Evaluation of Freeway-Merging Safety as Influenced by Ramp-Metering Control

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The traffic-conflict technique was modified to evaluate the relative safety of freeway merging with and without the use of entrance ramp-metering control. Six types of traffic conflicts were defined for the entrance ramp and acceleration lane: braking on ramp, braking for lead vehicle, weaving around lead vehicle, entering second lane, entering side by side, and entering late. Five conflicts were specified for the freeway lane (merge lane) adjacent to the acceleration lane: weaving around entering vehicle, braking for entering vehicle, weaving around lead and entering vehicles, braking for lead and entering vehicles, and avoiding encroaching vehicle. A three-level severity rating (routine, moderate, and serious) was also developed to assess the seriousness of each conflict. An existing ramp-metering control installation was investigated during freeway levels of service C and D. A two-way analysis of variance was performed on the traffic-conflict data by using, as the independent variables, ramp-control condition (on and off) and freeway level of service (C and D). The study revealed a significant reduction of 11.6 percent in all traffic conflicts when ramp control was activated. Analysis results indicate that acceleration-lane conflicts significantly decreased when ramp-metering control was used. Merge-lane conflicts were found to be related more to freeway level of service than to ramp control. However, merge-lane, multiple-vehicle conflicts and their severity decreased when ramp control was in effect. An analysis of accident records supported these conclusions.

The use of ramp-metering control has been shown to reduce both freeway congestion and accidents (1). Most of these control-system evaluations concerned the benefits obtained for the entire affected freeway section and especially the relationship between the operational safety of freeway merging and the effect of ramp metering. To measure safety, previous studies generally relied on accident records that can require a considerable length of time to accumulate. To quickly capture the localized safety effects of ramp-metering control, a measure is needed that reflects the relative safety of driver behavior during the merging maneuver.

The following study was designed to evaluate freeway-merging safety as influenced by ramp-metering control. A modified traffic-conflict technique (TCT) was developed for the rapid assessment of the safety contribution of metering, separate from the broader aim of reducing congestion. This technique was used to appraise merging safety with and without the use of control at an existing metered entrance ramp.

FREEWAY-MERGING TCT

The TCT involves the systematic surveillance and recording of defined driver behavior at a highway location. The traffic-conflict data are collected by a team that is either observing at the site or viewing the visual recordings.

The TCT employed in this study is a combination of the methods developed at the U.K. Transport and Road Research Laboratory (2, 3) and by Perkins and Harris (4). The U.K. procedure defines a traffic conflict as a situation in which a driver takes evasive action to avoid a collision. Each conflict is ranked according to a five-point severity scale that ranges from a precautionary maneuver to "emergency action followed by a collision" (2). The technique developed by Perkins and Harris defined certain driver behaviors to be traffic conflicts for over 20 intersection-accident patterns (4).

For the freeway-merging application, 11 traffic conflicts were identified based on freeway-accident patterns. These conflicts were divided into acceleration-lane conflicts that occur on the freeway-entrance ramp and the connecting acceleration lane and merge-lane conflicts that occur on the mainline freeway lane adjacent to the entrance ramp. The conflicts were then classified by severity. The six acceleration-lane conflicts are defined below.

1. Braking on ramp occurs when the speed of a single merging vehicle must be reduced on the acceleration lane because no acceptable gap appears in the freeway traffic stream (Figure 1). A brake light signals this situation. A slowing vehicle is a routine conflict, but a stopped vehicle is a moderate conflict.
2. Braking for lead vehicle occurs when the lead vehicle in a platoon of vehicles entering the freeway causes any of the following vehicles to be braked or stopped (Figure 2). A brake light indicates this situation. A stopped vehicle is a moderate conflict.
3. Weaving around lead vehicle occurs when a following vehicle is merged into the mainstream flow ahead of a lead vehicle (Figure 3). The degree to which the lead vehicle is affected by the following vehicle determines the severity of the conflict.
4. Entering second lane occurs when a merging vehicle enters the freeway and crosses immediately to lane 2 or the center lane of the mainline (Figure 4). The severity of this maneuver is determined by its smoothness, speed, and angle of entry. A high-angle, fast, fishtail entrance is considered more dangerous than a small-angle, controlled merge.
5. Entering side by side occurs when two entering vehicles arrive at the acceleration lane at the same time and are positioned side by side (Figure 5). The danger created by these vehicles as drivers accommodate each other's movements determines severity.
6. Entering late occurs when an entering vehicle reaches the end of the acceleration lane and traverses the shoulder before merging (Figure 6). Severity can be judged by the driver's control during the maneuver and by the nearness of collision between the entering vehicle and any mainline freeway vehicles.

The five merge-lane conflicts are defined as follows:

1. Weaving around entering vehicle occurs when a mainline vehicle in the merge lane must change lanes to avoid a merging vehicle (Figure 7). The severity of this conflict is assessed by the smoothness of the maneuver and the danger of collision between the mainline and entering vehicles.
2. Braking for entering vehicle occurs when a mainline vehicle must reduce its speed because of an entering vehicle (Figure 8). The conflict is signaled by a brake light. A conflict in which a freeway vehicle slows quickly and comes close to the entering vehicle is ranked more severely than a conflict in which a freeway vehicle slows only

slightly and does not come near the merging vehicle.

