OPERATIONAL EFFECTS OF SOME ENTRANCE RAMP GEOMETRICS ON FREEWAY MERGING

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Report 430-1: "A Nationwide Study of Freeway Merging Operations"

Report 430-2: "Gap Acceptance in the Freeway Merging Process"

Report 430-3: "Operational Effects of Some Entrance Ramp Geometrics on Freeway Merging"

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NEED FOR THE STUDY

A wide range of geometric design standards have been used on the freeways which are now open to traffic and these different geometrics as well as different traffic patterns have caused a considerable range of traffic operation and safety. The designs used on early freeways were influenced by experience in street design and by lack of experience in dealing with very high traffic volumes. In many cases very poor design features were accepted and built into some early freeways because it was not known what constituted good or bad design features. Since operational studies were unknown there was little feedback of operational information to the designer and, indeed, in many cases the volumes remained low enough that these poor design features did not cause severe operational problems. In recent years, however, much more operational experience has been gained and reported. In spite of this, the design standards in some areas have failed to keep pace with the rapidly expanding body of knowledge on the operation of freeways and as a result some outmoded concepts of design are still being used in the design of present-day freeways. This is especially true in some primarily rural areas where some rural design philosophies are carried over into urban design situations.

On most urban freeways the volumes have increased considerably and are so high that operational problems are commonplace, especially during the peak traffic periods. In fact, peak-period control of urban freeways has been necessitated to a large extent to prevent the overloading of bottleneck areas, many of which are caused by poor geometric features. The order of magnitude of the increase in volumes strived for by these projects are the same as the lost capacity due to the bottlenecks so better design could have decreased the need for peak-period operational control and the associated costs.
Closely correlated to poor operation is low safety. Geometric features which are bottlenecks can cause shock waves (poor operation) to be generated and propagated upstream and the shock waves can cause many rear end accidents. Also entrance ramp designs which cause a high percentage of merging vehicles to stop before merging generally have a high accident experience as well. Many other examples showing the correlation of operations and safety could be cited.

In spite of the knowledge gained from previous studies\(^1, 2, 3\), of entrance ramp operation there was a need of research of a more comprehensive nature to define more clearly the operational effects of some entrance ramp geometrics, the most important of which are acceleration lane length, angle of convergence of the ramp with the freeway and the ramp grade. One reason for this is emphasis. In spite of the suggested ramp designs based on these past studies, there is still a tendency on the part of some designers to compromise from good designs because of other (sometimes very important) considerations such as cost, right of way restrictions, desire for frequent access points or, in many instances, still a carryover of past design standards which may be believed to "work all right". This carryover of past designs which "work all right" may in most cases be due merely to a lack of adequate traffic volumes to test the operational capacities of the designs or may be due to a lack of cognizance on the part of the designer of the operation of some of his designs. This report should place emphasis on the correlation of design and operations which will hopefully lead to improved design on future freeways.

In addition to the need to assure that future freeway designs are going to lead to desirable operation another area of freeway design which is beginning to receive deserved attention is redesign or "remodeling" of existing freeways. Many of the older designs have led to poor operation and/or high accident rates and it is being increasingly realized that, along with the need for construction of new freeways, important benefits to the motoring public can be realized by modification of design on existing freeways to eliminate bottlenecks and hazards. The Los Angeles District of the California Division of Highways recently established a Freeway Operations Department\(^4\) which is responsible for the selection of locations on the Los Angeles freeways which most need redesign or traffic control. The present study will help (1) to determine which entrance ramp designs warrant remodelling, (2) to determine the type of improvement which would best alleviate the problem and (3) to determine the amount of operational improvement or benefits to motorists to be expected from the remodeling.

In the area of ramp control, the data on capacity and service volumes
related to geometrics should be quite helpful. There are many ways to operate ramp controls and the geometrics have never been specifically considered in any of the control theories except through the effect on traffic parameters such as capacity. This study of different types of merging areas should provide many insights into the effects of geometrics on the ramp control requirements.

Many freeway simulation programs have been developed but their testing and calibration have been retarded by a lack of adequate field data on (1) gap acceptance characteristics and (2) effect of geometrics on the operational characteristics. This study will help to answer some of the need for information on the effects of geometrics on the behavior of vehicles in the freeway merging area.
SCOPE AND OBJECTIVES

The general objective of this study was to determine the effects of entrance ramp geometrics on the traffic interaction in the freeway merging process. More specifically the objective was to study the effects of the following specific geometric variables on entrance ramp operation: acceleration lane length, angle of convergence and ramp grade. Indeed most of the analyses presented in this report concentrate on the first two of these.

To accomplish this objective it was necessary to conduct studies at many entrance ramps in order to include a fairly wide range of the geometric elements. Studies were made at 29 entrance ramps (listed in Appendix A) in Houston, Los Angeles, San Francisco, Sacramento, Chicago, Detroit, and New York City. The acceleration lanes of the ramps studied ranged from 240 to 1500 feet in length and the convergence angles ranged from $1^\circ$ to $14^\circ$. Data from 23 of these entrance ramps are presented in this report.

A technique involving time lapse photography from a circling airplane was developed (5) for these studies so that a fairly long section of freeway and merging area could be filmed continuously in time. One to five rolls of film, each covering a 24 minute period, were obtained at each study location.
STUDY PROCEDURES

In order to study the merging operation microscopically at about 40 entrance ramp locations throughout the country a special aerial photographic study technique was developed. A 35 mm, time-lapse movie camera was used with a film speed of 5 frames per second. In order to obtain a continual coverage of traffic conditions, the area of interest was circled by a Cessna 206 type airplane from which the time-lapse photographs were taken. The radius of the circle was about 1/4 mile and the altitude and lens were selected (1) to obtain adequate coverage of the merging area, (2) to locate the plane at the altitude of least air turbulence, (3) to locate the airplane below any clouds. Figure 1 shows the camera mounted in the plane.

The airplane made a complete circle around the study site about once every 40 seconds. The rotation of the scene during analysis was not a problem because a stop-frame analysis was used.

Reference marks were placed at 200' intervals on the right shoulder of the freeway and on the ramp shoulder. A reference mark was placed at the physical nose of the ramp and the marked area extended 400 feet upstream of the physical nose and downstream to a point past the end of the ramp taper. Figure 2 shows a typical reference configuration at an entrance ramp.

A film speed of 5 frames per second was selected as the minimum speed which would provide the necessary accuracy of measurements. A lower film speed is more desirable from several points of view, namely, lower film cost and lower film analysis cost and a longer filming period could have been used at each ramp. In each frame of the film the freeway scene was accompanied by a data chamber showing (1) the time of day, (2) the frame number and (3) a data slate containing information on the ramp name, film number, etc. Figure 3 shows a sequence of four frames taken at four points on the flight circle.

Because of the large amount of film obtained, analysis of the data became somewhat of a problem. During one period, three 8-hour shifts on each of three projectors were used to expedite the analysis. The data taken from the film included for each vehicle (1) the vehicle type, (2) the location of the vehicle (ramp or freeway lane) and (3) the time the vehicle passed each reference mark. The data were recorded in a format to facilitate direct key punching on IBM cards and all data processing was done on a large-scale computer.
AIRCRAFT DOOR MODIFICATION

CAMERA MOUNTED IN AIRCRAFT

Figure 1
NOTE:
ALL STRIPES ARE WHITE NON-REFLECTIVE LANE MARKING TAPE

TYPICAL STUDY SECTION

Figure 2
TYPICAL FRAMES FROM DATA FILM

Figure 3
A companion report (5) contains further details on the procedures used in the study.
SELECTION OF STUDY LOCATIONS

The study locations were selected to meet several geometric and traffic requirements. In the selection of the ramps to be studied, pure merging situations were sought, that is, locations at which the traffic operation was unaffected by upstream or downstream conditions. Merging operation at or near capacity was also desired. Local authorities were extremely helpful in suggesting study sites and in providing volume and geometric data as well as plan and profile sheets for possible study sites which were used in the final selection of sites. Before any filming was done at a location, the operation there was field checked to determine the approximate volumes and to evaluate the possible effect of any downstream restrictions. In spite of this careful checking of the study sites, the operation during the film studies was not always the same as during the field checks because of changes in traffic patterns, accidents, or some other temporary situation.

In the selection of study sites one of the objectives was to obtain a wide range of geometrics in the ramps studied. Particularly, variations in acceleration lane length, angles of convergence and ramp grade were sought. Locations having straight, level freeway alinement were of primary interest since the effect of freeway geometrics was not being studied. Figure 4 shows a geometric summary of the twenty-three entrance ramps for which data are included in the report. The coordinates consist of the acceleration lane length and angle of convergence. It can be seen in this figure that a considerable distribution of ramp geometrics was obtained among the ramps selected. Data at several other entrance ramp locations were collected but are not presented because accidents or other downstream interference caused primarily congested merging operation.

The study period was selected on the basis of the traffic operations during the time of the field checking. The time was selected so that free flow merging operation prevailed and so the merging volume was near capacity.

