Operational Effects of Some Entrance Ramp Geometrics on Freeway Merging

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•A wide range of geometric design standards has been used on freeways which are now open to traffic. These different geometrics as well as different traffic patterns have resulted in 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, poor design features were accepted and built into some early freeways because it was not known what constituted good or bad design. Since operational studies were unknown, there was little feedback of operational information to the designer, and in many cases the volumes remained low enough so that the 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, traffic 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 is 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 for 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. Despite 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 may in most cases be due merely to a lack of adequate traffic volumes to test the operational capabilities of the designs or may be due to a lack of cognizance on the part of the designer of the operation of

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some of his designs. This report places emphasis on the correlation of design and operations which will hopefully lead to improved design on future freeways.

Another area of freeway design which is receiving 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 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 that most need redesign or traffic control. The present study will help (a) determine which entrance ramp designs warrant remodeling; (b) determine the type of improvement which would best alleviate the problem; and (c) 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 gap acceptance characteristics and 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.

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. Most of the analyses presented in this report concentrate on the first two variables.

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 (Appendix) in Houston, Los Angeles, San Francisco, Sacramento, Chicago, Detroit, St. Louis, and New York City. The acceleration lanes of the ramps studied ranged from 240 to 1500 ft and the convergence angles ranged from 1 to 14 deg. Data from 23 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-min period, were exposed at each study location.

STUDY PROCEDURES

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 airplane from which the time-lapse photographs were taken. The radius of the circle was about ¼ mile and the altitude and lens were selected (a) to obtain adequate coverage of the merging area, (b) to locate the plane at the altitude of least air turbulence, and (c) 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 sec. The rotation of the scene during analysis was not a problem because a stop-frame analysis was used.

Reference marks were placed at 200-ft intervals on the right shoulder of the freeway and on the ramp shoulder. A reference mark was placed at the physical nose of the

Figure 1. Camera mounted in aircraft.

ramp and the marked area extended 400 ft 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 the freeway scene was accompanied by a data chamber showing the time of day, the frame number, and 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 circles.

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: (a) the vehicle type, (b) the location of the vehicle (ramp or freeway lane), and (c) 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. 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 studied, pure merging situations were sought, i.e., locations at which the traffic operation was unaffected by upstream or downstream conditions. Merging operation at or near capacity was also desired. Local

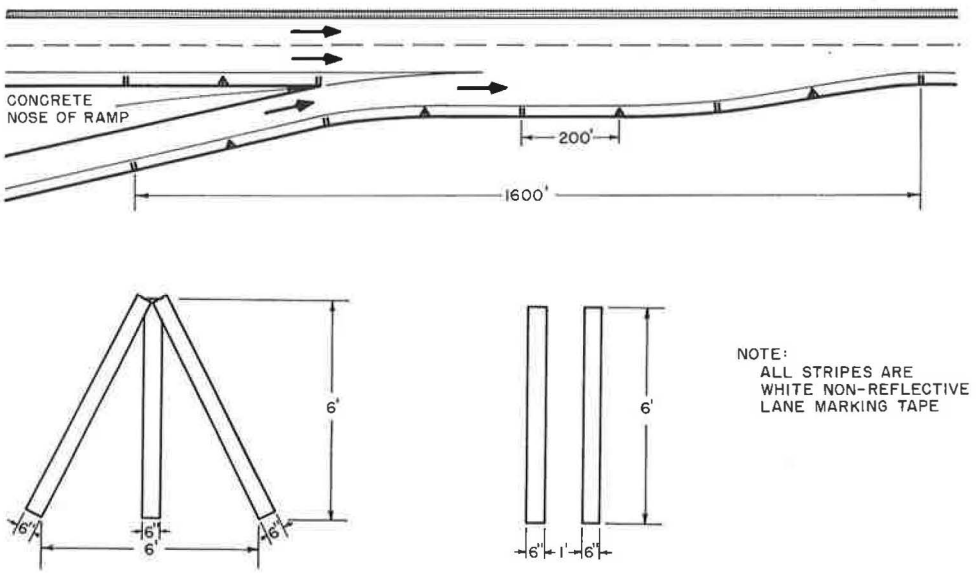


Figure 2. Typical study section.

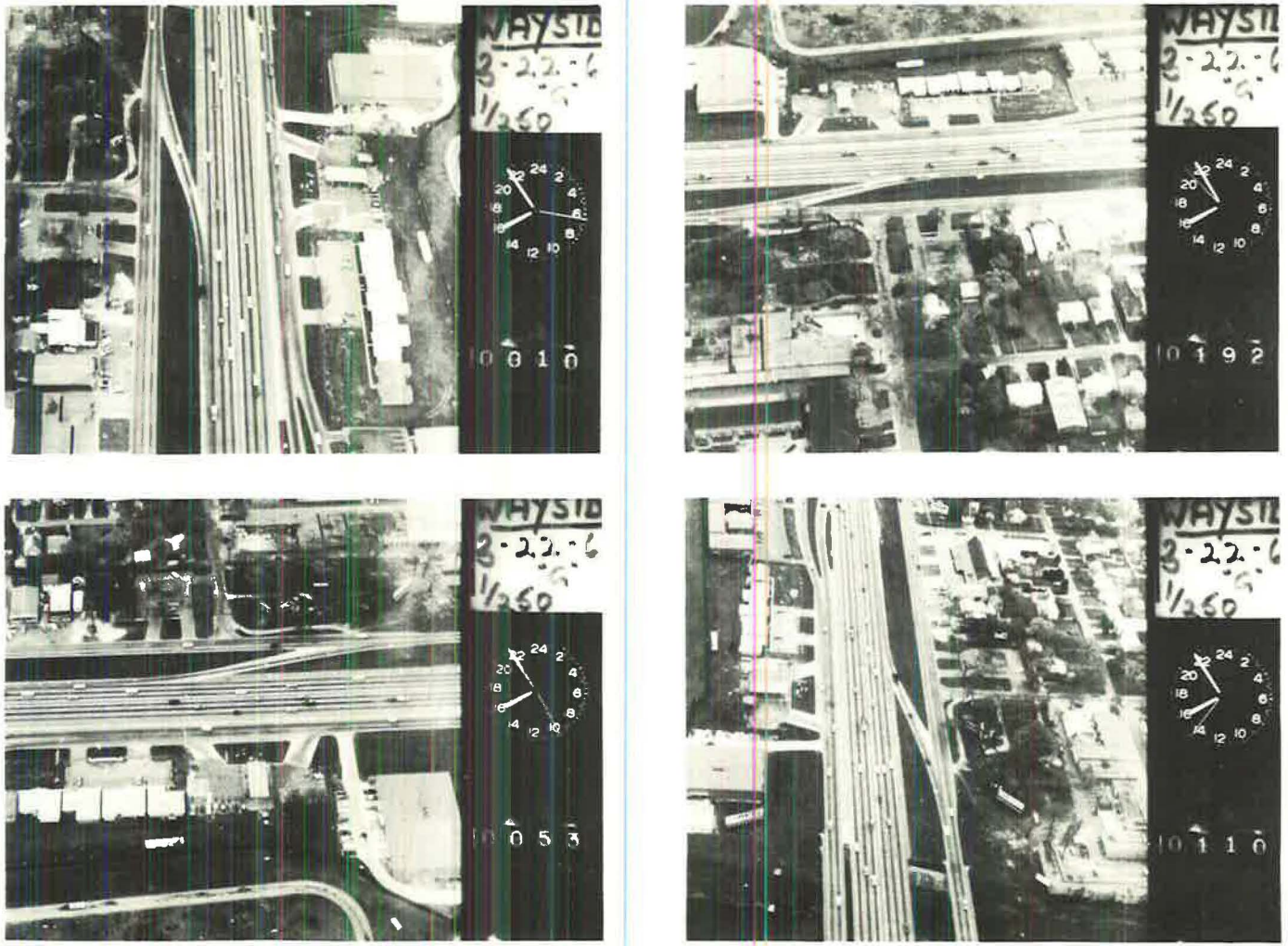


Figure 3. Typical frames from data film.

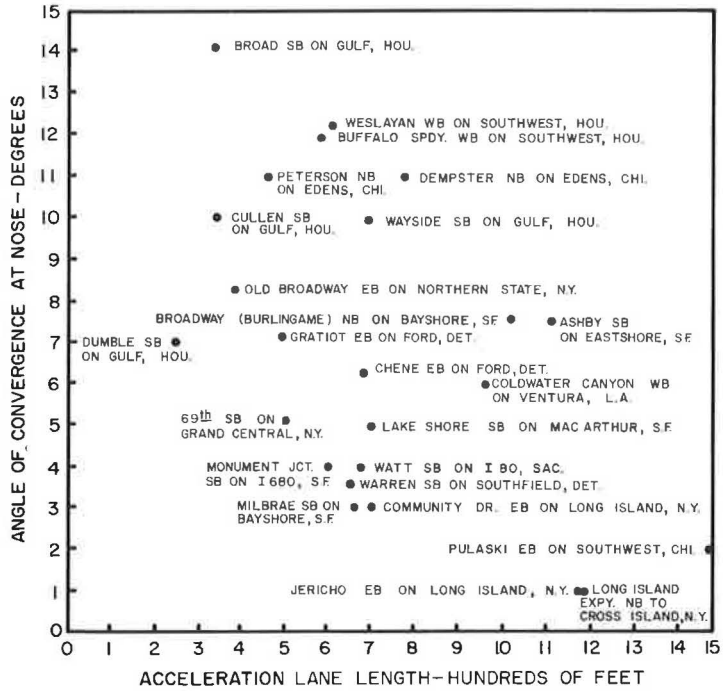


Figure 4. Summary of acceleration lane lengths and convergence angles.

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, 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.

One of the objectives in selecting study sites was to obtain a wide range of geometrics in the ramps studied: particularly, variations in acceleration lane length, angles of convergence, and ramp grade. Locations having straight, level freeway alignment were of primary interest, since the effect of freeway geometrics was not being studied. Figure 4 shows a geometric summary of the 24 entrance ramps for which data are included in the report. The coordinates consist of the acceleration lane length and angle of convergence. Figure 4 shows 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 operations.

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 that the merging volume was near capacity.

Entrance ramps included in the study 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.

RAMP GEOMETRICS

The following geometric data were obtained for each of the entrance ramps which were studied:

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, and
9. Curb offset at the nose.

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. For example, a 600-ft acceleration lane on a ramp at which the offset at the nose is 10 ft is not equivalent to a 600-ft acceleration lane on a ramp at which the offset is 2 ft. 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-ft 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 ft, at a point where the left edge of the ramp (as delineated by the paint markings) was 2 ft off the edge of pavement of the freeway. Both of these angles are discussed in the analyses which follow.

Most of the geometric data were 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.