3. Weaving around lead and entering vehicles occurs when a mainline vehicle slows for an entering vehicle and causes a following mainline vehicle to change lanes (Figure 9). The lead mainline vehicle need not be involved for this type of conflict to occur, but the presence of an entering vehicle is required. Severity is determined by the smoothness of the lane-changing maneuver and the chance of contact between the mainline lead and following vehicles.

4. Braking for lead and entering vehicles occurs when a mainline vehicle is braked for an entering vehicle and causes the following mainline vehicle to slow (Figure 10). A brake light indicates this situation. The lead vehicle need not be involved in this conflict. Severity is based on the degree of braking of the following vehicle and the danger of collision between the two mainline vehicles.

5. Avoiding encroaching vehicles occurs when a mainline vehicle moves into the adjacent lane to avoid an entering vehicle but does not change lanes (Figure 11). Severity is determined by the degree of swerving involved during the maneuver.

Each conflict is also classified according to the three-point severity scale given below.

1. A routine conflict involves precautionary braking or lane changing when the risk of collision is small. For example, a freeway driver might feel threatened by a merging vehicle and change speed or position although the chance of contact is slight.

2. A moderate conflict involves controlled braking or lane changing to avoid a situation with high collision potential. This maneuver clearly requires controlled evasive action.

3. A serious conflict involves rapid deceleration, swerving to change lanes, or stopping to avoid a collision. The driver has no time for a controlled maneuver. Often termed "a very near miss," this maneuver involves fish tailing and causes forward lurching of a vehicle being quickly stopped. This conflict is similar to the one used by the Washington Department of Highways for intersection-conflict counts (5).

The traffic-conflict data were obtained in time intervals of 5 min to be consistent with the calculation method for determining freeway peak-hour factors. Additional information concerning ramp and freeway volumes and environmental conditions was collected during the course of the study.

Figure 1. Braking-on-ramp conflict.

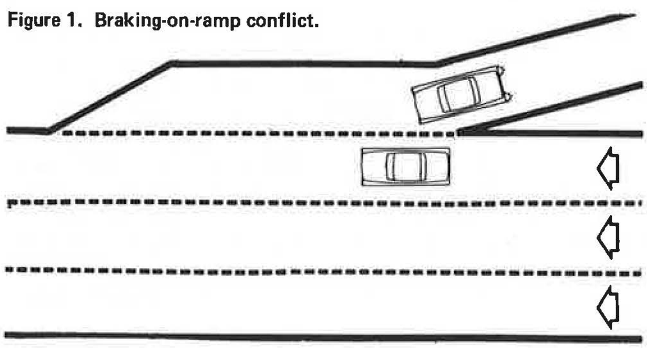


Figure 2. Braking-for-lead-vehicle conflict.

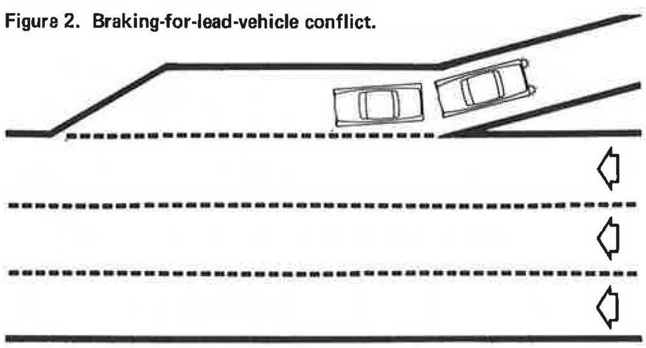


Figure 3. Weaving-around-lead-vehicle conflict.

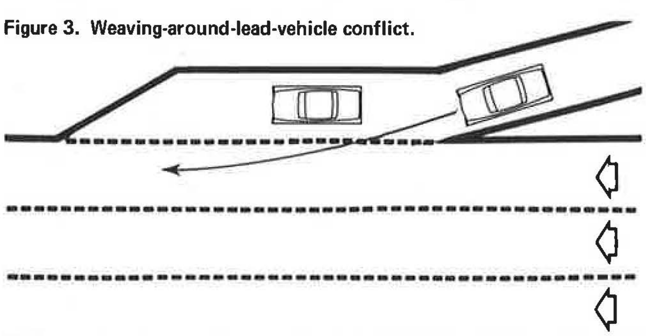


Figure 4. Entering-second-lane conflict.

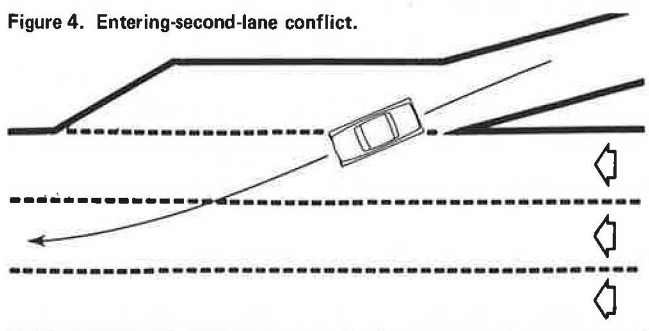


Figure 5. Entering-side-by-side conflict.

