables

Step 4: prediction of safety measures using the prediction model from Step 2.

4.2 Proposed Accident Prediction Model

A fundamental assumption that influenced both the data preparation and data analysis was that the frequency of accident is influenced by an exposure (vehicle-miles), by disturbances (on-/off- ramp volumes) and by the dynamic effects of queue building. To incorporate the effect of operational variables, the accident data was summarized over 15 minute interval. Therefore, a total of 46 observations (a period from 6:30 a.m. to 6:00 p.m. yields the 46 intervals of 15 minutes) was available for the regression analysis. An aggregate specification was developed in multivariate regression form to predict the level of safety for a freeway section, as reflected by its traffic flow and disturbances. The general forms of the models explored here was:

ACC = f [MNVM, ONV, OFFV, OCCU, ODIF]

4.3 Estimated Coefficients and Analysis

The preferred regression model specifications are as follows:

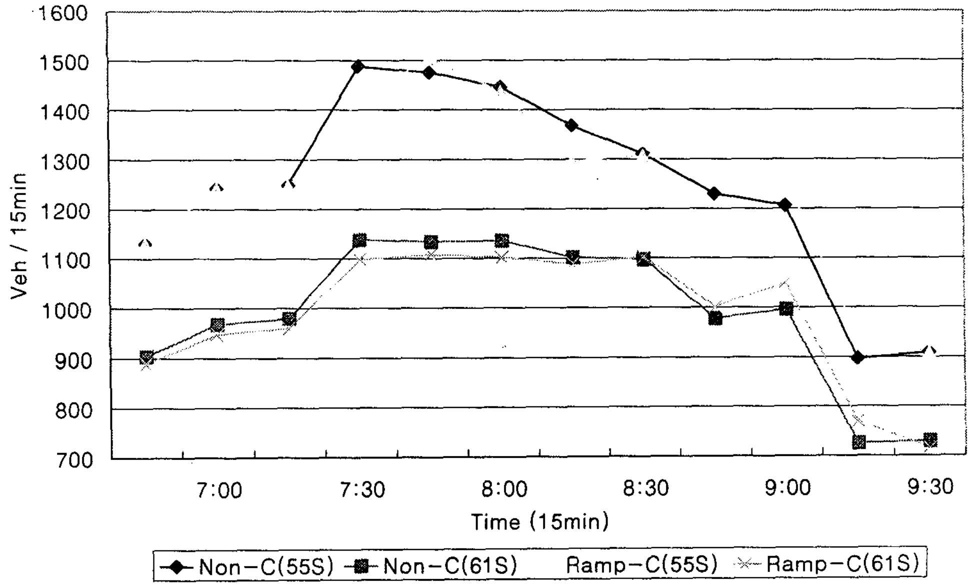
ACC-1 = -10.35 + .00026MNODIF + .035ONV + .037OFFV ($R^2 = 0.42$)
ACC-2 = -14.99 + .00054MNVM + .00015ONV + .023OFFV ($R^2 = 0.46$)

These models have logical signs for their coefficients and marginally significant t-statistics.
The previously stated hypothesis about the expected positive influence of mainline vehicle-miles is reflected by the parameters associated with variables MNVM. Another contributing factor was the entrance-ramp volume (ONV). When a vehicle merges onto the freeway, it creates a disturbance in mainline flow. As a result, adjacent mainline vehicles may adjust their speed or change lanes, giving rise to a merging disturbance. If these actions are not properly executed, the disturbance may lead to accident. Also, the hypothesis that the positive influence of congestion (queue-building), which is a control-related variable, on safety measures was entertained with variable MNODIF. Since off-ramp volume OFFV is highly correlated with MNVM and MNVO, the calibration of a model incorporating mainline, on-ramp, exit-ramp related variables were not possible.

4.4 Simulation Study

Once a safety prediction model was formulated, the effect of ramp metering strategies on freeway safety was evaluated. An efficient and cost-effective simulation is an essential element tool for evaluating with/without ramp metering. In this study the Control Emulation Program (CEP) developed at the University of Minnesota(Stephanedes et al., 1994) was used for this purpose. In Minneapolis, metering rates at a ramp are determined from volume data from a mainline station upstream and occupancy data from five mainline stations downstream of the controlled ramp. This program emulates real-time ramp metering systems currently operating at the Minnesota Department of Transportation.

A 4.2-km section, includes 2 on-ramps and 3 off-ramps, of the I-35W freeway south of Minneapolis was simulated using CEP. Three-hour simulation runs with and without ramp metering were performed. To create congestion, 70 % higher on-ramp demands were assumed. It was further assumed that enough room is supplied at the entrance ramp for the waiting vehicles. Figure 4 displays the simulation results of 15 minutes average volume at



detector station 55S and 61S with and without control strategies.
Figure 4. Simulated Flow Distribution (NON-control vs. Ramp-Control)

Figure 4 displays the simulation results of 15 minutes average lane occupancy with and without control strategies. It is clear that a homogeneity of traffic is achieved with control. A consequence of the control is that it reduces number of accidents (Figure 4) while reducing congestion.