REDUCTION 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 (Fig. 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 ft apart so that 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; thus, it was quite simple to obtain a time-space trajectory for each vehicle in the merging area of each ramp studied. For each roll of film 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 solid lines and the trajectory of vehicles on the ramp were plotted in

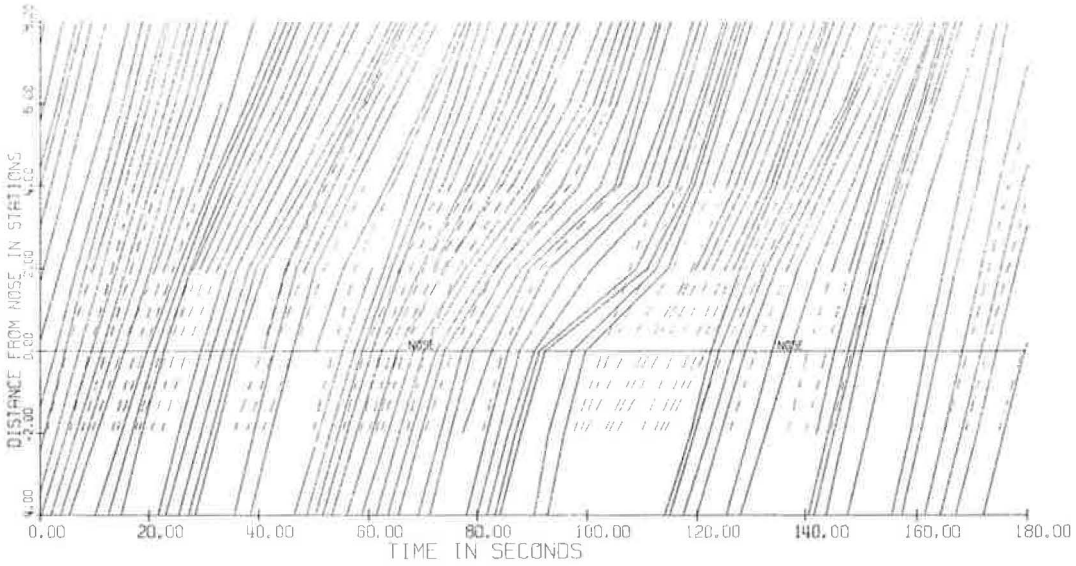


Figure 5. Time-space diagram: Broadway northbound entrance ramp, Bayshore Freeway, San Francisco. Dashed lines represent vehicles on ramp, solid lines represent vehicles on freeway.

dashed lines. The point at which a dashed line turned into a solid line 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. Further details of the film reduction process are given elsewhere (5).

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 less than 25 mph, between 25 and 40 mph, and 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 that the operations above 40 mph are the type intended when the freeways were designed, and that the operation at this level is more variable than in the other, since the drivers' decisions are less constrained.

Speeds of Ramp Vehicles at Ramp Nose

For each of the entrance ramps included in the study, the distribution of speeds of vehicles on the ramp over the 200-ft 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 (a) freeway traffic conditions, (b) ramp alignment, (c) ramp grade, (d) ramp angle of convergence, and (e) acceleration lane length. The last two factors affect the speed at the nose because they affect the gap acceptance characteristics and hence the (queuing) 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 queuing 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, thus, 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 by Fukutome and Moskowitz (3), instead of by freeway speeds alone, but the sample sizes of the data did not permit such a classification.

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 ft, 400-600 ft, 600-800 ft and 950-1200 ft). 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 (0-3 deg 30 min, 6-8 deg and 10-14 deg). 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.

Speeds of Ramp Vehicles at Merge Point

The distributions of the speeds of ramp vehicles in the 200-ft 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 vs acceleration lane length for various ranges of convergence angles, and were plotted vs 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; a high relative speed between vehicles on the ramp and those on the freeway indicates 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.

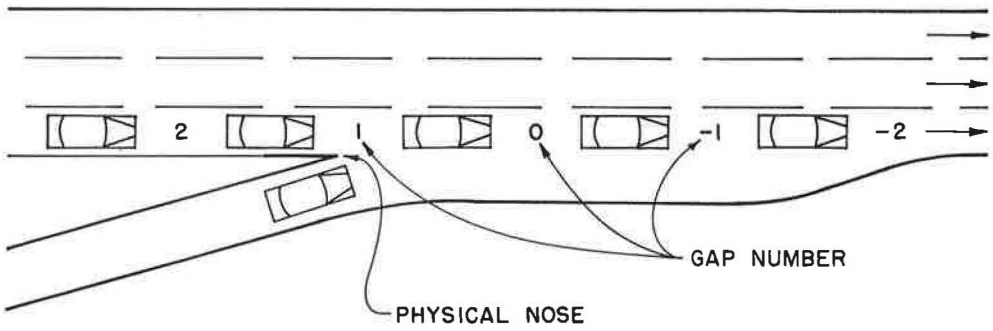


Figure 6. Number of gaps in the right lane.

The relative speed between each ramp vehicle and its lag vehicle was computed at several locations along the merging area. The first speed trap is the 200-ft length upstream of the ramp nose, and each 200-ft 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 speeds are presented as functions of acceleration lane length and angle of convergence in a manner similar to the presentation of the other distributions; the means of the distributions are also shown as a 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 10 or 15 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 (Fig. 6). The gap that is adjacent to the ramp vehicle when it is at the nose is gap 1; 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 (6).

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.

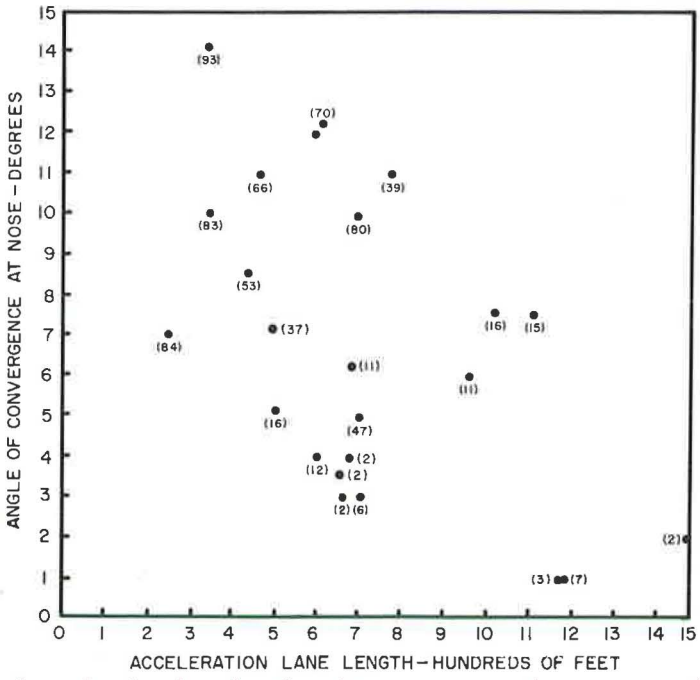


Figure 7. Effect of acceleration lane length and convergence angle on percent of ramp vehicles traveling less than 30 mph at the ramp nose.

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 represent 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 deg. The percent of ramp vehicles passing the ramp nose at speeds less than 30 mph ranges from a low of 2 for three ramps with acceleration lanes between 600 and 700 ft and with angles of convergence between about 2 to 4 deg to a high of 93 percent for a ramp with an acceleration lane of 335 ft and a 14-deg 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 ft, three ramps; 400-500 ft, four ramps; 600-800 ft, ten ramps; and 950-1200 ft, five ramps. Each distribution represents the speed of ramp vehicles at the ramp nose when freeway speeds were 40 mph or higher. Figure 8 shows these distributions.

Figure 8a shows the ramp speed distributions for three entrance ramps with acceleration lanes less than 350 ft. 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 deg. The lengths of these two ramps are nearly equal so that the difference in speeds can be attributed almost entirely to the difference in convergence angles. The speed distribution of the third ramp on which $\theta = 7$ deg falls between the distributions for the other two ramps. Based 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

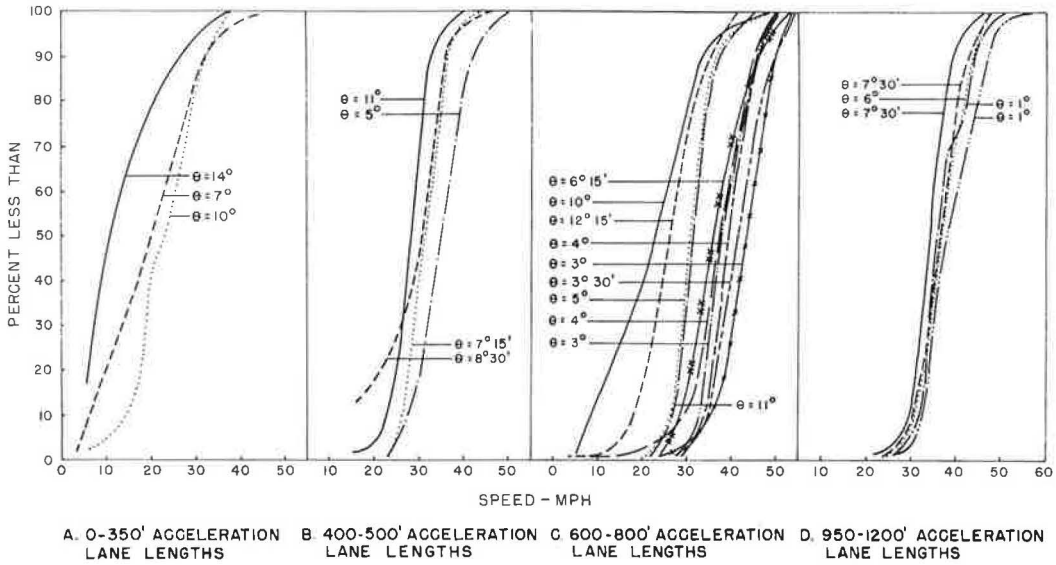


Figure 8. Effect of angle of convergence on ramp speed distribution at ramp nose.

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 ft. The angles of convergence of these ramps range from 5 to 11 deg and the operational effects of the convergence angle can be clearly seen. The ramp with the lowest speeds is the ramp θ = 11 deg (66 percent of ramp speeds less than 30 mph) followed by the ramps with θ = 7 deg (41 percent less than 30 mph) and θ = 8 deg 30 min (50 percent less than 30 mph), while the ramp with the lowest convergence angle (5 deg) has the highest speeds, with only 16 percent of speeds below 30 mph.

Thus, for entrance ramps with short (400-500 ft) acceleration lanes, a change in convergence angle from 11 deg to 5 or 6 deg would result in about 50 percent more of the entrance ramp vehicles passing the ramp nose at speeds greater than 30 mph 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 is plotted for entrance ramps with acceleration lane lengths between 600 and 800 ft. 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 deg 30 min to 6 deg 15 min. 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 percent. For the other four ramps (θ = 5 deg, 10 deg, 11 deg, and 12 deg 15 min), the median speed ranges from 22 mph to 31 mph, while the percent of speeds below 30 mph is between 39 percent and 80 percent. Thus, the operation on the six ramps with the lower convergence angles is much better than on the other four ramps.