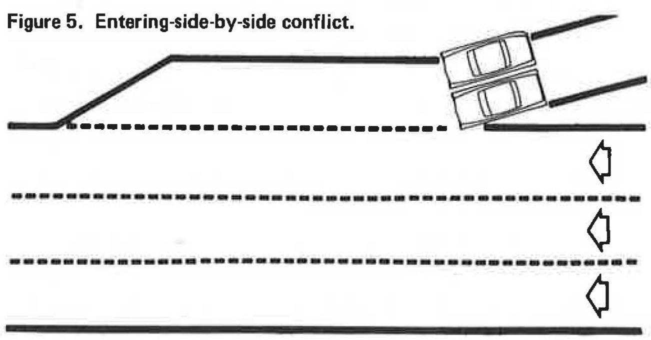
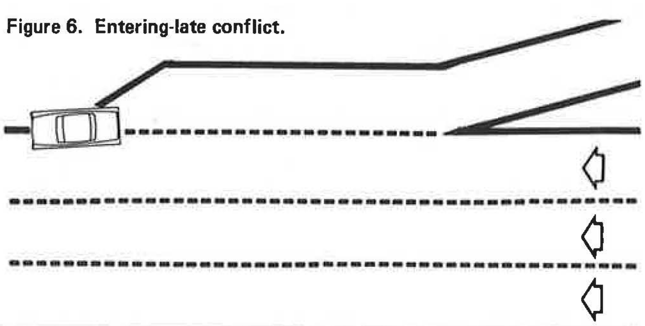


Figure 6. Entering-late conflict.



STUDY DESIGN

The goal of traffic-control devices is to modify driver performance and thus promote the efficient and safe flow of traffic. Focusing on the safety aspect of traffic-control devices, the engineer seeks to direct the behavior of the driver to reduce driving hazards. The control devices guide, warn, and regulate traffic movements. Assuming traffic conflicts reflect the safety of a highway site, we measure driver behavior to obtain an objective measurement of roadway safety. Evaluating the effects of controlled stimuli on human behavior is a major concern within the field of psychology, which has provided a study design for evaluating the safety effects of ramp-metering control.

The purpose of a psychological experiment is to investigate the relationship between the stimulus, in this case ramp-metering control, and the target behavior, i.e., traffic conflicts. The reversal design provides an appropriate way to explore this relationship.

In this study design, the number of occurrences of target behaviors under original environmental conditions is determined. Then the stimulus is introduced into the environment, and again the target behavior occurrences are counted. A change may be evident at this point, but the cause of the change is unclear. The next step is to remove the stimulus and survey the behaviors. The reversal design receives its name from this step. The environment is reversed to the state in which the stimulus was absent. Finally, the stimulus is reintroduced and the result is recorded. Evidence that the stimulus is responsible for the change is provided if the occurrence of target behaviors in the stimulus phase changes relative to the occurrence under the original conditions, returns to the occurrence under the original conditions when the stimulus is removed, and again changes in the final stimulus phase (6).

For this study, users of the selected entrance ramp were first presented with the metering signal operating in a one-vehicle-at-a-time mode (ramp control on), because this was the existing condition. No data were collected on days when the road was wet. Under this control condition, data were collected for 5 dry, nonholiday weekdays (period 1). On the following weekday, the metering signal was set to present a constant green indication (ramp control off). These signals rest in this state whenever control is not applied. Again, data were collected for 5 dry, nonholiday weekdays (period 2). At this point, control was turned on again, and data were collected for 3 d (period 3). Finally, control was turned off, and data were collected for 3 d (period 4). Thus, data were collected for 8 d under each control condition.

STUDY SITE

The metering installation selected for study is located at the Wilson Avenue entrance ramp to northbound Interstate 94. The site is just north of the junction between Ill-194 and I-94. The interchange, a half-diamond design typical of urban areas, joins the three-lane freeway on a level segment at the end of a 3°curve. The acceleration-lane taper is 198 m (650 ft) from the ramp nose, which yields a usable length of approximately 183 m (600 ft). The ramp-metering signal is 91 m (300 ft) from the ramp nose.

Data were collected between 3:30 and 5:30 p.m. just

Figure 7. Weaving-around-entering-vehicle conflict.

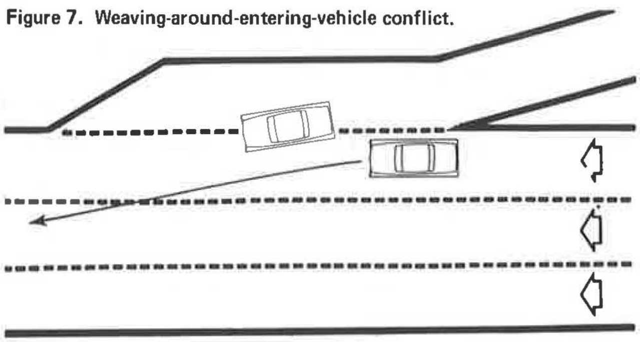


Figure 8. Braking-for-entering-vehicle conflict.