A complete list of the entrance ramps included in the study can be found in Appendix A. The ramps are listed according to the metropolitan area in which they are located and not according to the exact suburb. For example, the Broadway northbound entrance ramp on the Bayshore Freeway is located in Burlingame, California, but is listed as being in the San Francisco area.
SUMMARY OF ACCELERATION LANE LENGTHS AND CONVERGENCE ANGLES FOR THE RAMPS INCLUDED IN THE ANALYSES

FIGURE 4
RAMP GEOMETRICS

Geometric data were obtained for each of the entrance ramps which were studied and included the following:
1. length and shape of acceleration lane
2. angle of convergence
3. ramp grade
4. freeway grade
5. length of ramp
6. width of acceleration lane
7. number of ramp and freeway lanes
8. freeway and ramp curvature
9. curb offset at the nose

Some comments on the definitions of the geometric variables are warranted and follow.

The length of the acceleration lane (L) was taken to be the distance from the physical nose to the end of taper. Because of different offset distances of the curb at the physical nose the length of two acceleration lanes may not be directly comparable. In example a 600 foot acceleration lane on a ramp at which the offset at the nose is 10 feet is not equivalent to a 600 foot acceleration lane on a ramp at which the offset is 2 feet. In the former case a portion of the acceleration lane would be used by vehicles in moving laterally to the same position as would be maintained by vehicles at the nose of ramp with a 2 feet offset. Therefore, the effective length of acceleration lane on the two ramps would be different. The difficulty in defining and measuring a length of acceleration lane which would be comparable for any curb offset made it necessary to use the distance from the physical nose to the end of taper as the acceleration lane length.

Similarly, the offset distance of the curb at the physical nose has an effect on the effective angle of convergence. In order to avoid use of a misleading angle, the angle of convergence (θ) was measured both at the physical nose and, for the ramps with curb offsets greater than 2 feet at a point where the left edge of the ramp (as delineated by the paint markings) was 2 feet off the edge of pavement of the freeway. Both of these angles are discussed in the analyses which follow.

Most of the geometric data was obtained from information furnished by local agencies. The form of the information supplied varied with the agencies and ranged from aerial photographs to construction drawings. The geometric data were read as accurately as possible from the plans and photographs provided but in some cases the scale of the drawings
furnished made accurate determination of the convergence angle, acceleration lane length, etc., difficult. Where such difficulties were encountered the local agencies were asked to check the geometric data obtained from the plans.
REDDUCTION AND ANALYSIS OF THE DATA

FILM REDUCTION

The aerial, time-lapse photographs were analyzed using a vehicle-by-vehicle type of data reduction to obtain the relevant data for each vehicle on the entrance ramp or in the right lane of the freeway. Each vehicle on the ramp was traced through the merging area and the frame number corresponding to the time the front end of the vehicle passed each reference mark (see Figure 2) was recorded. When the vehicle entered the freeway it was treated as a freeway vehicle in the remainder of the merging area. Vehicles in the right lane of the freeway were also traced through the merging area in a similar manner.

The reference marks were normally placed 200 feet apart so the speed of each vehicle between each pair of reference marks could be obtained. The time which each vehicle passed each reference point was known so it was quite simple to obtain a time-space trajectory for each vehicle in the merging area of each ramp which was studied. For each roll of film which was analyzed a time-space plot was made using a Cal-Comp plotter driven by an IBM 1401 computer. The time-space trajectories of vehicles on the freeway were plotted in blue and the trajectory of vehicles on the ramp were plotted in red. The point at which a red line turned blue on the time-space diagram indicated that a vehicle from the ramp had merged onto the freeway at that point. Figure 5 shows a sample of the time-space diagrams. Note that the only vehicles on the freeway which are included in this drawing are those on the right lane. Reference 5 contains further details of the film reduction process.

ANALYSES

Many analyses were made of various operational characteristics. Most of these were made for each of three levels of freeway operation based on freeway speeds, (1) less than 25 mph, (2) between 25 and 40 mph and (3) above 40 mph. In this report the characteristics presented are limited primarily to those for which the freeway speeds were above 40 mph. The reasons for this are (1) the operations above 40 mph is the type intended when the freeways were designed and (2) the operation in this level is more variable than in the other since the drivers' decisions are less constrained.
TIME - SPACE DIAGRAM
BROADWAY NORTHBOUND ENTRANCE RAMP
BAYSHORE FREEWAY, SAN FRANCISCO

Figure 5
For each of the entrance ramps included in the study, the distribution of speeds of vehicles on the ramp over the 200 foot section upstream of the ramp nose was obtained. The speed of a vehicle on a ramp approaching the nose can be affected by several factors. Among them are (1) freeway traffic conditions, (2) ramp alignment, (3) ramp grade, (4) ramp angle of convergence and (5) acceleration lane length. The last two factors affect the speed at the nose because they affect the gap acceptance characteristics and hence the (queueing) service rate on the ramp. At entrance ramps with minimum design standards the merging maneuver is more difficult for the motorists and therefore the approach speeds tend to be lower than on ramps with better designs. A great deal of interference between ramp vehicles is noted on poorly designed ramps because of the relatively high frequency of very low speed merges and the arrival of vehicles on the ramp while others are stopped waiting to merge. Considerable queueing of ramp vehicles is noted at this type of ramp.

Most of the ramps studied had a ramp alignment which would not cause a severe reduction in approach speeds. Most were diamond type ramps, cloverleaf outer connectors or direct connections so the alignment was fairly good in all cases. The effect of different freeway conditions was accounted for by considering the three speed ranges on the freeway. It would have been more desirable to have grouped the data by ramp and freeway volumes (such as was done in Reference 3) instead of by freeway speeds alone but the sample sizes of the data did not permit such a classification.

In order to show the effect of ramp angle of convergence on the merging operation, the ramp speed distribution was plotted for ramps in four ranges of acceleration lane lengths (0-350’, 400-600’, 600-800’ and 950-1200’). The distribution of ramp speeds was obtained only for vehicles which arrive at the ramp nose when freeway speeds are over 40 mph. Within each range of acceleration lane lengths, differences in ramp speeds are primarily caused by different angles of convergence.

Similarly the effect of acceleration lane length on ramp speeds was obtained by examining speed distributions for ramps within three ranges of convergence angle (0-30°, 60-80° and 100-140°). Within each range of convergence angles, the differences in ramp speeds are primarily caused by differences in acceleration lengths.

Several analyses involving a single statistic (such as the mean of a distribution) were made by writing the value of the statistic near a point representing an entrance ramp on a special data paper. The point for
each ramp was located according to the angle of convergence and acceleration lane length. The special data sheets are similar to Figure 4 with the ramp names omitted. The mean ramp speed at the nose for periods during which freeway speeds were above 40 mph was treated in this manner.

Spèeds of Ramp Vehicles at Merge Point

The distributions of the speeds of ramp vehicles in the 200 foot distance in which the ramp vehicle actually merges were treated in the same manner as were the distributions of ramp speeds at the nose. For freeway speeds over 40 mph the distributions of merging speeds were plotted versus acceleration lane length for various ranges of convergence angles and were plotted versus convergence angles for various acceleration lane lengths. Also the mean merge speed for each ramp (for freeway speeds over 40 mph) was plotted against the angle of convergence and acceleration lane length for the ramp.

Speed Changes on the Acceleration Lane

The speed change for each ramp vehicle between the ramp nose and the point at which it merged onto the freeway was computed during times when the freeway operating speed was over 40 mph. The distribution of these speeds is an indication of the efficiency of the operation on the acceleration lane. These distributions (one for each ramp studied) are presented as functions of convergence angle and acceleration lane length in the same manner as were the distributions of speed at the ramp nose and at the merge points. The mean speed change is also shown for each ramp by acceleration lane length and convergence angle.

Relative Speed

In an ideal merge the relative speed between a vehicle on the ramp and vehicles on the freeway is quite low at each location on the acceleration lane. A vehicle on the ramp should pass the ramp nose at a speed approximately the same as the operating speed on the freeway. It should then adjust its speed to reach the gap selected and should enter that gap at the same speed as that of the lag vehicle.

High relative speeds between vehicles generally indicate poor operation on any facility and a high relative speed between vehicles on the ramp and those on the freeway indicate poor merging operation. When
freeway speeds are high (over 40 mph), a high relative speed is generally caused by the geometric design of the ramp causing low speed operation on the ramp.

The relative speed between each ramp vehicle and its lag vehicle were computed at several locations along the merging area. The first speed trap is the 200 foot length upstream of the ramp nose and each 200 foot trap along the acceleration lane was used to compute relative speed. In addition, for each ramp vehicle the relative speed was computed at the actual trap in which the merge maneuver was completed. The distributions of these relative speeds are presented as functions of acceleration lane length and angle of convergence in a manner similar to the presentation of the other distributions and the means of the distributions are also shown as function of these two geometric variables.

Accepted Gap Number

Another indication of the operational efficiency of a merging area is the gap into which the ramp vehicles merge. If the vehicles on the ramp normally select the first or second gap, the operation is better than it would be at a location at which ten or fifteen gaps pass by before the vehicle on the ramp finds an acceptable gap. The gap numbers are defined according to their locations at the instant the front of the ramp vehicle reaches the physical nose as shown in Figure 6. The gap that is adjacent to the ramp vehicle when it is at the nose is gap 1 and the gaps are numbered from downstream to upstream.