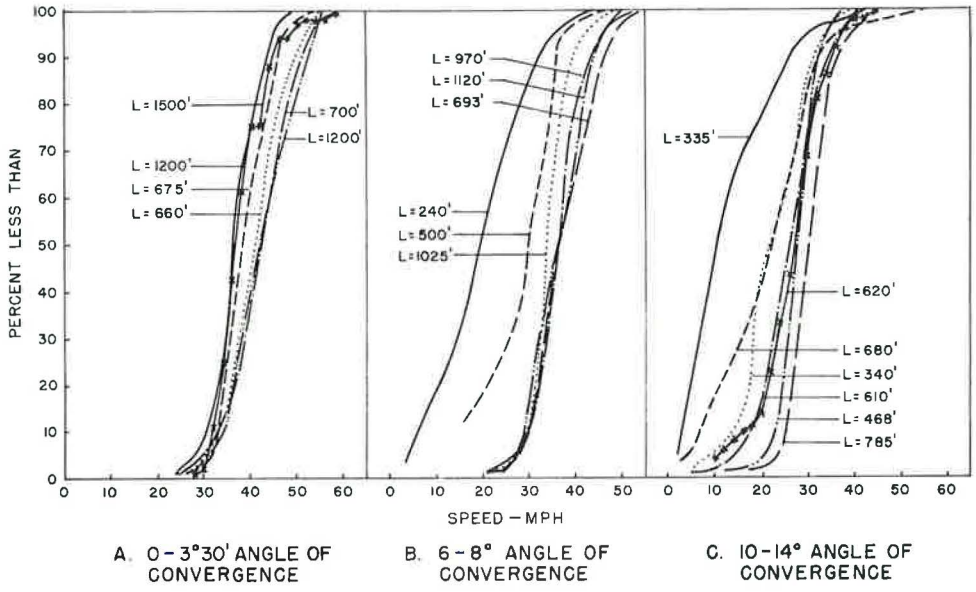


Figure 9. Effect of acceleration lane length on ramp speed distribution at ramp nose.

One of the ramps on which the speeds were relatively low had an angle of 5 deg. One would not expect to find such a large difference in operation between the ramp with a 5-deg convergence angle and the other ramps with generally lower convergence angles. The operational difference probably reflects the extremely high volume (1000-1200 vph) on the ramp with θ = 5 deg, rather than the difference in convergence angles.

Similar speed distributions for five entrance ramps with long (950 to 1200 ft) acceleration lanes are shown in Figure 8d. For these ramps, θ varies between 1 deg and 7 deg 30 min. The operation at these ramps was generally similar. On each ramp the percent of speeds less than 30 mph was less than 25 percent 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 percent and 26 percent for the two ramps with θ = 7 deg 30 min and is a minimum of 40 percent for the three other ramps (θ = 1 deg, 1 deg and 6 deg). Thus, the traffic operation was good on each of the ramps on which the acceleration lane length is at least 950 ft and the convergence angle is less than 7 deg 30 min.

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 deg 30 min, 6-8 deg and 10-14 deg. The speed distribution of ramp vehicles passing the ramp nose for each ramp was plotted in its proper angle group (Fig. 9). For ramps with approximately the same convergence angle, the effect of different acceleration lane lengths can be observed. All ramp speed distributions in Figure 9 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 ft. As might be expected of these ramps which all have low convergence angles and at least an adequate (600 ft) 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 percent 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-ft 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.

Because of a greater range of acceleration lane lengths, the effect of this geometric element can be seen quite clearly in Figure 9b. Here the distribution of speeds or ramp vehicles passing the ramp nose is shown for six ramps having a convergence angle lying between 6 and 8 deg. The acceleration lanes vary in length from 240 ft to 1120 ft. The ramp which experienced the worst operation had an acceleration lane length of 240 ft. The median speed for this ramp was 19 mph, whereas 84 percent 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 percent of the speeds below 30 mph.

On one ramp the operation was surprisingly good. This ramp has a θ of 6 deg 15 min, an L of 693 ft 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 deg group, in spite of its comparatively short acceleration lane length. At this location the ramp itself is on a 4.1 percent downgrade preceding the nose for a distance of about 450 ft. 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 the lane in which the gap is located, and 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 deg. The median speeds for these ramps range from 11 mph for a ramp which has an acceleration lane length of 335 ft to 31 mph for a ramp with L = 785 ft. On the ramp with L = 785 ft, 39 percent of the vehicles pass the nose at speeds of 30 mph or less, whereas for the other ramps this percent ranges from 66 percent to 93 percent, indicating a much poorer operation.

The ramp with L = 680 ft (θ = 10 deg) has a poorer operation than might be expected considering the acceleration lane length. The width of acceleration lane at this location,

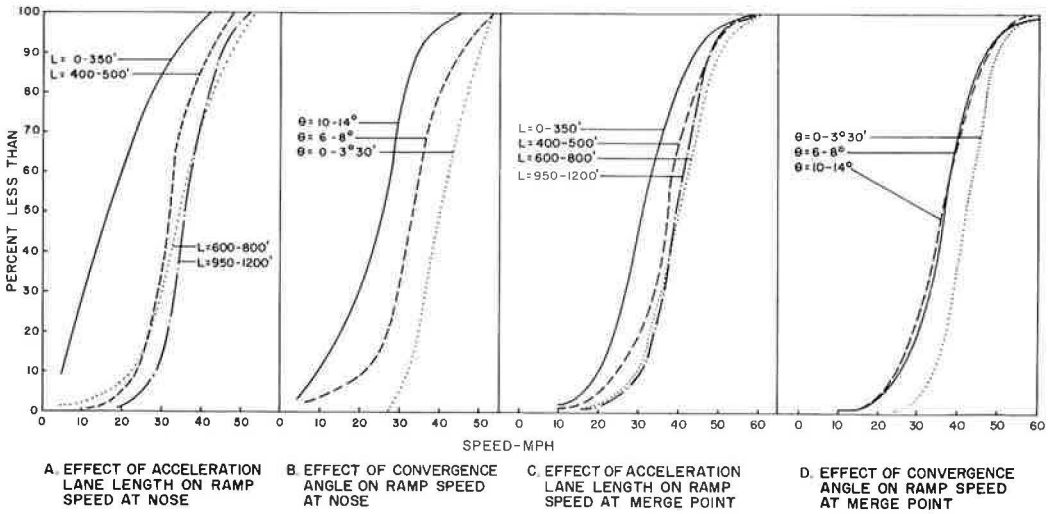


Figure 10. Effect of acceleration lane length and convergence angle on speeds of ramp vehicles at nose and at merge point.

however, is only about 9 ft 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 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 ft are much lower than those of the other ramps, and the speeds on the ramps with acceleration lanes between 400 and 500 ft are somewhat less than the speeds for the ramps with acceleration lanes longer than 600 ft.

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 deg are much higher than the speeds on the ramps with convergence angles greater than 6 deg. The lowest speeds were observed on the ramps with θ between 10 and 14 deg. 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

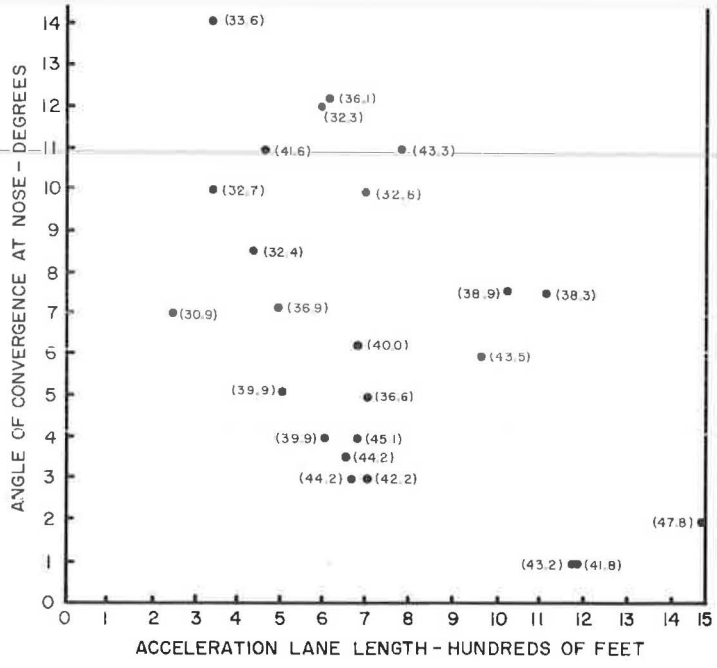


Figure 11. Effect of acceleration lane length and convergence angle on mean merge speed of ramp vehicles.

vehicle on each ramp was obtained at the 200-ft section in which the ramp vehicle first encroached on the right lane of the freeway. This was the vehicle merging speed; 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.

The mean merging speed on each of the ramps included in the analyses is shown 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 deg was about 40 mph or higher. In this group no ramp has an acceleration lane less than 600 ft and, with a convergence angle less than 4 deg, the merging speeds would be expected to exceed 40 mph when the freeway speeds were also over 40 mph.

The effect of angle of convergence on the distribution of merging speeds of ramp vehicles is shown in Figure 12. For acceleration lanes less than 350 ft in length (Fig. 12a), there seems to be little effect of convergence angle, at least over the range included (7 to 14 deg). 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 ft, 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 ft. The two ramps with the lowest merge speeds have θ = 10 deg and θ = 12 deg 15 min. Of the five ramps which have the highest merging speeds, four have convergence angles between 3 deg 30 min and 4 deg. The fifth, however, has a large convergence angle (11 deg). 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 ft. The two ramps with the highest convergence angle (θ = 7 deg 30 min 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 deg. It would appear that the effect of convergence angle on merge speeds is greater on entrance ramps with longer acceleration lanes.

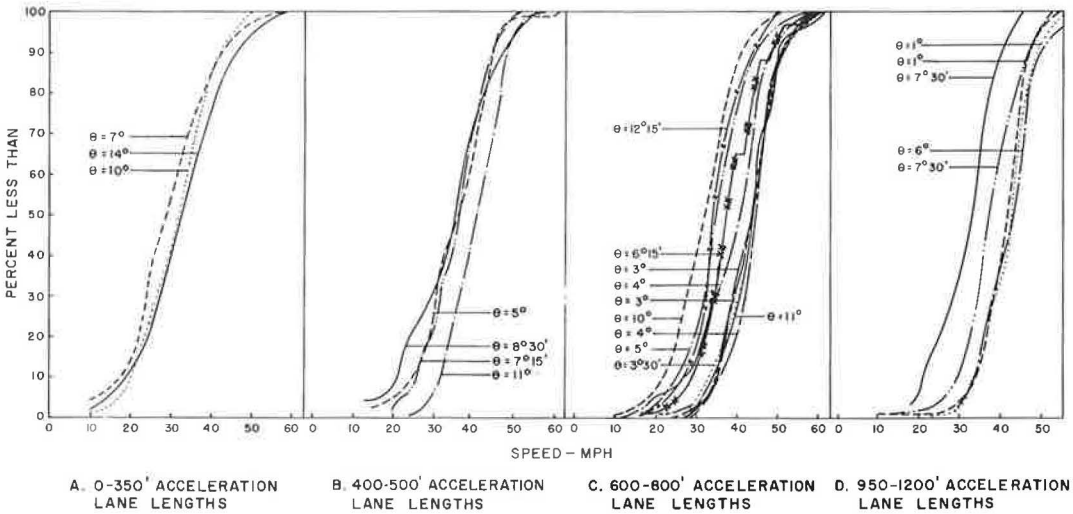


Figure 12. Effect of angle of convergence on merging speed of ramp vehicles.