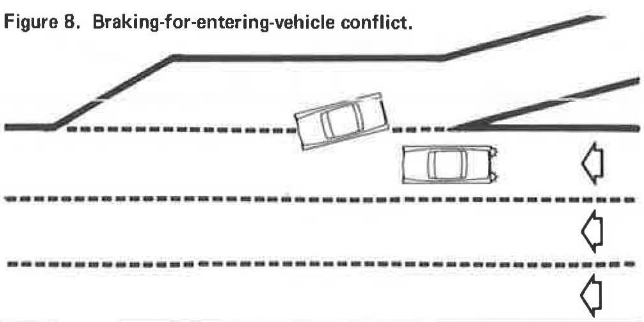


Figure 9. Weaving-around-lead-and-entering-vehicles conflict.

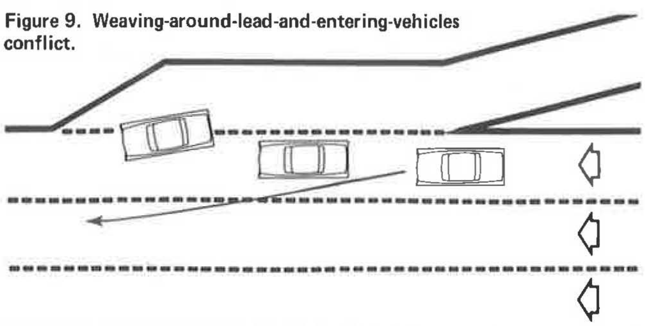


Figure 10. Braking-for-lead-and-entering-vehicles conflict.

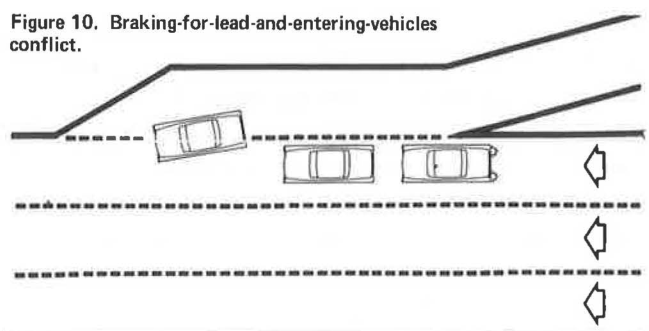
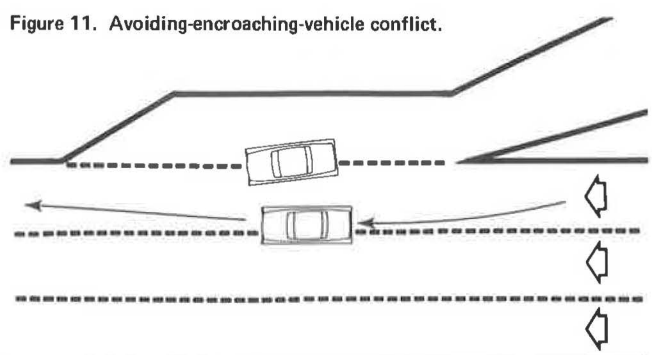


Figure 11. Avoiding-encroaching-vehicle conflict.



before the onset of stop-and-go traffic conditions. Average freeway volume during this 2-h period is 4300 vehicles/h upstream of the ramp, and average ramp volume is 700 vehicles/h. When on, the ramp-metering control was kept at a constant rate of 13 vehicles/min throughout the study.

DATA ANALYSIS

The 5-min interval for traffic-conflict counts was used as the basic unit of analysis. All results relate to the number of conflicts per 5 min. The study design planned for a total of 336 count intervals. But because of poor visibility, bad weather, and equipment problems, the number of usable intervals was reduced to 242. This reduction results in 85 count intervals for the first 5 d of the study when ramp control was on (period 1), 81 count intervals for the next 5 d when control was off (period 2), 38 count intervals for the next 3 d when control was on (period 3), and 38 count intevals for the last 3 d when control was off (period 4).

The investigation of the relationship between ramp-metering control and traffic conflicts requires an accounting for confounding factors. Environmental conditions have been dealt with by not considering count intervals that occurred during bad weather or poor-visibility conditions. However, there is evidence that traffic conflicts increase with volume (3). Therefore, variations in volume from day to day could affect the traffic-conflict data. One way to determine the possible effect of these daily variations would be to perform an analysis of variance (ANOVA) by using traffic flows as the dependent variable and the individual study days as the independent variable.

The two traffic characteristics chosen were the entrance-ramp and merge-lane volumes expressed in 5-min flow rates. Traffic conflicts measure the interaction of these two traffic streams. Based on the ANOVA results, the hypothesis that there is no difference among the study days for entrance-ramp volumes could not be rejected at the 5 percent significance level. The F-ratio (ratio of the larger mean square to the smaller mean square) is 1.008, which indicates near equality of within-day and between-day variances.

For merge-lane flows, the hypothesis that there is no difference among study days can be rejected at the 5 percent significance level. Thus, merge-lane conflicts can possibly be affected by traffic-flow variations.

A reversal design was selected for use in this study. This type of design attempts to demonstrate a causal link between an experimental condition and a target behavior by alternating the presence and absence of the condition. If ramp-metering control can increase the safety of freeway merging, traffic conflicts can be expected to decrease when ramp signals are on and to increase when ramp signals are off. The expected pattern according to the experimental design would be that the level of conflicts would be low during period 1, increase during period 2, decrease during period 3, and increase during period 4. One could reasonably expect that the difference between the two periods when ramp control was on and the difference between the two periods when ramp control was off would be significant.