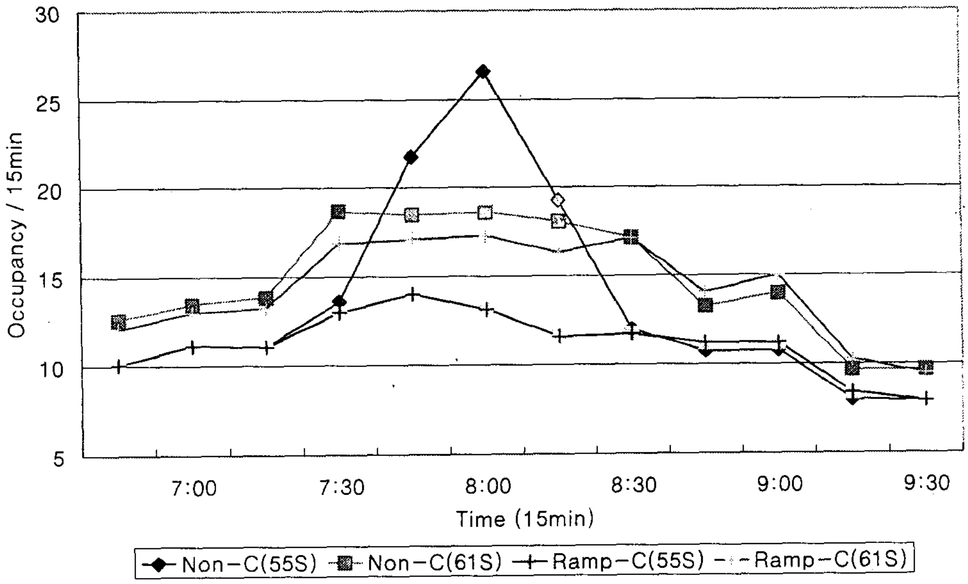


Figure 5. Simulated Occupancy Distribution (Non-Control vs. Ramp-Control)

Figure 6 shows the distribution of the predicted accident frequencies for every 15 minutes, with/without ramp metering. The total predicted accident frequency for 2 years during morning peak period (6:30 - 9:30 a.m.) is 281 without control and 229 with control. Prediction of accidents using Model ACC-1 resulted in even higher safety improvements due to control.

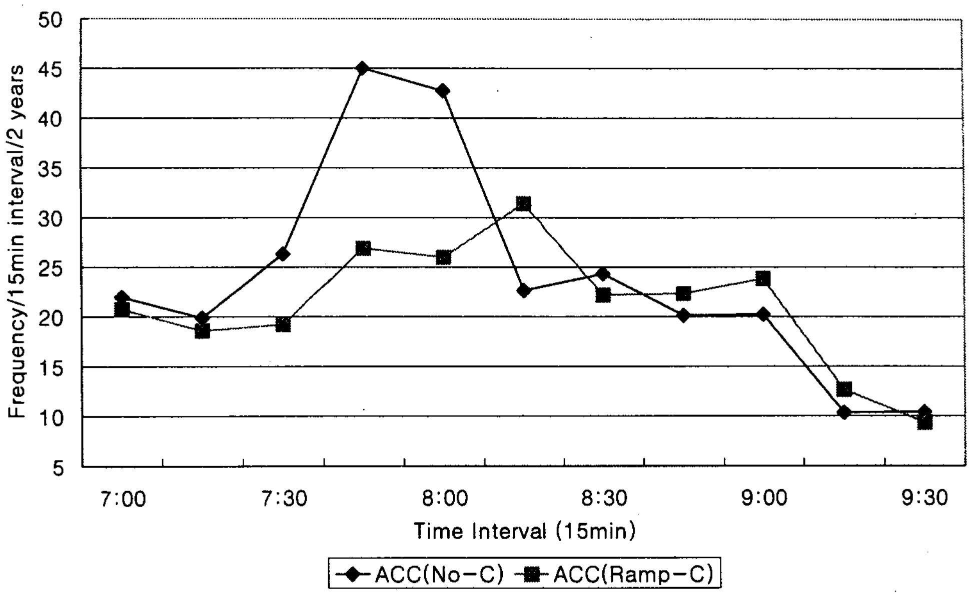


Figure 6. Predicted Accident and Incident Distribution (Non-Control vs. Ramp-Control)

5. CONCLUSIONS

The objective of this study was to investigate the potential benefit of ramp metering on freeway safety. This study was first concerned with the identification of the operational variables causing accidents on a "high-hazard" urban freeway section in the Minneapolis area. The accident rate on a freeway with congestion was far higher than the rate on a freeway with freely flowing traffic. Safety declined as mainline queue formed.
Next, a freeway safety prediction model was developed. The inclusion of demand and operational variables allowed the use of a model for the evaluation of freeway traffic control strategies.

Finally, potential benefits of control strategies for freeway safety were investigated via a simulation study. It was concluded that an improvement of freeway safety is achievable by control strategies which stabilizes traffic conditions around reference values. Alternative ATMS strategies, such as variable speed signal control or route guidance, could improve freeway safety more dramatically, since those control strategies have a significant positive effect on the stability of the traffic system.

ACKNOWLEDGEMENTS

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