The mean number of the accepted gap and its standard deviation were computed for each ramp and each of the three freeway speed ranges. Some of these are presented as functions of acceleration lane length and convergence angles.

Gap acceptance is studied in much more detail in a companion report.

Acceleration Lane Use

The use of the acceleration lane was also investigated at each of the entrance ramps. For each a distribution of encroachment points (the location relative to the physical nose at which the ramp vehicle first encroaches on the freeway) was determined. These are presented as functions of angle of convergence and acceleration lane length in order to show the effects of these geometric variables. In addition,
mathematical distributions were fitted to the actual distributions.
RESULTS

SPEEDS OF RAMP VEHICLES AT RAMP NOSE

Ideally the geometrics of an entrance ramp should not prevent a vehicle which is about to merge onto a freeway from attaining a speed nearly equal to the operating speed on the freeway when the vehicle passes the ramp nose. Under some freeway operating conditions, namely congestion, this is not always possible. However, when the freeway speeds are greater than 40 mph it should be possible for vehicles on the ramp to pass the nose at high speed.

In Figure 7 the number beside each point is the percent of ramp vehicles traveling less than 30 mph at the ramp nose when the freeway speeds are over 40 mph. Each point represents an entrance ramp and the coordinates of the point represents its acceleration lane length and angle of convergence. The effects of these geometric variables can be clearly seen in this figure. The percent of slow ramp vehicles can be seen to increase quite rapidly for ramps with angles of convergence greater than about 6°. The percent of ramp vehicles passing the ramp nose at speeds less than 30 mph ranges from a low of 2 for 3 ramps with acceleration lanes between 6 and 700 feet and with angles of convergence between about 2° to 4° to a high of 93% for a ramp with an acceleration lane of 335 feet and a 14° angle of convergence.

To show the effect of convergence angle on the ramp speed at the nose the ramps studied were classified according to length and the cumulative ramp speed distributions were plotted for all ramps falling in each length class. The four length classifications which were selected are 0-350 feet (3 ramps), 400-500 feet (4 ramps), 600-800 feet (10 ramps) and 950-1200 feet (5 ramps). Each distribution represents the speed of ramp vehicles at the ramp nose when freeway speeds were 40 mph or higher. Figure 8 contains these distributions.

In Figure 8a the ramp speed distributions for three entrance ramps with acceleration lanes less than 350 feet are shown. The speeds at the ramp on which \( \theta = 14 \) are generally about 10 mph lower than on the ramp with a smaller convergence angle of 10°. The lengths of these two ramps are nearly equal so the difference in speeds can be attributed almost entirely to the difference in convergence angles. The speed distribution of the third ramp on which \( \theta = 7° \) falls between the distributions for the other two ramps. Based
EFFECT OF ACCELERATION LANE LENGTH AND CONVERGENCE ANGLE ON PERCENT OF RAMP VEHICLES TRAVELLING LESS THAN 30 MPH AT THE RAMP NOSE
FREeway OPERATING SPEEDS OVER 40 MPH

FIGURE 7
on convergence angle alone it would have been expected that the speeds on this ramp would be higher than on either of the other two ramps. However this ramp has a shorter acceleration lane and much higher ramp volumes than either of the other two ramps and these factors account for the speeds at this location being lower than expected. That the operation at all three of these ramps is bad can clearly be seen by their speed distributions. The speed distributions in Figure 8 contain only data for times when the freeway speeds were over 40 mph.

Figure 8b shows the speed distribution for ramp vehicles at the nose of each of four entrance ramps which have acceleration lane lengths between 400 and 500 feet. The angles of convergence of these ramps range from 5° to 11° and the operational effects of the convergence angle can be clearly seen. The ramp with the lowest speeds is the ramp θ = 11° (66% of ramp speeds less than 30 mph) followed by the ramps with θ = 7° (41% less than 30 mph) and θ = 8°30' (50% less than 30 mph) while the ramp with the lowest convergence angle (5°) has the highest speeds, with only 16 percent of speeds below 30 mph.

Thus, for entrance ramps with short (400-500 feet) acceleration lanes, a change in convergence angle from 11° to 5° or 6° would result in about 50% more of the entrance ramp vehicles passing the ramp nose at speeds greater than 30 miles per hour at times when freeway operating speeds exceed 40 mph. This change would also result in an increase in the average speed of ramp vehicles at the nose of about 8 mph and this would reduce the relative speed (difference in speed of vehicles on the freeway and on the ramp) there by about the same amount. The relative speed at the nose is more critical for entrance ramps with short acceleration lanes since, on this type of ramp, there is little opportunity for acceleration after passing the ramp nose.

In Figure 8c the same type of speed distributions are plotted for entrance ramps with acceleration lane lengths between 600 and 800 feet. There appear to be two clusters of data - one for the six distributions to the right of the figure and the other for the four distributions to the left. The six ramps which correspond to the higher speeds of ramp vehicles passing the nose have convergence angles ranging from 3°30' to 6°15'. The median speeds at these ramps are between 38 and 44 mph and the percent of speeds less than 30 mph ranges from 2 to 15%. For the other 4 ramps (θ = 5°, 10°, 11°, and 12° 15'), the median speed ranges from 22 mph to 31 mph while the percent of speeds below 30 mph is between 39% and 80%. Thus the operation on the six ramps with the lower convergence angles is much better than on the other four ramps.
EFFECT OF ANGLE OF CONVERGENCE ON RAMP SPEED DISTRIBUTION AT RAMP NOSE

FREEWAY OPERATING SPEEDS OVER 40 MPH

FIGURE 8
It can be noted that one of the ramps on which the speeds were relatively low had an angle of 5°. One would not expect to find such a large difference in operation between the ramp with a 5° convergence angle and the other ramps with generally lower convergence angles. The operational difference probably reflects in the extremely high volume (1000-1200 vph) on the ramp with \( \theta = 5^\circ \), rather than the difference in convergence angles.

Similar speed distributions for five entrance ramps with long (950 to 1200 feet) acceleration lanes are presented in Figure 8d. For these ramps \( \theta \) varies between 1° and 7° 30'. The operation at these ramps was generally similar. On each ramp the percent of speeds less than 30 mph was less than 25% and the median speed ranged from 35 to 38 mph. The percent of ramp vehicles passing the ramp nose at 40 mph or faster is 10% and 26% for the two ramps with \( \theta = 7 \frac{1}{2}^\circ \) and is a minimum of 40% for the three other ramps (\( \theta = 1^\circ \), 1° and 6°). Thus, the traffic operation was good on each of these ramps on which the acceleration lane length is at least 950 feet and the convergence angle is less than 7° 30'.

In order to show the effect of acceleration lane length on the ramp speeds at the nose, the entrance ramps studied were grouped according to convergence angles with the angle categories being 0-3° 30', 6°-8° and 10°-14°. The speed distribution of ramp vehicles passing the ramp nose for each ramp was plotted in its proper angle group as is shown in Figure 9. Thus for ramps with approximately the same convergence angle the effect of different acceleration lane lengths can be seen. All ramp speed distributions in this Figure represent times during which the freeway operating speed was 40 mph or higher.

Figure 9a contains the speed distributions. The acceleration lane lengths vary from 660 to 1200 feet. As might be expected of these ramps which all have low convergence angles and at least an adequate (600') acceleration lane length, the speed distributions are fairly closely clustered. The median speeds range from 36 mph to 43 mph and not more than 7% of the vehicles passed the nose at less than 30 mph on any of the ramps. The speeds generally increase as the acceleration lane increases with one exception-one ramp with a 1200 foot acceleration lane has the lowest speeds. The volume on this ramp during the periods studied ranged from 1200 to 1600 vehicles per hour and the total right lane merge volume was generally in excess of 2000 vph. Thus, the very high ramp volume probably caused the ramp speeds to be lower at this location and, if the acceleration lane had been much shorter, the ramp speeds would probably be a great deal lower.
EFFECT OF ACCELERATION LANE LENGTH ON RAMP SPEED DISTRIBUTION AT RAMP NOSE

FREEWAY OPERATING SPEEDS OVER 40 MPH

FIGURE 9
Because of a greater range of acceleration lane lengths the effect of this geometric element can be seen quite clearly in Figure 9b. In this Figure the distribution of speeds of ramp vehicles passing the ramp nose is shown for six ramps having a convergence angle lying between 6° and 8°. The acceleration lanes vary in length from 240 feet to 1120 feet. The ramp which experienced the worst operation had an acceleration lane length of 240 feet. The median speed for this ramp was 19 mph, while 84% of the ramp speeds were less than 30 mph. The distributions for the other ramps are fairly closely clustered with the median speeds ranging from 34 mph to 37 mph and from 11% to 16% of the speeds below 30 mph.

On one ramp the operation was surprisingly good. This ramp has a θ of 6° 15', and L of 693 feet and was a diamond interchange ramp of the direct taper type. High merging volumes (1700-2200 vph) were maintained in the right freeway lane with about 500-700 vph on the ramp. The speeds at this location are as high or higher than those of any other ramp in the 6°-8° group in spite of its comparatively short acceleration lane length. At this location the ramp itself is on a 4.1% downgrade preceding the nose for a distance of about 450 feet. In this long distance vehicles have a good view and perspective of the freeway and are able to select a gap before reaching the physical nose and, while still on the ramp, can accelerate in order to meet the gap when it reaches the relatively short acceleration lane. This demonstrates the value of the view of the freeway which gives drivers on the ramp the ability to determine (1) the lane in which the gap is located, and (2) the speed of the gap before reaching the acceleration lane.