Three aggregated conflicts were used to investigate the trend as the ramp-metering control was turned on and off according to the experimental design. The 5-min-interval count summations of all conflicts, all acceleration-lane conflicts, and all merge-lane conflicts were chosen as representative measures of the underlying process.

A heuristic analysis was made of the conflict trends by plotting the daily averages of the aggregated conflicts by study day (Figures 12, 13, and 14). The vertical line separates experimental periods, and the dashed horizontal line indicates the period mean. The plot of all conflicts (Figure 12) shows that the basic predicted trend holds; however, some daily averages overlap. The measure is the sum of the acceleration-lane and merge-lane conflicts and reflects driver behavior. Acceleration-lane conflicts conform to the predicted pattern as shown by Figure 13. However, the merge-lane conflicts do not match the predicted pattern (Figure 14). Factors such as traffic volume possibly affect the results. The plot also helps to account for driver behavior in all conflicts, especially in period 4.

The statistical significance of these observed trends can be found by testing for the differences between the means of the aggregated traffic conflicts for each possible pair of experimental periods. There are six possible combinations of these periods: four that compare ramp-control-on conditions with ramp-control-off conditions and two that compare like conditions. The Student's t-test was employed to test the differences in the means at the 5 percent level. A one-tailed test was used to compare the four different experimental condition pairs. This test was chosen because the major interest of this study is to demonstrate that more conflicts occur when ramp control is off than when ramp control is on. A one-tailed test is more restrictive in rejecting the null hypothesis when there is no difference and has a lesser risk of making a type II error. For the two like-condition pairs, the two-tailed test was chosen because there is no interest in the direction of the relationship. The results of the tests for the means are given in Table 1. The results for all traffic conflicts show a difference for period 1 comparisons and no difference for period 3 comparisons. This disparity could be due to two reasons. First, the merge-lane conflicts that are part of this summary do not conform in period 4 and are higher than hoped for in period 3. Second, the smaller sample size may have caused periods 3 and 4 to be less representative.

The analysis of test results for acceleration-lane conflicts shows that the conflicts follow the expected pattern. Having controlled for other rival factors, we can state that the use of ramp-metering control helps reduce the occurrence of acceleration-lane conflicts and thus eases driver tension and increases merging safety for the vehicle entering the freeway.

Figure 14 shows that merge-lane conflicts have no relationship to ramp-metering control. Traffic characteristics appear to have a significant effect on these types of conflicts.

The relationship between selected traffic conflicts and ramp control is investigated later in this paper. Because no statistical differences were found between the periods with the same experimental conditions, further analysis will be concerned only with comparing the data for the 8 d for which ramp control was on with data for the 8 d for which control was off.

A further division is made by determining freeway level of service (LOS) during each count interval (7). All traffic conditions during the study were classified as LOS C or D. This classification allows for the further investigation of the relationship between traffic conflicts and traffic characteristics. Two-way ANOVA was used to determine statistical significance; ramp control and freeway LOS were independent variables.

The ANOVA results for the aggregation of all traffic conflicts showed a significant effect at the 5 percent level for both ramp control and freeway LOS. Ramp metering reduces traffic conflicts 11.6 percent. The significance of LOS supports the concept that some conflicts are related to traffic characteristics. That the number of

Figure 12. All conflicts by study day.