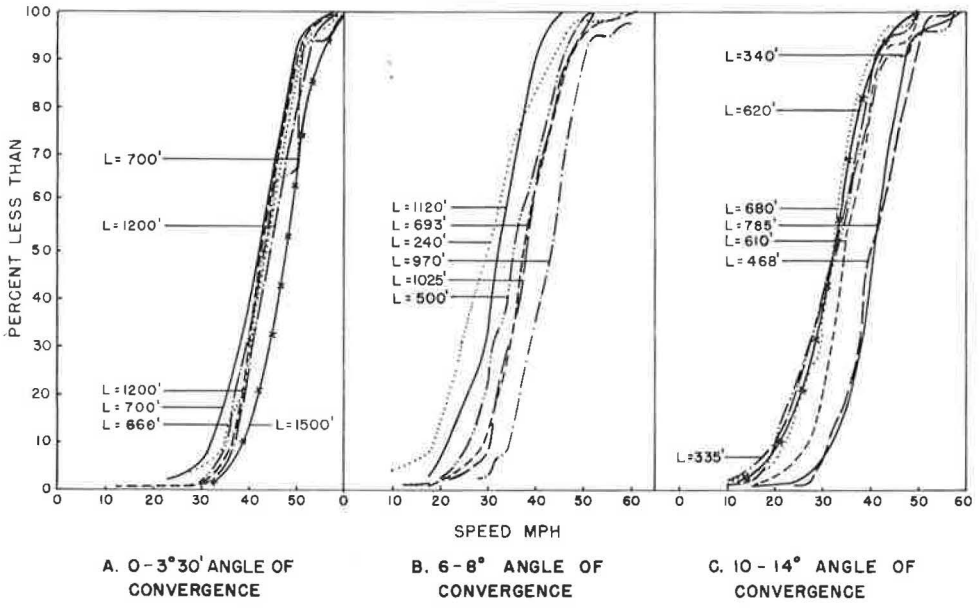


Figure 13. Effect of acceleration lane length on merging speeds of ramp vehicles.

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 deg 30 min is shown in Fig-

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 ft of acceleration lane.

The pattern is more mixed at the ramps with convergence angles between 6 and 8 deg, 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 (970 and 1025 ft), while two of the three ramps with the lowest speeds have short acceleration lanes (240 and 500 ft). For ramps with convergence angles between 10 and 14 deg (Fig. 13c), 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 is plotted. In Figure 10c, the lowest merge speed distribution is associated with ramps with acceleration lanes less than 350 ft. Highest merge speeds are related to ramps with acceleration lanes longer than 600 ft.

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

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

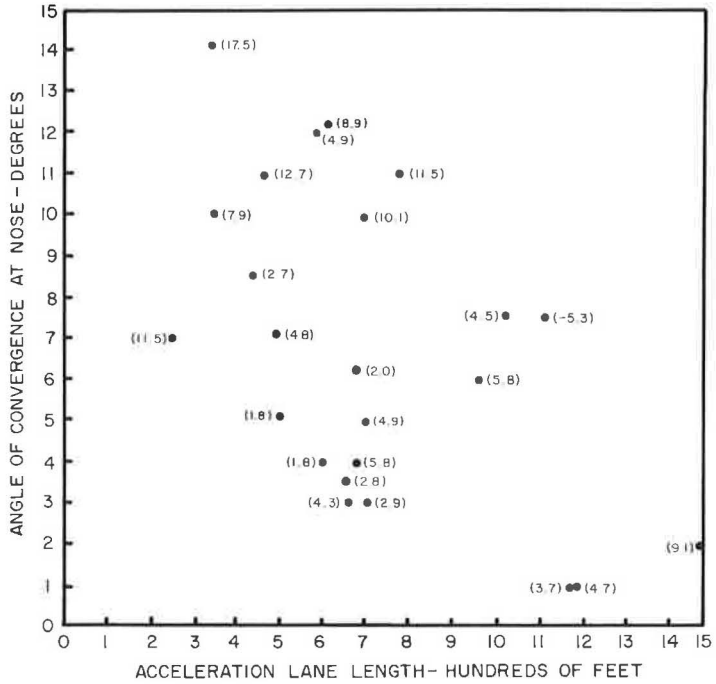


Figure 14. Effect of acceleration lane length and convergence angle on mean speed change of ramp vehicles between nose and merge point.

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 ft and the convergence angle is less than 8 deg, none of the speed increases was greater than 6 mph. On only one of the ramps outside this group (acceleration lanes shorter than 450 ft and/or convergence angles greater than 8 deg) 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 on an entrance ramp between the ramp nose and the point of merge is shown 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, 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,

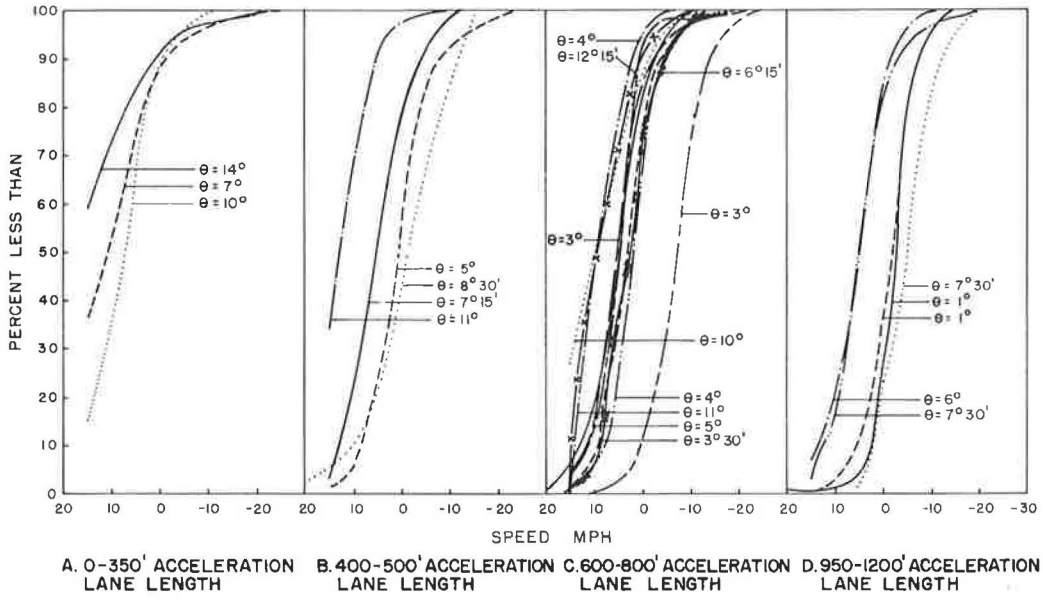


Figure 15. Effect of angle of convergence on speed changes between ramp nose and merge point for ramp vehicles.

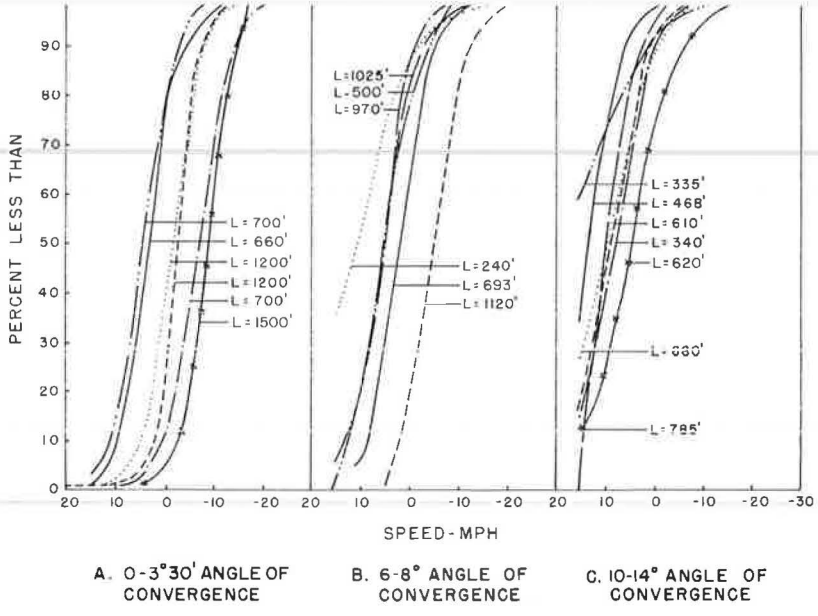


Figure 16. Effect of acceleration lane length on speed changes between ramp nose and merge point for ramp vehicles.

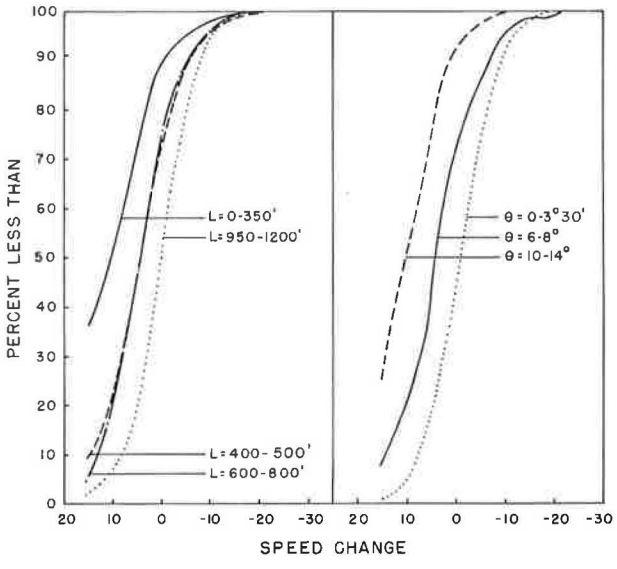


Figure 17. Effect of acceleration lane length and angle of convergence on ramp speed changes between ramp nose and merge point.

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.

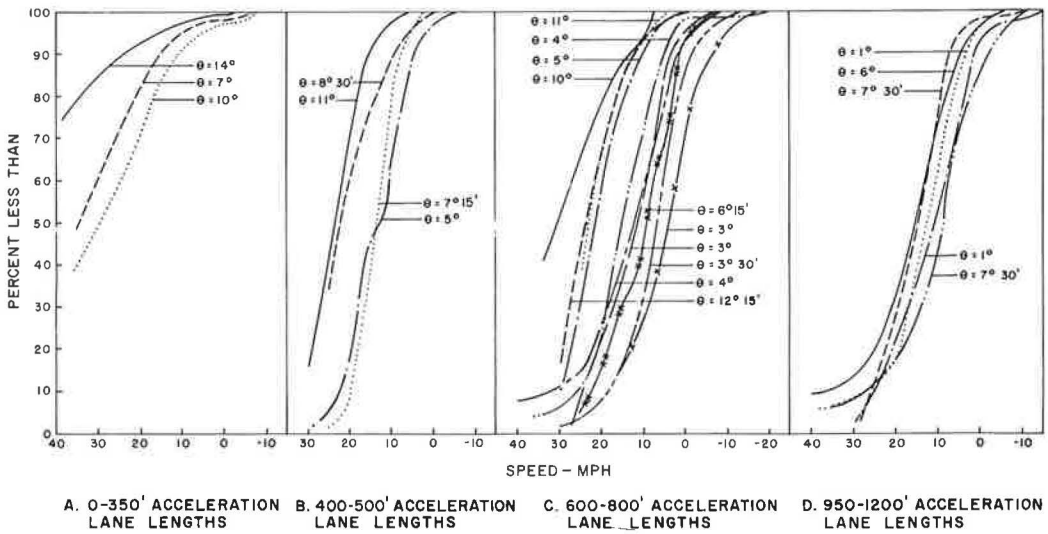


Figure 18. Effect of angle of convergence on relative speed distribution at ramp nose.