In Figure 9c similar speed distributions are shown for five entrance ramps for which θ lies between 10° and 14°. The median speeds for these ramps range from 11 mph for a ramp which has an acceleration lane length of 335 feet to 31 mph for a ramp with L = 785 feet. On the ramp with L = 785 feet, 39% of the vehicles pass the nose at speeds of 30 mph or less while for the other ramps this percent ranges from 66% to 93% indicating a much poorer operation.

The ramp with L = 680 feet (and θ = 10°) has a poorer operation than might be expected considering the acceleration lane length. The width of acceleration lane at this location, however, is only about 9 feet and this probably contributes to the poorer operation. This location presents another interesting study of perspective. Here the freeway and ramp are both level and at the same grade. With the high convergence angle and narrow acceleration lane it is difficult for drivers on the ramp to distinguish that there is an acceleration lane which is available to them. A wider acceleration lane and a higher radius curve would likely improve operation.
of transition on the right edge of the ramp and the acceleration lane (making possible a higher speed from the ramp to acceleration lane) would undoubtedly improve the operation at this ramp.

For each of the four acceleration lane length groups used in Figure 8, the average speed distribution for ramp vehicles passing the nose was plotted and is shown in Figure 10a. In this figure the effect of acceleration lane length can be clearly seen. Speeds of vehicles on the ramps with acceleration lanes less than 350 feet in length are much lower than those of the other ramps and the speeds on the ramps with acceleration lanes between 400 and 500 feet in length are somewhat less than the speeds for the ramps with acceleration lanes longer than 600 feet.

In Figure 10b the average ramp speed distribution at the nose is plotted for the ramps in the three groups based on convergence angles. The speeds on the ramps with angles of convergence less than $3^\circ$ are much higher than the speeds on the ramps with convergence angles greater than $6^\circ$. The lowest speeds were observed on the ramps with $\theta$ between $10^\circ$ and $14^\circ$. The effect of the angle of convergence on ramp speeds at the nose can clearly be seen in Figure 10b.

**Speeds of Ramp Vehicles at the Merge Point**

The merging speed of the vehicles from the ramp during periods of free flow on the freeway has a great effect on the operation in the merging area. Normally higher merging speeds of ramp vehicles indicate a better operation. The speed of each ramp vehicle on each ramp was obtained at the 200 foot section in which the ramp vehicle first encroached on the right lane of the freeway. This was the vehicles' merging speed and various analyses of the merging speeds were made and several are presented. Only periods in which the freeway operating speed exceeded 40 mph were included in these analyses which are presented.

The mean merging speed on each of the ramps included in the analyses is presented in Figure 11. The general trend is that the mean merging speeds tend to decrease as the acceleration lane lengths decrease and as the angles of convergence increase. The mean merging speed for all entrance ramps with a convergence angle less than $4^\circ$ was about 40 mph or higher. In this group no ramp has an acceleration lane less than 600 feet and with a convergence angle less than $4^\circ$ the merging speeds would be expected to exceed 40 mph when the freeway speeds were also over 40 mph.
EFFECT OF ACCELERATION LANE LENGTH AND CONVERGENCE ANGLE ON SPEEDS OF RAMP VEHICLES AT NOSE AND AT MERGE POINT

FREEWAY OPERATING SPEEDS OVER 40 MPH

FIGURE 10
EFFECT OF ACCELERATION LANE LENGTH AND CONVERGENCE ANGLE ON MEAN MERGE SPEED OF RAMP VEHICLES FREEWAY OPERATING SPEEDS OVER 40 MPH

FIGURE 11
The effect of angle of convergence on the distribution of merging speeds of ramp vehicles can be seen in Figure 12. For acceleration lanes less than 350 feet in length, as shown in Figure 12a, there seems to be little effect of convergence angle, at least over the range included (7° to 14°). For this range of convergence angles it appears that the short acceleration lane length has the most important effect on merging speeds.

A somewhat divergent pattern was observed in Figure 12b. For the ramps studied with acceleration lanes between 400 and 500 feet, a distinct relationship between merge speeds and convergence angle was not apparent.

A better relationship between merge speeds and convergence angles can be seen in Figure 12c for the ramps with acceleration lane lengths between 600 and 800 feet. The two ramps with the lowest merge speeds have $\theta = 10^\circ$ and $\theta = 12^\circ 15'$. All of the five ramps which have the highest merging speeds, four have convergence angles between 3°30' and 4°. The fifth, however, has a large convergence angle (11°). It appears then that, in general, higher merge speeds can be expected at ramps which have a small convergence angle.

A similar trend was observed for the five entrance ramps with acceleration lanes between 950 and 1200 feet in length. The two ramps with the highest convergence angle ($\theta = 7^\circ 30'$ at both) can be seen in Figure 12d to have the lowest merge speeds. On the other three ramps, which have considerably higher merge speeds, the angles range from 1° to 6°. It would appear that the effect of convergence angle on merge speeds is greater on entrance ramps with longer acceleration lanes.

For entrance ramps grouped by convergence angle the effect of acceleration lane length on merge speeds can be seen in Figure 13. The distributions of merge speeds for five ramps which have convergence angles less than 3°30' is shown in Figure 13a. Very little difference in operation is evidenced by these curves but the two entrance ramps in this group which have the longest acceleration lane lengths have the highest merge speeds. The consistency of these distributions and the high merging speed indicate that good merging operation can be expected on ramps with a small convergence angle and at least 650 feet of acceleration lane.

The pattern is more mixed at the ramps with convergence angles between 6° and 8°, although a higher speed merging operation tends to be associated with ramps with longer acceleration lanes. The two ramps with the highest merging speeds have long acceleration lanes.
EFFECT OF ANGLE OF CONVERGENCE ON MERGING SPEED OF RAMP VEHICLES

FREEWAY OPERATING SPEEDS OVER 40 MPH

FIGURE 12
(970 and 1025 feet) while two of the three ramps with the lowest speeds have short acceleration lanes (240 and 500 feet). In Figure 13c, for ramps with convergence angles between 10° and 14°, no apparent patterns were observed.

When these same data which were presented in Figures 12 and 13 are averaged, the trends become much more clear. In Figure 10c and d the average distribution of merge speeds for all ramps in each of the four acceleration lane length categories and each of the three convergence angle categories are plotted. In Figure 10c the lowest merge speed distribution is associated with ramps with acceleration lanes less than 350 feet. Highest merge speeds can be seen to be related to ramps with acceleration lanes longer than 600 feet.

Figure 10d shows that entrance ramps with convergence angles less than 3° can be expected to have higher merging speeds than ramps on which the angle of convergence is greater than 6°. Again it can be seen that the best operation can be expected on entrance ramps with an acceleration lane length in excess of 600 feet and with a convergence angle less than 6°.

**Speed Changes on the Acceleration Lane**

The mean speed change on each acceleration lane was determined and is equal to the difference in speed of a ramp vehicle at its merge point and its speed at the nose. These means are shown in Figure 14 and were somewhat surprising. Before the analysis it was supposed that the increase in speed on the acceleration lane would be greater on the entrance ramps with the highest type of geometric design than on more poorly designed ramps. However, the opposite seemed to be the case.

For the ramps on which the acceleration lane length is greater than 450 feet and the convergence angle is less than 8° none of the speed increases was greater than 6 mph. On only one of the ramps outside this group (acceleration lanes shorter than 450 feet and/or convergence angles greater than 8°) was the increase in speed less than 6 mph and it ranged up to 17.5 mph. This is apparently caused by the extremely low speeds at the ramp nose on the ramps with poor designs and shows quite clearly that the design of the merging area has a strong influence on the speeds on the ramp approaching the merging area.

The effect of convergence angle on the increase in speed of vehicles
EFFECT OF ACCELERATION LANE LENGTH ON MERGING SPEEDS OF RAMP VEHICLES
FREEWAY OPERATING SPEED OVER 40 MPH

FIGURE 13
EFFECT OF ACCELERATION LANE LENGTH AND CONVERGENCE ANGLE ON MEAN SPEED CHANGE OF RAMP VEHICLES BETWEEN NOSE AND MERGE POINT FREEWAY OPERATING SPEEDS OVER 40 MPH

FIGURE 14
EFFECT OF ANGLE OF CONVERGENCE ON SPEED CHANGES BETWEEN RAMP NOSE AND MERGE POINT FOR RAMP VEHICLES
FREEWAY OPERATING SPEEDS OVER 40 MPH
FIGURE 15
on an entrance ramp between the ramp nose and the point of merge is presented in Figure 15. In each of the acceleration lane length categories, larger speed changes generally take place on entrance ramps which have larger angles of convergence. At entrance ramps with large convergence angles, vehicles on the ramp must follow a curved path to move from the ramp to the acceleration lane. The radius of this curve is a function of the convergence angle and the safe operating speed on the curve is a function of the radius of the curve. Therefore the speed at which vehicles can turn from the ramp to the acceleration lane can be limited by the convergence angle, so at entrance ramps with large convergence angles the speed of ramp vehicles at the nose can be lowered because of the angle. Thus a large increase in speed is required on the acceleration lane in order that the vehicles merge at approximately the freeway speed.