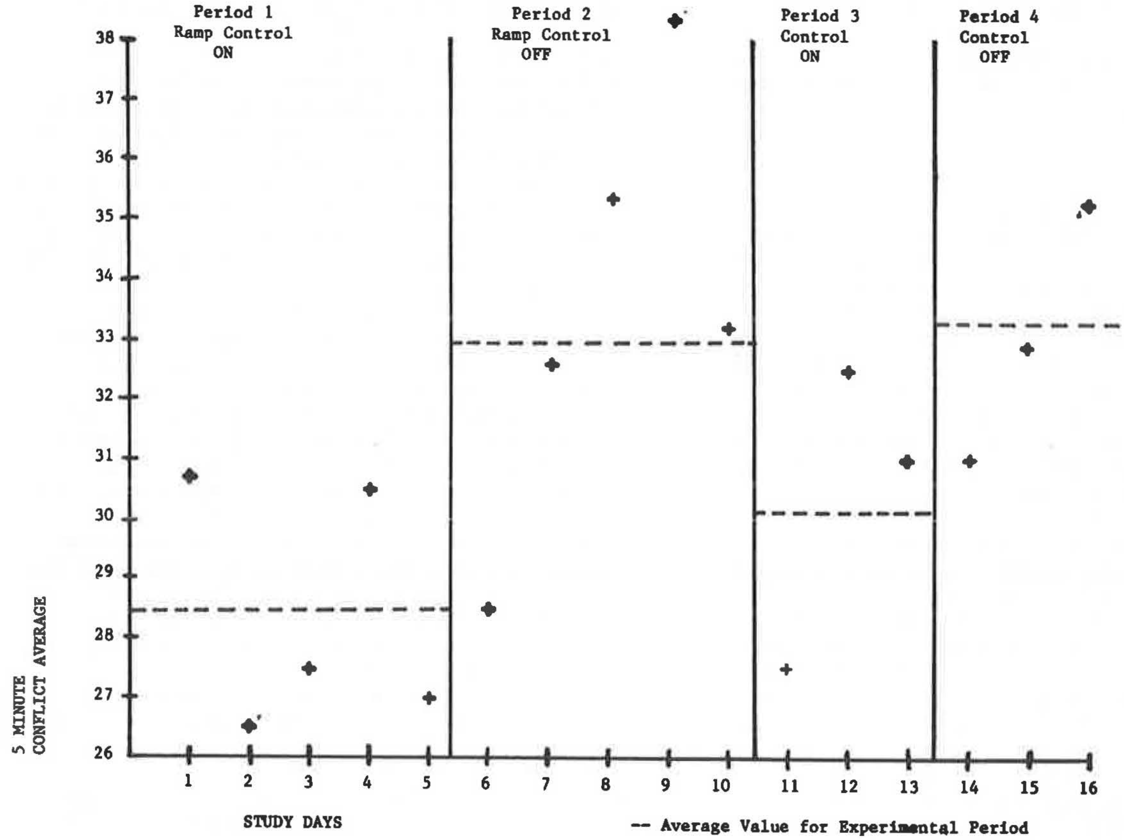


Figure 13. All acceleration-lane conflicts by study day.

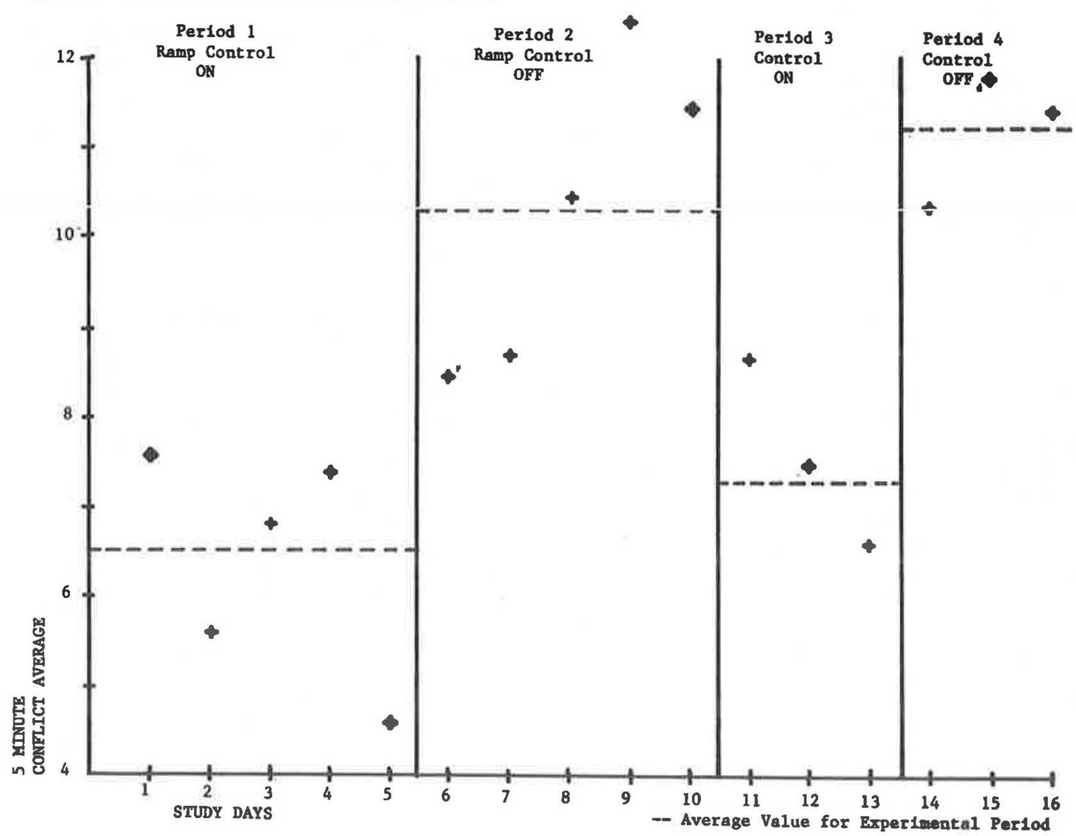


Figure 14. All merge-lane conflicts by study day.