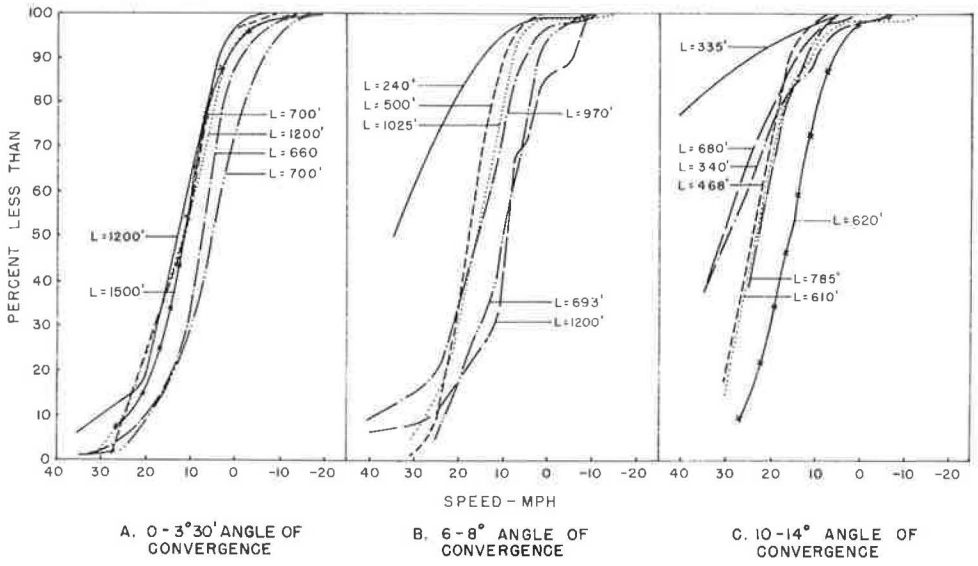


Figure 19. Effect of acceleration lane length on relative speed distribution at ramp nose.

The effects of acceleration lane length and convergence angle on the changes in speed of ramp vehicles on the acceleration lane are shown in Figure 17. Figure 17a shows that the speed changes are higher on ramps with shorter acceleration lanes, and Figure 17b shows that the speed changes are higher on ramps with large convergence

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 (Fig. 18). To show the effect of acceleration lane length, the ramps were placed in three groups of convergence angles (Fig. 19).

Figure 18a shows the plots of relative speed distribution at the ramp nose for each of three ramps with acceleration lanes of less than 350 ft. The median relative speed on each of these ramps is greater than 30 mph, whereas the percent of relative speeds greater than 20 mph ranges from 73 percent to 93 percent. 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 deg).

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

The relative speed distributions for the ramps having acceleration lane lengths between 600 and 800 ft 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 deg and 12 deg 15 min and have median relative speeds ranging from 23 mph to 30 mph. On the other five ramps on which θ is between 3 deg 30 min and 4 deg, the median relative speeds were

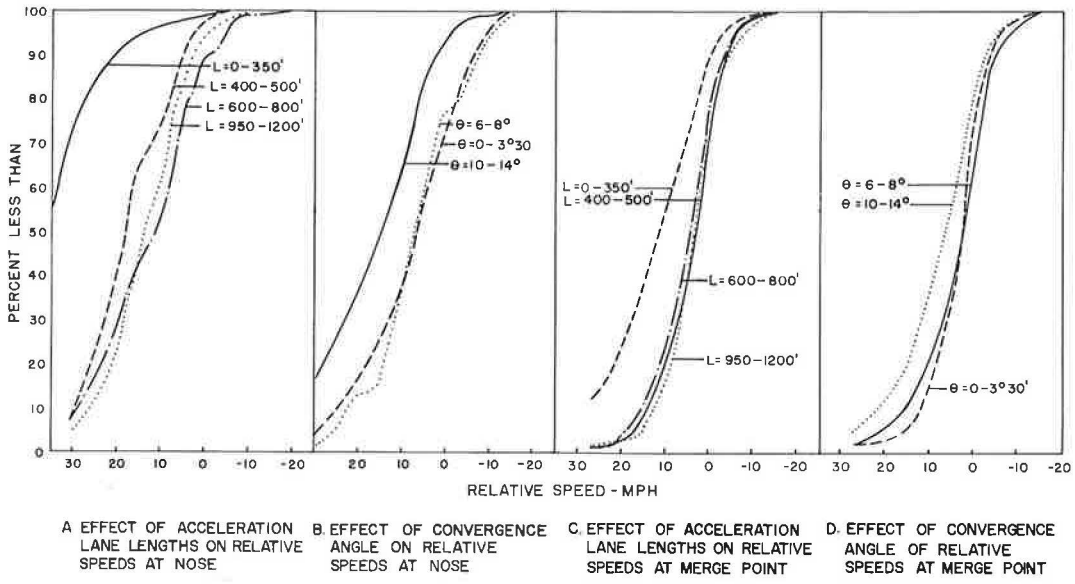


Figure 20. Effect of acceleration lane length and convergence angle on relative speeds at ramp nose and at merge point.

between 6 mph and 15 mph. (The ramp with θ = 5 deg 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 ft.

For five ramps having acceleration lane lengths between 950 and 1200 ft, the effect of convergence angles on the relative speeds is somewhat inconclusive (Fig. 18d). The two ramps with the highest relative speeds (median relative speed = 16 mph) have the high convergence angles (θ = 6 deg and 7 deg 30 min), but the ramp with the lowest relative speed (median relative speed = 9 mph) has a θ of 7 deg 30 min. The two intermediate ramps both have θ = 1 deg.

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 deg 30 min, 6-8 deg and 10-14 deg). Within each group the relative speed distribution at the ramp nose is a function of acceleration lane length.

For small convergence angles (0-3 deg 30 min) 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 deg the effect on relative speeds of acceleration lane length is more apparent. The shortest ramp (L = 240 ft) 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 ft, 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.

Figure 19c shows the relative speed distributions for five entrance ramps with θ between 10 and 14 deg. With the exception of the ramp with L = 680 ft, the relative

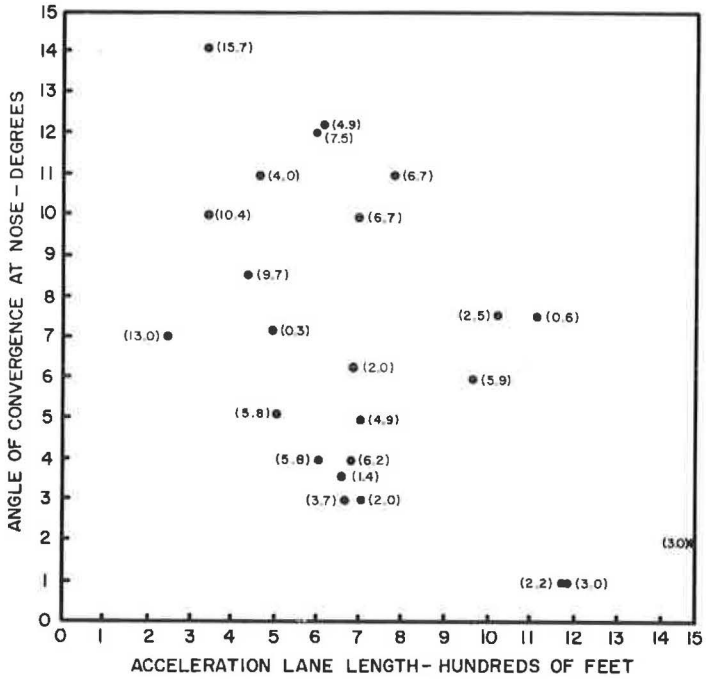


Figure 21. Effect of acceleration lane length and convergence angle on mean relative speed at merge point.

speeds decrease as L increases. For L = 335 ft, the median relative speed is greater than 40 mph, for L = 340 ft, the median is 29 mph, for L = 468 ft, the median is 24 mph, and for L = 785 ft, the median speed is 23 mph. The acceleration lane of the other ramp is 680 ft, but it is only 9 ft 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 ft, 400-500 ft, 600-800 ft and 950-1200 ft. Each distribution represents an average of the distribution for the ramps in each corresponding set of ramps in Figure 18a, b, c, and d.

The relative speeds at the ramp nose for the short ramps (0-350 ft) 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 ft acceleration lanes a bit higher than those for the ramps with acceleration lanes longer than 600 ft.

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 Figure 19a, b, and c. The relative speed distributions for the 0-3 deg 30 min set and the 6-8 deg set are very similar. However, the distribution for the ramps with convergence angles between 10 and 14 deg indicates much higher relative speeds at these ramps. Thus, it appears that convergence angles up to 6 or 8 deg do not have a great effect on relative speeds at the ramp nose. Convergence angles greater than 8 or 10 deg do appear to have a significantly adverse effect on relative speeds at the ramp nose.

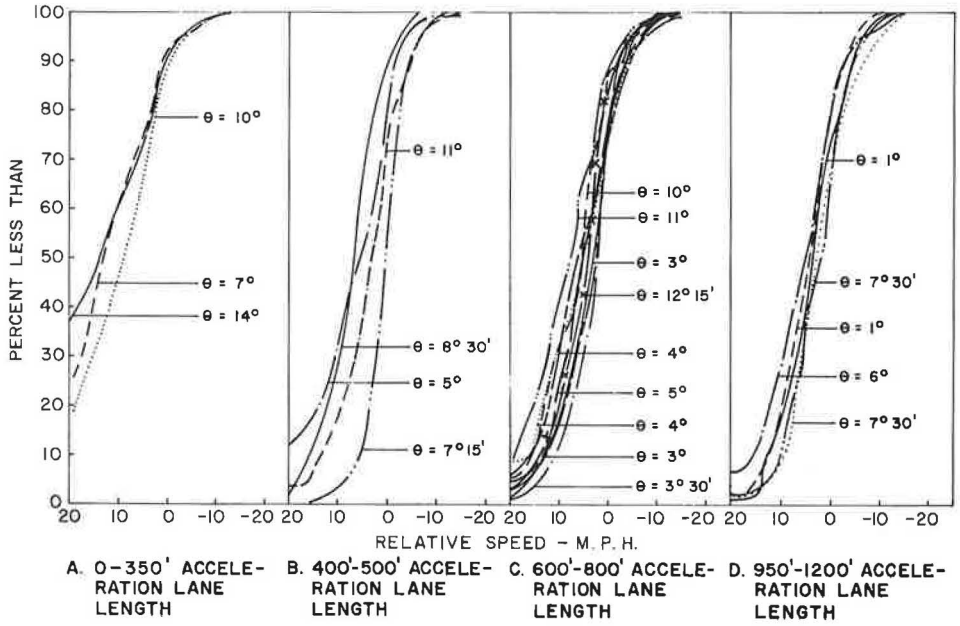


Figure 22. Effect of angle of convergence on relative merging speed.