In Figure 16 it appears that for a given angle category, a shorter acceleration lane length, in general, increases the amount by which vehicles increase their speed on the acceleration lane between the ramp nose and the merge point. As discussed previously this phenomenon can probably be attributed to vehicles approaching the ramp nose at higher speeds on ramps at which the merging maneuver is easier (i.e., longer acceleration lane and lower convergence angle). Thus on ramps with a long acceleration lane and a low convergence angle, the acceleration lane is not used to a great extent for acceleration but merely to accomplish a simple lane change. This is the type of operation for which the ramps are designed.

The effects of acceleration lane length and convergence angle on the changes in speed of ramp vehicles on the acceleration lane can be seen in Figure 17. In Figure 17a it can be seen that the speed changes are higher on ramps with shorter acceleration lanes and in Figure 17b it can be seen that the speed changes are higher on ramps with large convergence angles.

**Relative Speeds at the Ramp Nose**

The distribution of relative speeds (freeway lag speed minus ramp vehicle speed) at the ramp nose was plotted for each ramp grouped with ramps with similar geometric elements. To show the effect of convergence angle the ramps were placed in four groups according to acceleration lane lengths and the data is shown in Figure 18. To show the effect of acceleration lane length the ramps were placed in three groups of convergence angles as seen in Figure 19.

Figure 18a shows the plots of relative speed distribution at the
A. 0-3°30' ANGLE OF CONVERGENCE  
B. 6-8° ANGLE OF CONVERGENCE  
C. 10-14° ANGLE OF CONVERGENCE

EFFECT OF ACCELERATION LANE LENGTH ON SPEED CHANGES BETWEEN RAMP NOSE AND MERGE POINT FOR RAMP VEHICLES

FREEWAY OPERATING SPEEDS OVER 40 MPH

FIGURE 16
EFFECT OF ACCELERATION LANE LENGTH AND ANGLE OF CONVERGENCE ON RAMP SPEED CHANGES BETWEEN RAMP NOSE AND MERGE POINT

FREEWAY OPERATING SPEEDS OVER 40 MPH

FIGURE 17
EFFECT OF ANGLE OF CONVERGENCE ON RELATIVE SPEED DISTRIBUTION AT RAMP NOSE

FREEWAY OPERATING SPEEDS OVER 40 MPH

FIGURE 18
FIGURE 19

EFFECT OF ACCELERATION LANE LENGTH ON RELATIVE SPEED DISTRIBUTION AT RAMP NOSE FREEWAY OPERATING SPEEDS OVER 40 MPH

A. 0 - 3°30′ ANGLE OF CONVERGENCE

B. 6 - 8° ANGLE OF CONVERGENCE

C. 10 - 14° ANGLE OF CONVERGENCE
ramp nose for each of three ramps with acceleration lanes less than 350 feet in length. The median relative speed on each of these ramps is greater than 30 mph while the percent of relative speeds greater than 20 mph ranges from 73% to 93%. This indicates the poor quality, and indeed hazardous, operation at these three ramps. The relative speeds are highest for the ramp with the largest convergence angle (θ = 14°).

For the four ramps with acceleration lanes between 400 and 500 feet in length, Figure 18b shows the relative speed distributions. The two ramps with the highest convergence angles have median relative speeds greater than 20 mph while the median speeds for the other ramps (θ = 5° and 7°) range from 9 mph to 13 mph. On the two ramps with the lowest convergence angles, from 15% to 18% of the relative speeds are greater than 20 mph but on the other two ramps with θ = 8°30' and 11° these corresponding percentages are 60% and 72%, respectively.

The relative speed distributions for the ramps having acceleration lane lengths between 600 and 800 feet are shown in Figure 18c. Four ramps have relative speed distributions which are much higher than those of the other six ramps. The four ramps having the highest relative speeds have convergence angles of 5°, 10°, 11° and 12°15' and have median relative speeds ranging from 23 mph to 30 mph. On the other five ramps on which θ is between 3°30' and 4° the median relative speeds were between 6 mph and 15 mph. (The ramp with θ = 5° has been previously discussed as having a ramp volume between 1000 and 1200 vph during the study which in part accounts for its high relative speeds). Thus, the convergence angle can be seen to have an important effect on the relative speeds at the ramp nose for ramps which have acceleration lane lengths between 600 and 800 feet.

For five ramps having acceleration lane lengths between 950 and 1200 feet the effect of convergence angles on the relative speeds is somewhat inconclusive as can be seen in Figure 18d. The two ramps with the highest relative speeds (median relative speed = 16 mph) have the high convergence angles (θ = 6° and 7°30') but the ramp with the lowest relative speed (median relative speed = 9 mph) has a θ of 7°30'. The two intermediate ramps both have θ = 1°.

The effect on relative speeds of different acceleration lane lengths is shown in Figure 19. The ramps are again placed in three groups of convergence angles (0-3°30', 6°-8° and 10°-14°). Within each group the relative speed distribution at the ramp nose is a function of acceleration lane length.
For small convergence angles (0-30°), shown in Figure 19a, relative speed distributions are closely grouped and no apparent relationship to acceleration lane length exists. In fact the relative speeds seem to be higher for the ramps with the longer acceleration lane. This is probably due to the traffic patterns - higher volumes on the longer ramps.

For six ramps with convergence angles between 6° and 8° the effect on relative speeds of acceleration lane length is more apparent. The shortest ramp (L = 240 feet) has a median relative speed of 34 mph. The distributions for the other five ramps are fairly closely clustered. The lengths of these five ramps are 500', 693', 970', 1025' and 1120' so it is somewhat surprising that the relative speed distributions are similar. The two short ramps are both at the foot of a downgrade to a depressed freeway (Edsel Ford Expressway in Detroit) and one was discussed in some detail earlier. Thus the grade of the ramp appears to be a geometric variable which has quite a significant effect on the merging operation.

In Figure 19c the relative speed distributions for five entrance ramps with θ between 10° and 14°. With the exception of the ramp with L = 680' the relative speeds decrease as L increases. For L = 335' the median relative speed is greater than 40 mph, for L = 340' the median is 29 mph, for L = 468' the median is 24 mph and for L = 785' the median speed is 23 mph. The acceleration lane of the other ramp is 680 feet in length but is only 9 feet wide and the width probably is a major factor in the 30 mph median relative speed. The relative speeds on all of these ramps are excessive and this is probably due primarily to the high convergence angles.

The effect of acceleration lane length on the relative speed at the ramp nose can be clearly seen in Figure 20a in which the relative speed distributions for four groups of ramps are presented. The four ramp groups are based on acceleration lane lengths of 0-350 feet, 400-500 feet, 600-800 feet and 950-1200 feet. Each distribution represents an average of the distribution for the ramps in each corresponding set of ramps in Figures 18a, 18b, 18c, and 18d.

The relative speeds at the ramp nose for the short ramps (0-350') are excessive with the median exceeding 35 mph. The three distributions for the other three ramp groups are somewhat similar with the relative speeds for the ramps with 400-500' acceleration lanes a bit higher than those for the ramps with acceleration lanes longer than 600 feet.
Figure 20b shows the effect of convergence angle on the relative speeds at the ramp nose. The three relative speed distributions represent averages for the ramps in the three angle groupings constituting Figures 19a, 19b, and 19c. The relative speed distributions for the 0°-30° set and the 6°-8° set are very similar. However, the distribution for the ramps with convergence angles between 10° and 14° indicates much higher relative speeds at these ramps. It thus appears that convergence angles up to six or eight degrees do not have a great effect on relative speeds at the ramp nose. Convergence angles greater than eight or ten degrees do appear to have a significantly adverse effect on relative speeds at the ramp nose.

Relative Speed at the Merge Point

The relative speed at the merge point was obtained for each vehicle for periods when the freeway operating speed was over 40 mph. For each ramp the mean relative speed (speed of freeway lag vehicle minus speed of ramp vehicle at merge point) is shown in Figure 21. While the general trend seems to be that ramps with better designs have lower relative merging speeds, there are many exceptions to this trend. Ramps with very short acceleration lanes and/or very large convergence angles have high relative merging speeds but the pattern is inconclusive for ramps with less extreme geometrics.

Two ramps with relatively high convergence angles (6°15' and 7°) and relatively short acceleration lanes (500 and 693 feet) have very low relative merging speeds (0.3 and 2.0 mph). These entrance ramps (Chene and Gratiot eastbound on the Edsel Ford Expressway in Detroit) are both downgrade ramps to the depressed freeway. The operation at each was very good and the merging volumes were quite high. This indicates the beneficial effect of the negative ramp grade on the merging operation as discussed previously.

Figure 22 presents the effect of angle of convergence on the relative merging speeds. Generally lower relative merging speeds are found on ramps with smaller convergence angles. The operation at the ramps with acceleration lanes between 950 and 1200 feet in length can be seen to be much more consistent (merging, speed distributions closely grouped) than the ramps with shorter acceleration lanes.