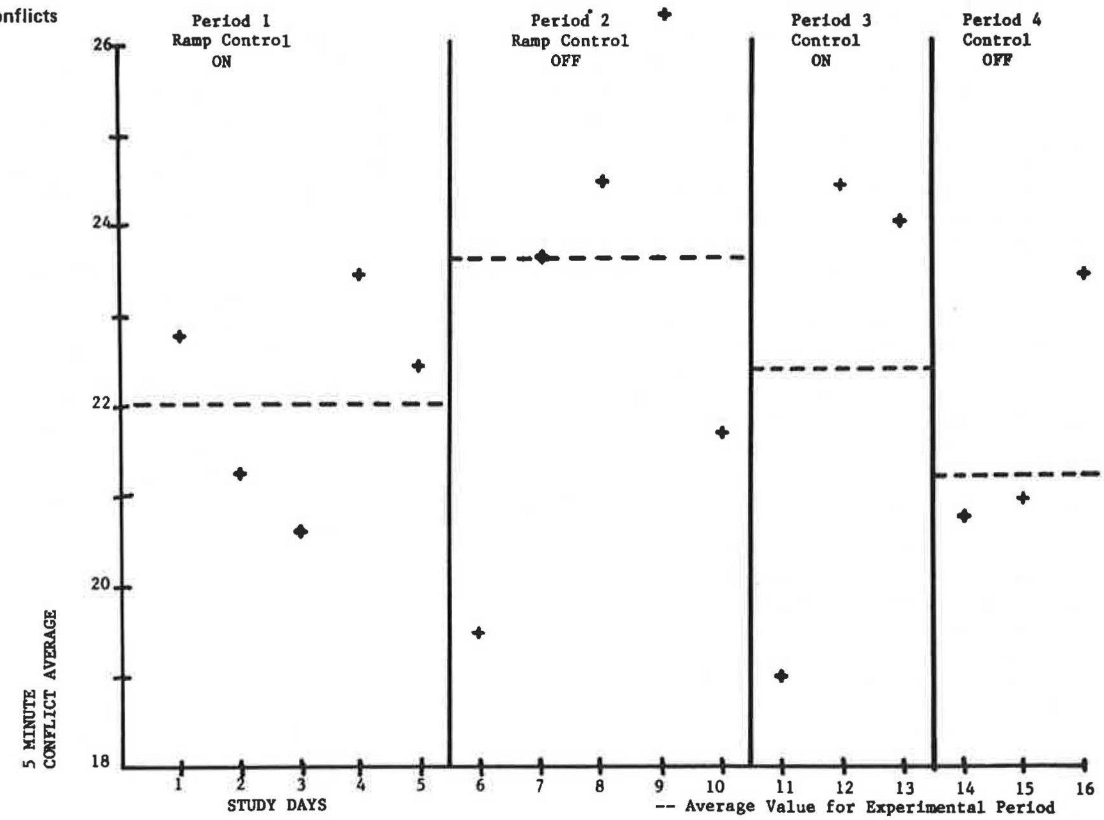


Table 1. Results of tests of statistical differences between means of aggregated conflicts.

Test	Ramp Control	Test Periods	Traffic Conflicts	Acceleration-Lane Conflicts	Merge-Lane Conflicts
One-tailed	On and off	1 and 2	Yes	Yes	No
		1 and 4	Yes	Yes	No
		3 and 2	No	Yes	No
		3 and 4	No	Yes	No
Two-tailed	On	1 and 3	No	No	No
	Off	2 and 4	No	No	No

Note: Yes indicates that the hypothesis that there is no difference between the means can be rejected, and no indicates that the hypothesis cannot be rejected.

conflicts increases as freeway LOS changes from C to D under both control condition offers additional evidence.

For all merge-lane conflicts, the ANOVA indicates, as expected, no effect for metering but an effect due to LOS at the 5 percent level of significance. There is an average increase of 11.3 percent in all merge-lane conflicts when traffic moves from LOS C to D. This result confirms the concept that these types of conflicts are related to variation in traffic flow.

The ANOVA results for the five individual kinds of merge-lane traffic conflicts provide additional insight into the interaction between metering conflicts and traffic characteristics. The ANOVA for all rear-end conflicts indicates no effect for ramp control but a significant effect for LOS at the 5 percent level. This result is in agreement with early results. As freeway level of service decreases, the number of speed adjustments required to maintain a safe spacing between mainline vehicles increases. This relationship is subsequently reflected in the number of brake-light indications. The same results were found for all braking-for-lead-and-entering-vehicle conflicts.

An examination of the ANOVA for all weaving-around-lead-and-entering-vehicle conflicts shows a significant effect at the 5 percent level for both ramp control and LOS. This conflict partially measures the magnitude of multiple-vehicle involvements in conflict situations. This outcome suggests that more mainline vehicles are adversely affected by merging vehicles when ramp control is off than when ramp control is on.

The ANOVA results for all weaving-around-entering-vehicle conflicts show no significant effect. The analysis of all avoiding-encroaching-vehicle conflicts could not be made because of a small sample size. Thus, for braking-for-entering-vehicle conflicts, the major link is with freeway level of service. However, the weaving-around-lead-and-entering-vehicle results indicate that multiple-vehicle merges, which only occur when ramp control is not in use, cause more mainline vehicles to be involved in the same conflict situation. The ANOVA results for all acceleration-lane conflicts show a significant effect for ramp control and none for level of service, as expected.

During data collection, the following sequence of events was observed. The driver of a lead vehicle in the platoon of entering vehicles would merge at a speed that was adequate for his lead vehicle to match its gap. However, the driver of a following vehicle apparently would perceive that the speed of the lead vehicle would not allow his vehicle to merge. Thus, the following-vehicle driver would speed up and enter directly into lane 2 or decrease his vehicle's speed. The first case resulted in an entering-second-lane conflict, and the second case resulted in a braking-for-lead-vehicle conflict.