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

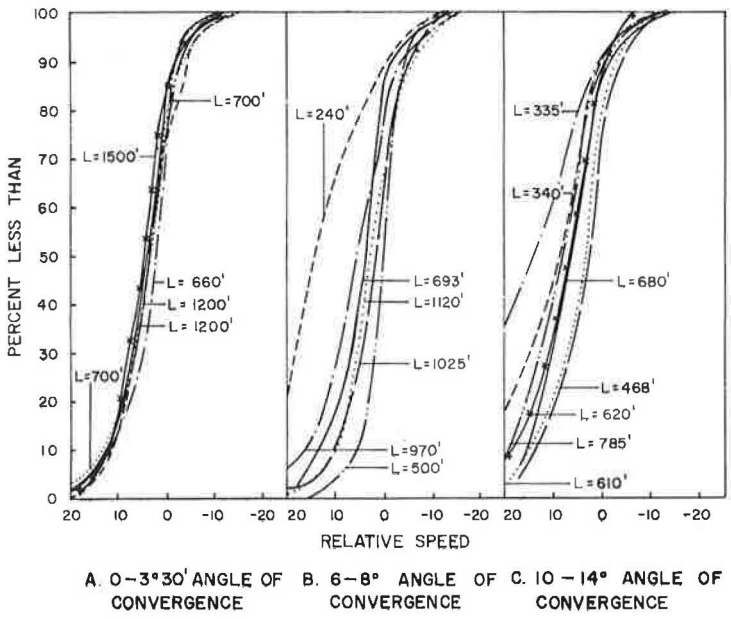


Figure 23. Effect of acceleration lane length on relative merging speeds.

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 deg 15 min and 7 deg) and relatively short acceleration lanes (500 and 693 ft) 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 shows 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 ft 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 on relative merging speed is shown. For the ramps with θ less than 3 deg 30 min, a variation of acceleration lane lengths between 600 and 1200 ft had virtually no effect on the relative merging speeds (Fig. 23a).

Figure 23b shows the effect of acceleration lane length on the ramps for which θ lies between 6 and 8 deg. The ramp with the highest relative merge speeds has a 240-ft acceleration lane. On the other ramps, L ranged from 500 to 1120 ft, 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 θ is between 10 and 14 deg, presents data that show generally a decrease in relative speed for increases in acceleration lane length.

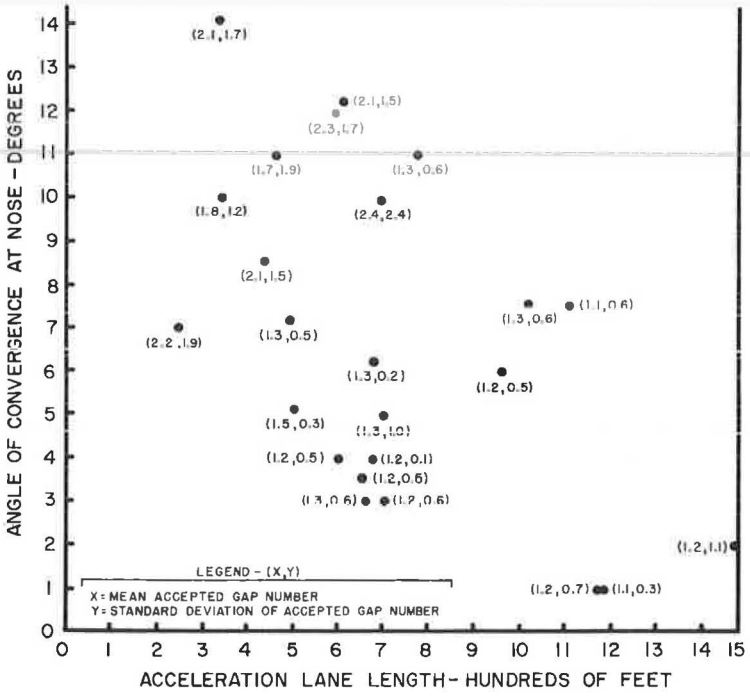


Figure 24. Mean and standard deviation of accepted gap number.

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 which had acceleration lane lengths below 350 ft had much higher relative speeds than did the ramps with longer acceleration lanes (Fig. 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 deg have little influence on relative merging speeds. However, angles in excess of 10 deg 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 1 for each ramp vehicle is the gap which is at the physical nose at the time the ramp vehicle arrives there. Gap 2 is behind (upstream of) gap 1 and gaps 0, -1, etc., are downstream of gap 1 (Fig. 6).

Figure 24 shows 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; 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. 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.

Figure 24 shows 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, and 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 had L greater than 600 ft and θ less than 7 deg 30 min generally had good gap acceptance characteristics. With the exception of one ramp, the mean

TABLE 1

COMPARISON OF ACCEPTED GAP NUMBER FOR TWO RAMP GROUPS

Groups	Accepted Gap Number	
	Range of Means	Range of Standard Deviations
Group 1 L > 600 ft θ < 7 deg 30 ft	1.1-1.5 gaps	0.1-0.7 gaps
Group 2 L < 600 ft $\theta \geq$ 10 deg	1.7-2.4 gaps	1.2-2.4 gaps

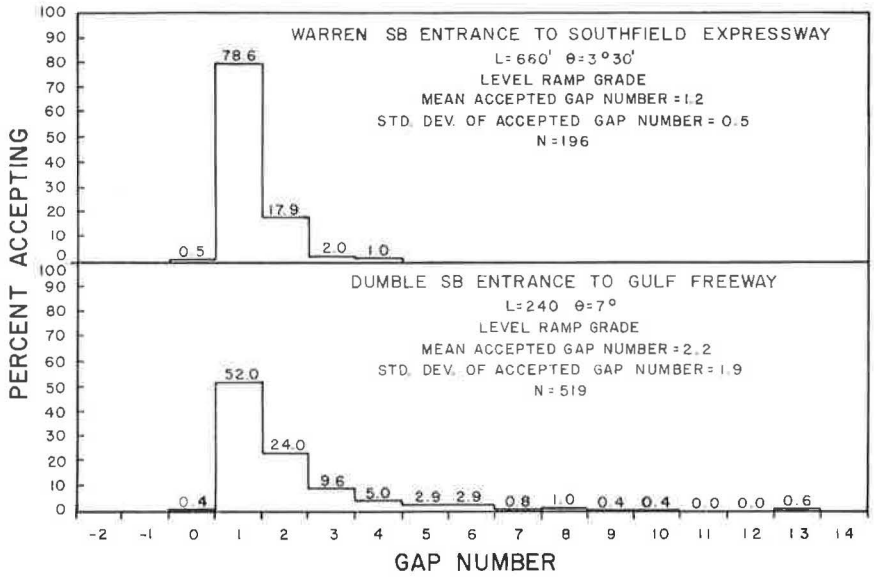


Figure 25. Effect of L and θ on frequency distributions of accepted gap number.

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 ft and θ = 5 deg had a standard deviation of 1.0 gaps. The flow rate on this ramp during the study period was about 1800 vph, which undoubtedly accounted for much of this variability. Even so, the means

similar group.

The ramps which have an acceleration lane of less than 600 ft and a convergence angle of 10 deg 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.

The effect of angle of convergence and acceleration lane length on the gap acceptance characteristics is shown in Figure 25. The frequency distributions of accepted gap numbers for two entrance ramps are also shown in this figure. The two ramps are 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

TABLE 2
OPERATIONAL DATA FOR THE DUMBLE AND WARREN ENTRANCE RAMPS

Data	Dumble	Warren
Acceleration lane length	240 ft	660 ft
Angle of convergence	7 deg	3 deg 30 min
Number of films taken	5	2
Total merging volume	1200-1500 vph	1410-2030 vph
Ramp volume	400-500 vph	400-500 vph
Operating speeds	35-50 mph	40-50 mph

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.

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 percent of the vehicles had not merged into gaps 0, 1, and 2, while at the Dumble ramp over 23 percent 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 the mathematics to the geometric and operational characteristics of the facility or facilities.

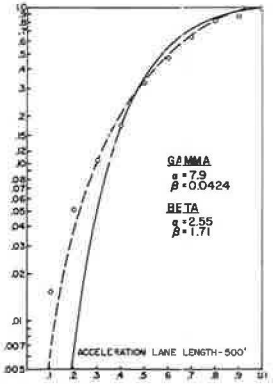
The distance from the nose to the point at which a ramp vehicle encroaches on the freeway shoulder lane is one measure of the manner in which an acceleration lane is used. It has been observed that the entry point is a result of the desire of the driver to follow a natural and easy path of entry, but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

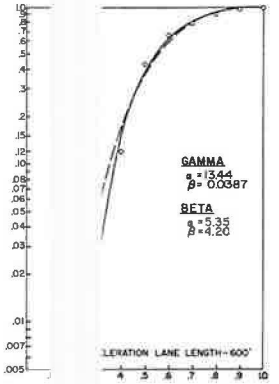
Examination of samples of data showed a frequency distribution that was not symmetrical but that had a very pronounced peak representing the activities of most drivers in entering the freeway. Generally, the entry points varied from quite near the nose to a point near the defined limit of the acceleration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

The Pearson Type I probability distribution (7) appears to satisfy the requirements of being nonsymmetrical, showing a pronounced peak, and having upper and lower limits imposed by the geometric design. By variation of the parameters α and β 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 α and β for each set of data (approximately 20 min 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 α and β. Acceptableness of the calculated curve as a valid description of the observed data was checked by the chi-square test.

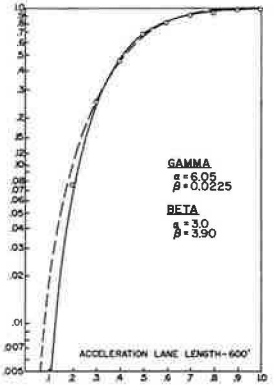
In analyzing the film, it was noted that not infrequently a vehicle would continue to travel far beyond the prescribed geometric limits of the acceleration lanes without entering the freeway shoulder lane. In some cases this meant driving over a mountable curb barrier. Consequently, since this additional 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 nonsymmetrical, 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 for the Type I distribution.



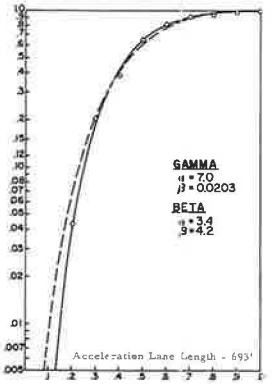
CHENE EASTBOUND ENTRANCE RAMP
EDSEL FORD EXPRESSWAY, DETROIT



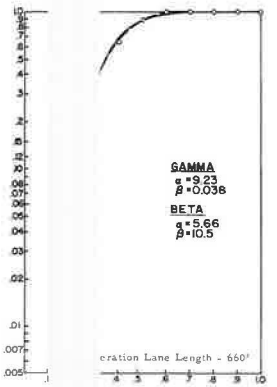
WARREN AVE
SOUTHF
OUTHBOUND ENTRANCE RAMP
EXPRESSWAY, DETROIT



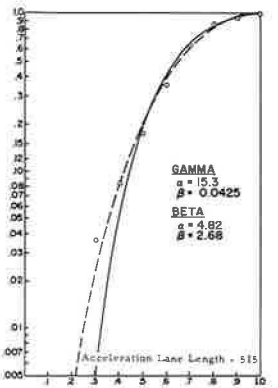
LINWOOD NORTHBOUND ENTRANCE RAMP
JOHN LODGE EXPRESSWAY, DETROIT



DEMPSTER STREET NORTHBOUND ENTRANCE RAMP
EDENS EXPRESSWAY, CHICAGO

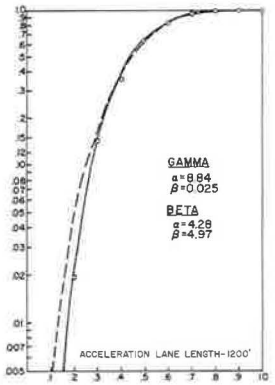


KOSTNE
EISENH
TBOUND ENTRANCE RAMP
EXPRESSWAY, CHICAGO

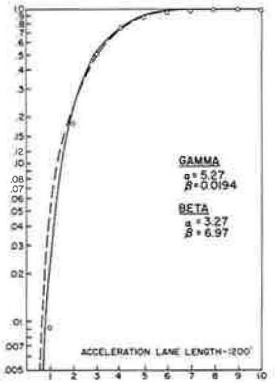


PETERSON NORTHBOUND ENTRANCE RAMP
EDENS EXPRESSWAY, CHICAGO

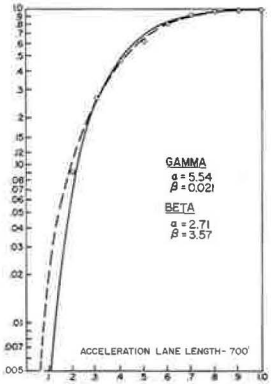
Figure 26. Freque distribution of entry points.