In Figure 23 the effect of acceleration lane length or relative merging speed can be seen. For the ramps with θ less than 3°30' a variation of acceleration lane lengths between 600 and 1200 feet had
EFFECT OF ACCELERATION LANE LENGTHS ON RELATIVE SPEEDS AT NOSE

EFFECT OF CONVERGENCE ANGLE ON RELATIVE SPEEDS AT NOSE

EFFECT OF ACCELERATION LANE LENGTHS ON RELATIVE SPEEDS AT MERGE POINT

EFFECT OF CONVERGENCE ANGLE OF RELATIVE SPEEDS AT MERGE POINT

EFFECT OF ACCELERATION LANE LENGTH AND CONVERGENCE ANGLE ON RELATIVE SPEEDS AT RAMP NOSE AND AT MERGE POINT

FREEWAY OPERATING SPEEDS OVER 40 MPH

FIGURE 20
EFFECT OF ACCELERATION LANE LENGTH AND CONVERGENCE ANGLE ON MEAN RELATIVE SPEED AT MERGE POINT
FREeway OPERATING SPEEDS OVER 40 MPH

Figure 21
EFFECT OF ANGLE OF CONVERGENCE ON RELATIVE MERGING SPEED

FREEWAY OPERATING SPEEDS OVER 40 MPH

FIGURE 22
EFFECT OF ACCELERATION LANE LENGTH ON RELATIVE MERGING SPEEDS

FREEWAY OPERATING SPEEDS OVER 40 MPH

FIGURE 23
virtually no effect on the relative merging speeds (Figure 23a).

In Figure 23b the effect of acceleration lane length on the ramps for which $\theta$ lies between $6^\circ$ and $8^\circ$ is shown. The ramp with the highest relative merge speeds has a 240 foot acceleration lane. On the other ramps $L$ ranged from 500 to 1120 feet and the effect of acceleration lane length is somewhat unclear due to a lack of any consistent relationship between $L$ and the relative merge speed distributions. Figure 23c which includes the ramps for which $\theta$ is between $10^\circ$ and $14^\circ$ presents data which show generally a decrease in relative speed for increases in acceleration lane length.

For freeway operating speed over 40 mph the effect of acceleration lane length and angle of convergence can be seen in Figure 20c and d. The average relative merging speed for all ramps included in the study with acceleration lane lengths below 350 feet, had much higher relative speeds than did the ramps with longer acceleration lanes (Figure 20c). The relative merge speed distributions for the other three ramp groups (based on length of acceleration lane) are very similar. Similarly, in Figure 20d it appears that convergence angles up to $8^\circ$ have little influence on relative merging speeds. However, angles in excess of $10^\circ$ lead to substantially higher relative speeds in the merging area.

It is interesting to compare Figure 20a to 20c and Figure 20b to 20d. It is quite apparent the relative speed decreases considerably between the ramp nose and the merge points.

**Accepted Gap Number**

The number of the gap which was accepted by each ramp vehicle on each ramp was obtained from the films. Gap number 1 for each ramp vehicle is the gap which is at the physical nose at the time the ramp vehicle arrives there. Gap number 2 is behind (upstream of) gap 1 and gap number 0, -1, etc. are downstream of gap 1 as shown in Figure 6.

Figure 24 presents the mean and standard deviation of the accepted gap number at each ramp. Each point represents a ramp with a particular set of geometric design features and the first number in parenthesis is the mean accepted gap for that ramp and the second number is the standard deviation of the accepted gap number. Only periods in which the freeway operating speed exceeded 40 mph were considered so the data reflect good freeway operation at each ramp.
MEAN AND STANDARD DEVIATION OF ACCEPTED GAP NUMBER
FREeways OPERATING SPEEDS OVER 40 MPH
FIGURE 24
If each ramp vehicle accepted the gap that was adjacent to the nose when the ramp vehicle reached the nose, the mean accepted gap number would be 1.0 and the standard deviation would be zero.

It can be seen in Figure 24 that ramps with low convergence angles and long acceleration lanes have associated with them a low mean and standard deviation of accepted gap number. This reflects on the ability of ramp drivers to select their gap at or before the nose on this type of ramp and indicates the consistency of operation on these ramps with good geometric designs. The consistency of behavior of ramp drivers is important in the achievement of a high degree of safety so the ramps with low standard deviations of accepted gap number probably have a lower accident record than the ramps on which the operation is more erratic. Many ramp accidents are caused by one driver assuming that the vehicle in front will accept a particular gap (2). If this assumption proves true, all is well. If not, the following vehicle may find it necessary to decelerate rapidly (especially at ramps with large convergence angles and short acceleration lanes where a "Russian roulette" type of merging operation is observed), possibly leading to hazardous maneuvers.

The ramps which have L greater than 600 feet and \( \theta \) less than 7-1/2° generally had good gap acceptance characteristics. With the exception of one ramp, the mean accepted gap number ranged from 1.1 to 1.5 and the standard deviation ranged from 0.1 to 0.7 gaps. One ramp in this group with \( L = 700, \ \theta = 5^\circ \) had a standard deviation of 1.0 gaps. The flow rate on this ramp during the study period was about 1200 vph which undoubtedly accounted for much of this variability. Even so, the operation there was much better than for most ramps which are not in this geometrically similar group.

The ramps which have an acceleration lane less than 600 feet in length and a convergence angle of 10° or larger exhibited poor gap acceptance characteristics. The mean accepted gap for this group was about 2.0 (a range of 1.7 to 2.4) and the standard deviation ranged from 1.2 to 2.4 gaps. This is considerably different than the similar data for the other geometric group. Table 1 summarizes the comparison of the two groups.
Table 1

Comparison of Accepted Gap Number for Two Ramp Groups

<table>
<thead>
<tr>
<th>Accepted Gap Number</th>
<th>Range of Means</th>
<th>Range of Standard Deviations</th>
</tr>
</thead>
<tbody>
<tr>
<td>Group 1</td>
<td>1.1-1.5 gaps</td>
<td>0.1-0.7 gaps</td>
</tr>
<tr>
<td>L &gt; 600'</td>
<td></td>
<td></td>
</tr>
<tr>
<td>θ &lt; 7°30'</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Group 2</td>
<td>1.7-2.4 gaps</td>
<td>1.2-2.4 gaps</td>
</tr>
<tr>
<td>L &lt; 600'</td>
<td></td>
<td></td>
</tr>
<tr>
<td>θ ≥ 10°</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

The effect of angle of convergence and acceleration lane length on the gap acceptance characteristics can be seen in Figure 25. The frequency distributions of accepted gap number for two entrance ramps are shown in this figure. The two ramps, the Dumble southbound entrance ramp on the Gulf Freeway in Houston and the Warren southbound entrance ramp on the Southfield Expressway in Detroit. Except for the length of acceleration lane and angle of convergence the two ramps are similar geometrically. Both ramps are basically level as is the freeway at each and both ramps are of the short, "slip ramp" type. Table 2 contains much of the pertinent information for the two ramps. Plan views of the two ramps can be seen in Appendix B.

Table 2

Operational Data for the Dumble and Warren Entrance Ramps

<table>
<thead>
<tr>
<th></th>
<th>Dumble</th>
<th>Warren</th>
</tr>
</thead>
<tbody>
<tr>
<td>Acceleration lane length</td>
<td>240'</td>
<td>660'</td>
</tr>
<tr>
<td>Angle of convergence</td>
<td>7°</td>
<td>3°30'</td>
</tr>
<tr>
<td>Number of films taken</td>
<td>5</td>
<td>2</td>
</tr>
<tr>
<td>Total merging volume</td>
<td>1200-1500 vph</td>
<td>1410-2030 vph</td>
</tr>
<tr>
<td>Ramp volume</td>
<td>400-500 vph</td>
<td>400-500 vph</td>
</tr>
<tr>
<td>Operating speeds</td>
<td>35-50 mph</td>
<td>40-50 mph</td>
</tr>
</tbody>
</table>

In Figure 25 the distribution of accepted gaps for the Warren entrance ramp can be seen to be much "tighter" (as reflected by the smaller standard deviation) than the distribution for the Dumble entrance ramp. At the Warren entrance only 3% of the vehicles had not
EFFECT OF L AND $\theta$ ON FREQUENCY DISTRIBUTIONS OF ACCEPTED GAP NUMBER

FIGURE 25
merged into gaps 0, 1, and 2 while at the Dumble ramp over 23% had not merged after gap 2 passed the ramp vehicle. (At a ramp similar in design to the Dumble ramp and also on the Gulf Freeway, a vehicle was observed to stop and wait for gap 35 before merging, i.e., it rejected the first 34 gaps.) These operational differences took place in spite of the substantially higher freeway volumes at the Warren entrance ramp. Thus, the better operation at the Warren entrance ramp can be attributed to the longer acceleration lane and smaller angle of convergence there.
FREQUENCY DISTRIBUTION OF MERGE POINTS

Much of the previous work in this field has involved the comparison of selected characteristics of geometry and traffic in describing acceleration lane use. This approach has certainly proved valuable in improving design of acceleration lanes, and it is used also in a later part of this paper. However, a purely mathematical description of acceleration lane use can contribute greatly to a basic understanding of the merging process. The next step will be to relate the parameters of this mathematics to the geometric and operational characteristics of the facility or facilities.