The analysis of all entering-second-lane conflicts showed a significant effect for control and no effect for LOS. When ramp control is on, the occurrence of those conflicts decreases for both levels of service. When ramp control is off, the opportunity for this type of maneuver decreases with level of service.

An examination of the ANOVA for braking-for-lead-vehicle conflicts shows a significant effect for control and none for level of service. Therefore, use of ramp control seems to reduce occurrence of braking by following vehicles during freeway merging.

The two-way ANOVA results for all braking-on-ramp conflicts indicate a significant effect for level of service and none for control. This result is not unexpected. This conflict specifically records the number of times that drivers of entering vehicles are unable to find an acceptable gap within the freeway traffic stream and are forced to reduce speed. As the level of service and subsequently the number of gaps decrease, the occurrence of this conflict increases.

For all entering-late conflicts and all weaving-around-lead-vehicle conflicts, the analysis is inconclusive because of small sample sizes.

As demonstrated above, when ramp control is on the number of acceleration-lane conflicts decreases and merging safety increases. This gain is mainly accomplished by reducing the interference between entering vehicles as manifested by the reduction in entering-second-lane and braking-for-lead-vehicle conflicts. The merging driver is able to give more attention to finding a suitable gap in the freeway traffic stream.

Each traffic conflict, in addition to being classified as one of the 11 individual conflicts, was also categorized into one of three severity ratings (routine, moderate, or serious). No serious conflicts were observed during the study.

The ANOVA results for the aggregation of all routine traffic conflicts show a significant effect for both metering and freeway LOS at the 5 percent level of significance. This outcome is in agreement with earlier analyses. However, the ANOVA for all moderate conflicts reveals only an effect for ramp control. The implication is that when metering is on the severity of conflicts is affected.

Further evidence is found in the ANOVA for all routine and all moderate merge-lane, rear-end conflicts. This type of conflict is the aggregation of braking-for-entering-vehicle and braking-for-lead-and-entering-vehicle conflicts. The ANOVA for the routine conflicts shows a significant effect only for LOS, as seen in previous results. The analysis for the moderate occurrences indicates a significant effect only for ramp control.

ACCIDENT ANALYSIS

Information was obtained from accident records of all reported freeway accidents occurring on northbound I-94 on a 0.603-km (0.375-mile) segment including the Wilson Avenue entrance ramp. The data spanned 8 years; data were collected 4 years before ramp metering was installed in March 1971 and 4 years after the installation. For the before period, only accidents occurring between the probable hours of ramp metering, 3:00 to 7:00 p.m., are considered for the analysis. For the after period, only those collisions that happened when ramp metering was on are used. Because ramp metering is manually activated according to traffic conditions, which results in daily time variations and the long time period for the accident data collection, a strict before-and-after comparison is difficult to make.

The list of property-damage accidents showed that the number of collisions in the study section decreased from 32 accidents before the installation of metering to 21 accidents after the installation, a 35 percent reduction. Based on a Poisson distribution for the accidents and an analysis technique developed by Michaels (8), this reduction is statistically significant at the 5 percent level, indicating that there is an improvement in accident experience when ramp metering is used.

The accident analysis supports the finding of increased safety reported elsewhere (1). But the analysis also serves to illustrate some of the problems encountered when accident records are used to evaluate a time-dependent traffic improvement. The modified traffic-conflict technique established a definite link between increased freeway-merging safety and ramp-metering control. Accident records are the prime measure of highway safety, but in the evaluation of certain traffic improvements need to be supplemented to provide a comprehensive analysis.

CONCLUSIONS

Based on the results of the data analysis, the use of ramp-metering control set at 13 vehicles/min helps to increase the safety of freeway merging during levels of service C and D. During this study an 11.6 percent reduction in all traffic conflicts occurred when metering was on.

Acceleration-lane conflicts exhibited the strongest link with the use of ramp control. The aggregation of all acceleration-lane conflicts followed exactly the pattern predicted by the reversal design. Ramp-metering control appears to reduce the interference between merging vehicles. This observation is demonstrated by the reduction in braking-on-ramp and entering-second-lane conflicts when metering is on.

Merge-lane conflicts are more strongly related to freeway level of service than to ramp control. However, fewer multiple-vehicle involvements occur when ramp control is on, and the severity of the merge-lane involvements decreases with the use of control.

This application of the TCT has demonstrated its usefulness in a freeway-merging setting. The accident analysis illustrated the ability of the TCT to provide a rapid and valid evaluation. The method furnished useful and reliable data that provide insights into the merging process.

The further testing of this modified technique at other entrance ramps is warranted. Testing would provide additional information concerning merging safety and insight into the operation of the technique. Applicability of the traffic-conflict technique at different entrance-ramp configurations, at other metering rates, and during various freeway traffic conditions (especially under congested conditions) still needs to be investigated.

ACKNOWLEDGMENTS

This study was conducted as part of the Illinois Department of Transportation research program on expressway surveillance and control. The study served as my thesis submitted in partial completion of the requirements for a master of science degree in civil engineering at Northwestern University. The paper reflects my views and I am responsible for the facts and accuracy of the data presented.

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Publication of this paper sponsored by Committee on Effectiveness of Operational Measures.

**Mr. Cima was with the Chicago Area Expressway Surveillance Project, Illinois Department of Transportation, when this research was performed.*