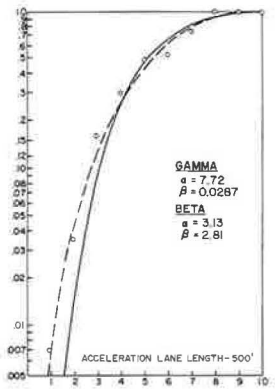
JERICHO (RT. 25) EASTBOUND ENTRANCE RAMP
LONG ISLAND EXPRESSWAY, NEW YORK



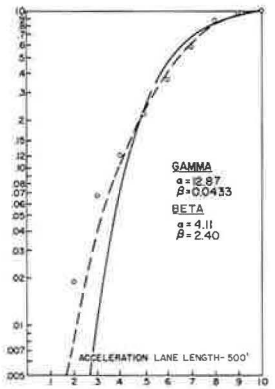
LONG ISLAND EXPRESSWAY NORTHBOUND ENTRANCE RAMP
CROSS ISLAND EXPRESSWAY, NEW YORK



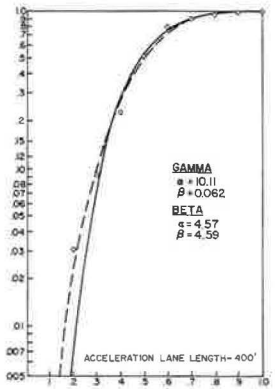
COMMUNITY DRIVE EASTBOUND ENTRANCE RAMP
LONG ISLAND EXPRESSWAY, NEW YORK



BRUSH HOLLOW ROAD EASTBOUND ENTRANCE RAMP
NORTHERN STATE PARKWAY, NEW YORK

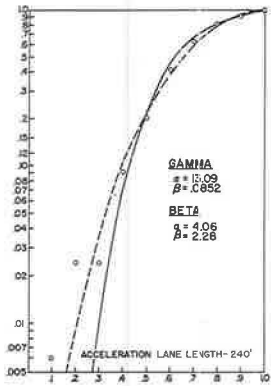


69TH ROAD (JEWEL STREET) SOUTHBOUND ENTRANCE RAMP
GRAND CENTRAL EXPRESSWAY, NEW YORK

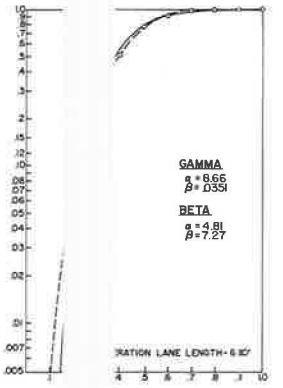


ROCKAWAY NORTHBOUND ENTRANCE RAMP
VAN WYCK EXPRESSWAY, NEW YORK

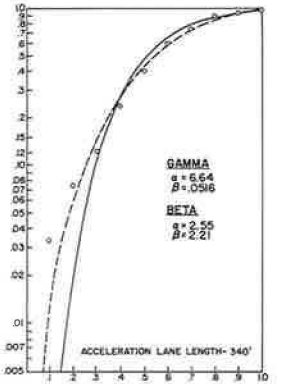
Figure 27. Frequency distribution of entry points.



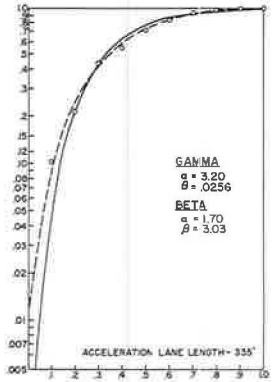
DUMBLE SOUTHBOUND ENTRANCE RAMP
GULF FREEWAY, HOUSTON



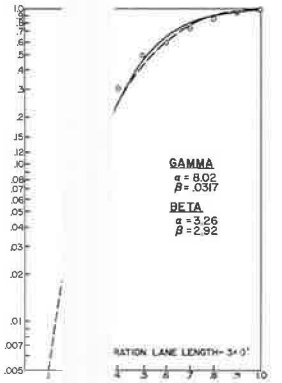
WAYSIDE S
GUL
)OUND ENTRANCE RAMP
EEWAY, HOUSTON



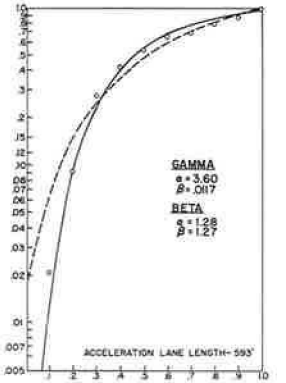
CULLEN SOUTHBOUND ENTRANCE RAMP
GULF FREEWAY, HOUSTON



BROAD STREET SOUTHBOUND ENTRANCE RAMP
GULF FREEWAY, HOUSTON

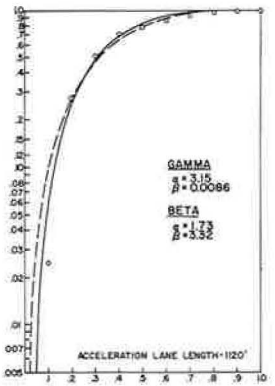


TELEPHONE
GUL
HBOUND ENTRANCE RAMP
EEWAY, HOUSTON

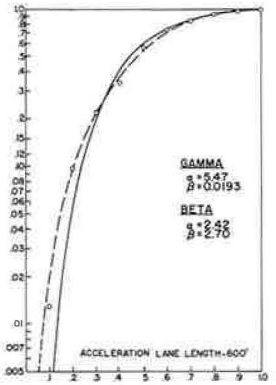


BRENTWOOD WESTBOUND ENTRANCE RAMP
DANIEL BOONE EXPRESSWAY, ST. LOUIS

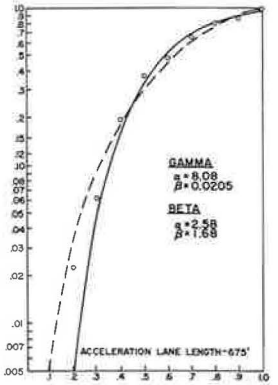
Figure 28. Freque distribution of entry points.



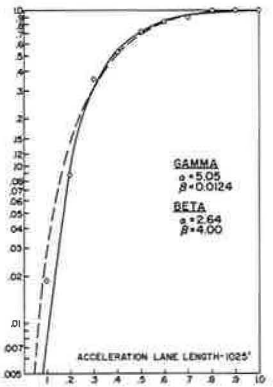
ASHBY AVENUE SOUTHBOUND ENTRANCE RAMP
EASTSHORE FREEWAY, SAN FRANCISCO



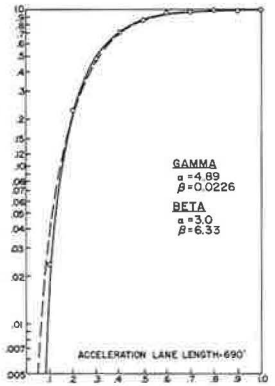
MONUMENT JUNCTION SOUTHBOUND ENTRANCE RAMP
I 680 IN PLEASANT HILL, SAN FRANCISCO



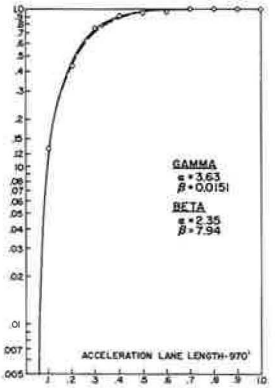
MILBRAE AVENUE SOUTHBOUND ENTRANCE RAMP
BAYSHORE FREEWAY, SAN FRANCISCO



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

Figure 29. Frequency distribution of entry points.

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 (dashed lines represent Type I distribution), plotted against normalized acceleration lane lengths. The circles are values of the raw data from which the curves were derived. Of the 24 sets of data shown in these figures, 14 (58 percent) were accepted at an 0.05 level of significance as fitting a Pearson Type III distribution and 16 (66.7 percent) were accepted as fitting a Pearson Type I distribution.

From this information, 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.

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 3-minute period as a dependent variable, the independent variables which were significant at the 5 percent 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 percent of trucks involved in the merge, the percent of ramp vehicles involved in the merge, the total merge volume, and the product of the 3-minute flow rate and average velocity of the freeway vehicles approaching the nose.

Notice 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, relative effective ramp grade, reflects the driver's ability to see or observe the freeway as he approaches it. Ramp grade at the nose seldom describes the grade or ele-

Ramp driver behavior when 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 the 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 a majority of drivers begin overtly to observe freeway traffic where possible at a distance greater than 200 ft before the nose, but generally not more than 500 ft. 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 ft upstream of the nose or the length of the ramp if it was shorter than 400 ft 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 percent level.

The following variables were found to be significant in the results of the regression analysis:

1. Acceleration lane length—drivers tend to take a longer distance to merge on ramps with longer acceleration lanes.
2. 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.

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 (ft)

Independent Variable, X_i	Coefficient (B_i)	Sig.
X_1 = acceleration lane length (ft)	0.128	Yes
X_2 = ramp length (ft)	- 0.087	Yes
X_3 = relative effective ramp grade (%)	+16.7	Yes
X_4 = angle of convergence (deg)	-16.9	Yes
X_5 = ramp offset at nose (ft)	18.1	Yes
X_6 = QU on freeway at nose (veh-mi/hr)	0.0026	Yes
X_7 = percent trucks in merge volume (%)		No
X_8 = percent ramp veh in merge volume		No
X_9 = merge volume (rate of flow) (veh/hr)		No

Multiple Regression Coefficient = 0.90
B_0 = 87.1 ft

3. 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 of the acceleration lane.
4. 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.
5. 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.
6. The product of the 3-minute rate of flow (expressed on a vph basis) times the average speed—for which an increase causes an increase in distance to entry point.