The distance from the nose to the point at which a ramp vehicle encroaches on the freeway shoulder lane is one measure of the manner in which an acceleration lane is used. It has been observed that the entry point is a result of the desire of the driver to follow a natural and easy path of entry, but that this path is affected by volumes and speeds of freeway shoulder lane traffic as well as by the geometrics of the entrance ramp and acceleration lane.

A mathematical description of entry distances must take into account not only the mean entry point, but also the dispersion of entries about this mean. Commonly this dispersion is best described by the variance. To be useful, particularly as a tool in simulation, a usable mathematical probability distribution must be defined and shown to describe the phenomena.

Examination of samples of data showed a frequency distribution that was not symmetrical but that had a very pronounced peak representing the activities of most drivers in entering the freeway. Generally, the entry points varied from quite near the nose to a point near the defined limit of the acceleration lane.

As developed in reference 7, the Pearson Type I probability distribution appears to satisfy these requirements of being non-symmetrical, showing a pronounced peak, and having upper and lower limits imposed by the geometric design. By variation of the parameters $\alpha$ and $\beta$ of the Pearson Type I distribution, the mean, variance, and mode can be shifted to approximately accord with the observed data on entry locations. Parameters $\alpha$ and $\beta$ for each set of data (approximately 20 minutes of film) were determined by equating the normalized sample mean and variance to the theoretical mean and variance of the distribution expressed in terms of $\alpha$ and $\beta$. 55
Acceptableness of the calculated curve as a valid description of the observed data was checked by the Chi-Square test.

In analyzing the film it was noted that not infrequently a vehicle would continue to travel far beyond the prescribed geometric limits of the acceleration lanes without entering the freeway shoulder lane. In some cases this meant driving over a mountable curb barrier. Consequently, since this additional travel was to greatly varying distances (although finite), the Pearson Type III distribution was investigated for its ability to describe the observed phenomena. It is non-symmetrical, shows a pronounced peak, and has a finite lower limit. Pearson Type III distributions were determined and tested for acceptability of fit in the same manner as described above for the Type I distribution.

The results are summarized in the following figures. Figures 26, 27, 28 and 29 show cumulative frequencies of Pearson Type III (Gamma) in solid lines and of Pearson Type I (Beta) in dashed lines, plotted against normalized acceleration lane lengths. The circles are values of the raw data from which the curves were derived.

Of the twenty-four sets of data shown in these figures, fourteen (58%) were accepted at an .05 level of significance as fitting a Pearson Type III distribution and sixteen (66.7%) were accepted as fitting a Pearson Type I distribution.

From the above, it appears feasible to describe the frequency distribution of freeway entry points mathematically. Such mathematical distributions can be used to check and validate computer simulation programs which are used to study the merging phenomena.
FREQUENCY DISTRIBUTION OF ENTRY POINTS

Figure 26
Frequency distribution of entry points

Figure 27
FREQUENCY DISTRIBUTION OF ENTRY POINTS

Figure 28
ASHBY AVENUE SOUTHBOUND ENTRANCE RAMP
EASTSHORE FREEWAY, SAN FRANCISCO

MONUMENT JUNCTION SOUTHBOUND ENTRANCE RAMP
I-680 IN PLEASANT HILL, SAN FRANCISCO

MILBRAE AVENUE SOUTHBOUND ENTRANCE RAMP
BAYSHORE FREEWAY, SAN FRANCISCO

BROADWAY NORTHBOUND ENTRANCE RAMP
BAYSHORE FREEWAY, SAN FRANCISCO

WATT AVENUE SOUTHBOUND ENTRANCE RAMP
I-80, SACRAMENTO

COLDWATER CANYON AVENUE WESTBOUND ENTRANCE RAMP
VENTURA FREEWAY, LOS ANGELES

FREQUENCY DISTRIBUTION OF ENTRY POINTS

Figure 29
REGRESSION ANALYSIS OF MERGING DISTANCE

In order to delineate those factors which affect the use of acceleration lanes as described by the distance from the physical nose to the entry point, a regression analysis was carried out using several geometric and traffic characteristics as the independent variables. Using the average distance from the nose to the point of entry during each three minute period as a dependent variable, the independent variables which were significant at the 5% level were determined.

The geometric variables used were the acceleration lane length, the length of the ramp, the effective ramp grade, the angle of convergence of the ramp at the nose, and the offset of the ramp at the nose. The variables which related to traffic characteristics were the per cent of trucks involved in the merge, the per cent of ramp vehicles involved in the merge, the total merge volume, and the product of the three minute flow rate and average velocity of the freeway vehicles approaching the nose.

It will be noticed that most of these variables have been used previously. But one of them requires some discussion, being introduced here for the first time. The new variable introduced, relative effective ramp grade, reflects the drivers ability to see or observe the freeway as he approaches it. Ramp grade at the nose seldom describes the grade or elevation characteristics of the approach ramp, since the ramp grade must closely match the freeway grade near the nose.

Ramp driver behavior as approaching a freeway can be described as follows. As soon as it is possible to see the freeway and the ramp driver is close enough to begin to adjust to and utilize an acceptable freeway gap, the ramp driver will begin to judge the speed of freeway vehicles and begin to search for a gap large enough for him to merge into. If the entrance ramp approaches the freeway from below (i.e. up a positive grade) a ramp vehicle driver can begin selecting a gap and merge only when the ramp elevation approximates that of the freeway.

On the other hand, if ramp approach is from above (i.e. down a negative grade) the driver has an earlier opportunity to begin selecting a gap and matching his speed with the freeway speed. Observation indicates that where possible, a majority of drivers begin overtly to observe freeway traffic where possible at a distance greater than 200 feet before the nose, but generally not more than 500 feet. In order
to reflect the effect of observing the freeway from the ramp, the Effective Ramp Grade expressed as a percent, was defined as the algebraic difference in the elevation at the nose and the elevation on the ramp 400 feet upstream of the nose or the length of the ramp if it was shorter than 400 feet divided by horizontal distance between these two points. The relative effective ramp grade is equal to the effective ramp grade minus the freeway grade.

Table 3 is a summary of the regression analyses. The test for significance was made at the 5% level. The variables considered in the regression model are:

### Table 3

**Summary of Regression Analysis**

Model: \( Y = B_0 + B_1X_1 + B_2X_2 + B_3X_3 + B_4X_4 + B_5X_5 + B_6X_6 + B_7X_7 + B_8X_8 + B_9X_9 \)

\( Y = \) Average distance from Nose to point of entry (Feet)

<table>
<thead>
<tr>
<th>Independent Variable, ( X_i )</th>
<th>Coefficient ( B_i )</th>
<th>Sign. ?</th>
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</thead>
<tbody>
<tr>
<td>( X_1 ) = Acceleration Lane Length (feet)</td>
<td>.128</td>
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<tr>
<td>( X_2 ) = Ramp Length (feet)</td>
<td>-.087</td>
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<tr>
<td>( X_3 ) = Relative Effective Ramp Grade (per cent)</td>
<td>+16.7</td>
<td>Yes</td>
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<tr>
<td>( X_4 ) = Angle of Convergence (degrees)</td>
<td>-16.9</td>
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<tr>
<td>( X_5 ) = Ramp Offset at Nose (feet)</td>
<td>18.1</td>
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<tr>
<td>( X_6 ) = QU on Freeway at Nose ( \frac{\text{(Veh-miles)}}{\text{hour}} )</td>
<td>.0026</td>
<td>Yes</td>
</tr>
<tr>
<td>( X_7 ) = Per Cent trucks in Merge Volume (per cent)</td>
<td></td>
<td>No</td>
</tr>
<tr>
<td>( X_8 ) = Per Cent Ramp Veh. in Merge Volume</td>
<td></td>
<td>No</td>
</tr>
<tr>
<td>( X_9 ) = Merge Volume (rate of flow) (Veh/hour)</td>
<td></td>
<td>No</td>
</tr>
</tbody>
</table>

Multiple Regression Coefficient = 0.90

\( B_0 = 87.1 \) feet
In summary, the results of the regression analysis are: 1) The following variables were found to be significant:

a. Acceleration lane length - drivers tend to take a longer distance to merge on ramps with longer acceleration lanes.

b. Ramp length - a longer ramp is associated with a shorter distance to entry point. This appears to result from the ramp drivers having a greater distance to adjust to freeway conditions before reaching the acceleration lane.

c. Relative effective grade - for which an increase in relative grade is associated with an increase in distance to entry point. As the percent grade increases from minus to plus (the ramp lower than the freeway), ramp drivers cannot begin selecting gap and adjusting speed until they get quite near the nose. Hence they tend to make more of the adjustment on the acceleration lane.

d. Angle of Convergence - for which an increase causes a decrease in distance to entry point. This apparently reflects a desire of drivers to continue a smooth, natural path of entry without having to perform the reverse curve that would be necessary when this angle is large and the driver went further down the acceleration lane to enter freeway. The drivers tend to stay on the path on which they are "aimed" by the ramp.

e. Ramp Offset at Nose - for which a larger offset distance causes an increase in distance to entry point. This is certainly to be expected since the ramp vehicle must move a greater transverse distance.

f. The product of the three minute rate of flow (expressed on a vehicle per hour basis) times the average speed - for which an increase causes an increase in distance to entry point.

2) Variables found not to be significant included the per cent trucks in the merge volume, the merge volume, and the per cent ramp vehicles in the merge volume.
INTERPRETATIONS AND CONCLUSIONS

From the results of these studies it is quite apparent that the operation in the merging area is to a great extent a function of the geometrics of the entrance ramp and acceleration lane. Among the geometric variables which were found to have a pronounced effect on the merging operation are the length of acceleration lane, angle of convergence, ramp grade and width of acceleration lane.

Based on these studies the following tentative conclusions are offered.

1. Based on the study of one entrance ramp with a 9 foot acceleration lane width and twenty three ramps with a 12 foot acceleration lane width, it appears that the narrower acceleration lane width has an adverse effect on the merging operation.

2. On each of the ramps for which the convergence angle was 30° or less the operation was extremely good. Each of these ramps had an acceleration lane at least 700 feet in length so it would appear that a desirable design standard include a low (less than 5° or 6°) convergence angle and a long (at least 700 feet) acceleration lane. (For the ramps studied which had a 700 foot length, this distance was measured from the physical nose which was about 2 feet off the pavement edge. If a more desirable 10 foot offset is used, the physical nose would be moved about 150 feet back so the desirable minimum acceleration lane length to be used with a 10 foot offset would be about 850 feet).

3. At each of the entrance ramps which had convergence angles 10° or greater and/or an acceleration lane length less than 350 feet very poor operation was noted. Based on these results and other observations, serious consideration should be given to the geometric modification or redesign of an entrance ramp if it has an angle of convergence greater than 10° and/or an acceleration lane length (based on a 2' offset at the nose) less than 600 feet for level or upgrade ramps or 500 feet for downgrade ramps. The resultant designs can lead to greatly improved merging operation and probably a substantial reduction in the number of minor accidents. If such redesign is impractical, a freeway merging control system can, in many cases, be used to improve the merging operation.

4. On the downgrade ramps which were studied, the operation was much better than would have been expected based on the acceleration lane length and convergence angle only. Apparently the better
field of view on these ramps allows ramp drivers to select a gap when they are 200 feet or so upstream of the nose and to accelerate to meet the gap near the nose and merge quickly. Thus some of the acceleration takes place in advance of the ramp nose and the need for a long acceleration lane may be somewhat diminished. Based on this conclusion, one could further conclude that better merging operation could be expected on a depressed freeway than on at grade or elevated freeway since downgrade entrance ramps are found on depressed freeways.

5. Variables which were found in the regression analysis to have a significant effect on the distance used by vehicles before merging are a) acceleration lane length, b) ramp length, c) relative effective grade between ramp and freeway, d) angle of convergence, e) ramp offset at the nose and f) the product of merging volume and speed. Factors which tended to decrease the distance used by vehicles to merge were: 1) shorter acceleration lane, 2) greater ramp length, 3) lower relative effective grade, 4) greater angle of convergence, 5) smaller offset at the nose and 6) a smaller product of merging volume and speed.

Further Research

This report was concentrated primarily on the effects of the angle of convergence and acceleration lane length. Several other important geometric variables (such as ramp grade) will be considered more fully in subsequent work.

In addition to the study of the effects of individual geometric elements a mathematical model is being developed describing the effect of all pertinent geometric variables on the traffic characteristics in the merging maneuver and in particular to determine the relative importance of each of the geometric variables. The probit mathematics, which have proved so valuable in describing the gap acceptance phenomena, appear to hold promise in this regard.
ACKNOWLEDGMENTS

In a large project with the national scope of its field studies the success depends to a very large extent on the cooperation of local governmental agencies. Throughout the course of this project the cooperation received from all such agencies was excellent. It is not possible to acknowledge each individual who helped the Project in some way and the following partial list is offered:

California Division of Highways: Messrs. James E. Wilson, Karl Moskowitz and Leonard Newman

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Michigan State Highway Department: Mr. Joseph Marlowe

New York Department of Public Works: Mr. N. C. Parsons

Long Island State Park Commission: Mr. Boyce

City of New York Department of Traffic: Mr. Edward Bonelli

Missouri Highway Department: Messrs. James Little and James Roberts

Texas Highway Department: Messrs. Dale D. Marvel, John N. Lipscomb and William V. Ward

The project sincerely appreciates and acknowledges the help of these agencies and their representatives.

Deserving special mention is Mr. Joseph W. Hess of the Bureau of Public Roads who, as the Project Contact Representative, aided the Project in major ways in making some contacts with local agencies, helping select some study sites and with some preliminary formulation of the Project scope and direction.

In addition, two other staff members of the Texas Transportation Institute were instrumental in much of the data collection work involved in the project. The data collection was quite extensive and the fine work of Mr. Thomas G. Williams, Research Assistant, and Mr. James Bradley, Motion Picture Production Technician, meant a
great deal to the success of the project and is certainly appreciated. Also greatly appreciated is the work of Mr. W. R. McCasland in making preparations for many of the Houston studies.
REFERENCES


## APPENDIX A

### Study of Geometries of Ramp Study Locations

<table>
<thead>
<tr>
<th>Location</th>
<th>Ramp Name</th>
<th>Length and Shape of Accel. Lane</th>
<th>Angle of Converg. at Ramp Nose</th>
<th>Angle of Converg. 2 Off Pavement Edge</th>
<th>Grade at Nose</th>
<th>Freeway Direction</th>
<th>Ramp Type</th>
<th>Ramp Curvature</th>
<th>Curb Offset at Nose</th>
<th>Length of Ramp</th>
<th>Comments</th>
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<td></td>
<td></td>
<td></td>
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<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
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<tr>
<td></td>
<td>Weslayan EB to Southwest Freeway</td>
<td>610'-P</td>
<td>12°15'</td>
<td>12°15'</td>
<td>level</td>
<td>East</td>
<td>diamond</td>
<td>tangent</td>
<td>2'</td>
<td>103'</td>
<td>4-lane</td>
</tr>
<tr>
<td></td>
<td>Buffalo Speedway EB to Southwest Freeway</td>
<td>620'-P</td>
<td>12°</td>
<td>12°</td>
<td>level</td>
<td>West</td>
<td>diamond</td>
<td>tangent</td>
<td>2'</td>
<td>160'</td>
<td>4-lane free-way curve</td>
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<td></td>
<td>Dumble SB to Gulf Freeway</td>
<td>240'-T</td>
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<td>5°</td>
<td>+0.5%</td>
<td>East</td>
<td>diamond</td>
<td>tangent</td>
<td>2'</td>
<td>170'</td>
<td>Freeway grade past ramp</td>
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<td>10°</td>
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<tr>
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<td>10°</td>
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<td>2'</td>
<td>180'</td>
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<td>14°</td>
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<td></td>
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<td>900'</td>
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<td>6°</td>
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<td>East</td>
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<td>2'</td>
<td>350'</td>
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<td>6°</td>
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<td>2'</td>
<td>432'</td>
<td>Free-way curve slight rt.</td>
</tr>
<tr>
<td></td>
<td>Dempster NB to Edens Expwy.</td>
<td>785'-P</td>
<td>11°</td>
<td>11°</td>
<td>level</td>
<td>North</td>
<td>outer con-</td>
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<td></td>
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<td>11°</td>
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<td>3'</td>
<td>600'</td>
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<td><strong>San Francisco Area</strong></td>
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<td>800'</td>
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<td>4°</td>
<td>tangent</td>
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<td>tangent</td>
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<td>diamond</td>
<td>Z' 500'</td>
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<td>2°</td>
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<td>North</td>
<td>diamond</td>
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<td>380'</td>
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<td>connector</td>
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<td>450'</td>
<td>Freeway curve slight left</td>
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<td>East</td>
<td>connector</td>
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<td>West</td>
<td>connector</td>
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<td>600'</td>
<td>2-lane</td>
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**GEOMETRIC CHARACTERISTICS DATA**

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<td>Shape of Acceleration Lane</td>
<td>Taper</td>
</tr>
<tr>
<td>Angle of Convergence at Ramp Nose</td>
<td>2(^\circ) 30'</td>
</tr>
<tr>
<td>Angle of Convergence 2 ft. Off Pavement Edge</td>
<td>2(^\circ) 30'</td>
</tr>
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</tr>
<tr>
<td>Freeway Grade</td>
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<tr>
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<td>Freeway Curvature</td>
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<tr>
<td>Ramp Curvature</td>
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<td>Length of Ramp</td>
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**GEOMETRIC CHARACTERISTICS**
WARREN EASTBOUND ENTRANCE RAMP
SOUTHFIELD EXPRESSWAY, DETROIT

*Figure B1*
GEOMETRIC CHARACTERISTICS DATA

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<tr>
<td>Freeway Grade at Nose</td>
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<td>Length of Ramp</td>
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GEOMETRIC CHARACTERISTICS

DUMBLE EASTBOUND ENTRANCE RAMP
GULF FREEWAY, HOUSTON

Figure B2