Variables found not to be significant included the percent trucks in the merge volume, the merge volume, and the percent 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-ft acceleration lane width and 23 ramps with a 12-ft 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 3 deg or less, the operation was extremely good. Each of these ramps had an acceleration lane at least 700 ft in length; it would appear that a desirable design standard include a low (less

than 5 or 6 deg) convergence angle and a long (at least 700 ft) acceleration lane. (For the ramps studied which had a 700-ft length, this distance was measured from the physical nose which was about 2 ft off the pavement edge. If a more desirable 10-ft offset is used, the physical nose would be moved about 150 ft back so that the desirable minimum acceleration lane length to be used with a 10-ft offset would be about 850 ft.)

3. At each of the entrance ramps which had convergence angles 10 deg or greater and/or an acceleration lane length less than 350 ft, 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 deg and/or an acceleration lane length (based on a 2-ft offset at the nose) less than 600 ft for level or upgrade ramps or 500 ft 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 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 ft 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 (a) shorter acceleration lane, (b) greater ramp length, (c) lower relative effective

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 (6), 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 so the following partial list is offered: California Division of Highways—James E. Wilson, Karl Moskowitz and Leonard Newman; Illinois Division of Highways—Charles H. McLean; City of Detroit Department of Traffic—Alger F. Malo; Michigan State Highway Department—Joseph Marlowe; New York Department of Public Works—N. C. Parsons; Long Island State Park Commission—Mr. Boyce; City of New York Department of Traffic—Edward Bonelli; Missouri Highway Department—James Little, and James Roberts; and Texas Highway Department—Dale D. Marvel, John N. Lipscomb, and William V. Ward.

Deserving special mention is 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 Thomas G. Williams, Research Assistant, and 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 W. R. McCasland in making preparations for many of the Houston studies.

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Appendix

STUDY OF GEOMETRICS OF RAMP STUDY LOCATIONS

Location	Ramp Name	Length and Shape of Accel. Lane P = Parallel T = Taper (ft)	Angle of Converg. at Ramp Nose (deg-min)	Angle of Converg. 2 Off Pave-ment Edge (deg-min)	Grade at Nose (%)	Freeway Direction	Ramp Type	Ramp Curvature	Curb Offset at Nose (ft)	Length of Ramp (ft)	Comments
Houston Area	Weslayan EB to Southwest Freeway	610-P	12-15	12-15	level	East	diamond	tangent	2	103	4-lane
	Buffalo Speedway WB to Southwest Freeway	620-P	12	12	level	West	diamond	tangent	2	160	4-lane free-way curve 10 right
	Dumble SB to Gulf Freeway	240-T	7	7	+0.5	East	diamond	tangent	2	170	Freeway grade past ramp +5.0%
	Wayside SB to Gulf Freeway	680-P	10	10	+0.4	East	diamond	tangent	2	380	
	Cullen SB to Gulf Freeway	340-T	10	10		East	diamond	tangent	2	180	
	Broad SB to Gulf Freeway	335-T	14	14	level	East	diamond	tangent	2	225	
Chicago Area	Pulaski EB to Southwest Expressway	1500-T	2	1-30	-0.80	East	diamond	tangent	10	900	Ramp grade is -4.7%
	Kostner EB to Eisenhower Expressway	712-T	6	6	+1.0	East	diamond	slight right	2	350	Ramp grade is -2.5%, freeway curve slight rt.
	Independence WB to Eisenhower Expressway	738-T	6	6	-0.4	West	diamond	tangent	2	432	
	Dempster NB to Edens Expressway	785-P	11	11	level	North	outer connector	slight right	2	785	
	Peterson NB to Edens Expressway	468-P	11	11	level	North	outer connector	slight right	2	1020	
Los Angeles Area	Coldwater Canyon WB to Ventura Freeway	970-P	6	6	-1.0	West	diamond	tangent	2	600	
San Francisco Area	Monument Junction SB to I080	600-T	4	4	+0.4	South	diamond	slight right	2	800	Rural, 2-lane fwy, curve slight right
	Ashby SB to East-shore Freeway	1120-T	7-30	2	level	South	trumpet directional	tangent	10	500	4-lane
	Lakeshore SB to MacArthur Freeway	700-T	5		+2.5	South	diamond	tangent	10	450	4-lane
	Milbrae SB to Bayshore Freeway	675-T	3	2	level	South	from clover-leaf CD road		6	350	
	Broadway NB to Bayshore Freeway	1025-T	7-30	2-30	level	South	trumpet directional	slight right	10	300	4-lane
Sacramento Area	Watt SB to I80	690-P	4	4	-0.2	South	diamond	slight right	2	500	2-lane freeway, curve slight right
	Warren EB to South-field Expressway	660-T	3-30	3-30	-0.4	South	diamond	tangent	2	50	Freeway grade is +3.0%
	Gratiot EB to Ford Expressway	500-T	7-15	7-15	+0.4	East	diamond	tangent	2	600	Ramp grade is -0.7%
New York City Area	Jewel SB to Grand Central Parkway	500-P	5	5	level	South	diamond	tangent	12	520	Ramp grade is -7.0%
	Rockaway NB to Van Wyck Expressway	400-T	2	2	-0.5	North	diamond	tangent	2	380	Ramp grade is -5.1%
	EB Long Island Expy. to NB Cross Island Pky.	1200-P	1	1	+0.8	North	outer connector	slight left	2	1220	Ramp grade -5.0%, fwy curve slight rt.
	Community Dr. EB to Long Island Expressway	700-P	3	3	-2.0	East	diamond	slight left	2	450	Freeway curve slight left
	Jericho EB to Long Island Expressway	1200-P	1	1	-1.0	East	outer connector	slight right	2	660	
	Broadway EB to Northern State Parkway	440-P	8-30	8-30	-1.0	East	outer connector	slight right	2	600	Ramp grade is -4.4%, free-way curve slight right
St. Louis Area	SB Brentwood to WB Daniel Boone Expressway	593-T	14-30	14-30	+0.4	West	outer connector	slight right	2	600	Ramp grade is +3.8%, 2-lane

Discussion

R. D. WORRALL, Northwestern University—In recent years, the Texas Transportation Institute has been responsible for many significant contributions to the field of freeway design. The present paper is no exception. It describes some of the initial findings of a research project which has considerable implications for both the design engineer and the traffic analyst.

The paper falls roughly into two parts: a discussion of study techniques and an analysis of the effect of three specific design variables—acceleration lane length, ramp

convergence angle, and ramp grade—on entrance ramp operations. I should like to comment breifly on part two.

The problem which the authors address is essentially one of multivariate analysis, of isolating the effect of each of a set of interdependent variables on the value of a single, dependent variable. Two alternate lines of attack suggest themselves: that of formal "experimental design" and that of inductive "statistical analysis." Both approaches, in somewhat modified format, are illustrated in the paper. The cross tabulations of merge speeds, for example, classified according to four values of acceleration lane length and five ramp convergence angles, represent an elementary form of experimental control. Similarly, the multiple regression analysis of merge distances is an example of a simple inductive analysis. In each case, the results of the analyses suggest some interesting conclusions. These conclusions should, however, be interpreted with some caution. They are based on a somewhat limited data set and on a set of analysis which are intended to be illustrative rather than statistically rigorous. For more definite conclusions, we must await the completion of the authors' research and the preparation of a final report.

The cross tabulations of merge speeds, for example, are no real substitute for a formal experimental design. They provide no control over the many external variables—external, that is, to the main analysis—which might be hypothesized to exert at least as significant an influence on the speed of a merging vehicle as do acceleration lane length or ramp convergence angle. Such factors as the ramp alignment upstream of the merge area, for example, merge visibility and short-term fluctuations in traffic flow all have been shown to significantly influence the efficiency of entrance ramp operations (8). Insofar as those variables are unidentified or uncontrolled in the authors' analysis, they represent potentially dangerous sources of statistical confusion. It is by no means apparent that ignoring them will result in an accurate identification of the desired "main effects" of acceleration lane length or ramp convergence angle.[1]

In a somewhat related vein, one may perhaps also question the diffusion of study locations. The data set developed by the authors embraces 24 different ramps in 8 different U.S. cities. Rather than adding generality to the analysis, however, such a procedure merely increases the level of residual statistical noise, and hence reduces the clarity of the results.[2]

A further point may also be noted with respect to the cross tabulation of small data samples. The distribution of 24 data points across a 4 × 5 matrix results in an extremely sparse cell composition (Table 4). In this case, it also results in a measurable degree of collinearity within the data set. A simple correlation analysis of the sample illustrated in Table 4 yields a value of $r^2 = 0.3$. Although this figure is nonsignificant statistically, it represents a sufficient degree of collinearity within the original data set to suggest that the concluded effects of acceleration lane length and convergence angle are non-independent. Any attempt to introduce a third variable into the analysis—e.g., ramp grade—would merely make matters worse. The sample size is simply too small to permit such a multidimensional analysis to be performed.[3]

Similar collinearity effects are also apparent in the regression equation summarized in the authors' Table 3. In this case, the result is an instability of the individual regression coefficients, their true values being variously under or overestimated. The

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[1]The presence of such confounding influences is tacitly acknowledged by the authors in their explanations of several apparently illogical or unexpected experimental results.

[2]One is tempted to suggest that the authors might better have concentrated their initial field studies in one area, possibly even at one location. In the latter case, at least, a "quasi-controlled" experiment would then be possible, in which the effect of acceleration lane length could be evaluated by successively lengthening the merge area at the given ramp and observing the resultant changes in traffic behavior.

[3]Despite the small sample size, the rigor of the analyses might have been enhanced somewhat by the application of any of several simple, nonparametric statistical tests to evaluate the significance of the differences between the distributions illustrated in text Figures 8-23. One cannot help thinking that some of these differences are perhaps exaggerated in the qualitative discussion.

TABLE 4

CLASSIFICATION OF SAMPLE OF 24 RAMPS BY ACCELERATION LANE LENGTH AND RAMP CONVERGENCE ANGLE

Ramp Convergence Angle	Acceleration Lane Length (100 ft)			
	0-3.5	4.0-6.0	6.0-8.0	9.5-12.0
10-14 deg	3	1	4	0
8-10 deg	0	1	0	0
6-8 deg	1	2	0	3
3-6 deg	0	0	4	0
0-3 deg	0	0	3	2

problem here might have been avoided by subjecting the original data set to an orthogonal factor analysis, and then regressing the values of the dependent variable against the orthogonal factor scores. The result would be essentially that intended in Table 3, with the advantage of a more meaningful, orthogonal set of stable equation coefficients.[4] An example of an analysis of this type, applied to data on merging at freeway entrance ramps, is given elsewhere (9).

Finally, I would like to make two comments relating to the authors' selection of criterion variables and to their conclusions concerning the operational effects of ramp grade.

The variables selected in the paper as measures of operational efficiency are basically of two types—speed measurements made somewhere within the ramp-freeway merge area and counts of the number of gaps rejected by a ramp driver before completing his merging maneuver. These parameters certainly reflect the general level under study. As noted, for example, the speed of a merging vehicle at the ramp nose may be hypothesized to be a function of the ramp alignment upstream of the nose, as well as of the acceleration lane length and convergence angle. It would be interesting if the authors could make available some alternate measures of merge efficiency—merge volumes, merge capacity, critical flow levels, accident records, etc.—for each location, to complement their present analyses. It would also be of considerable interest to know whether the different design locations were differentially sensitive to specific combinations of ramp-mainstream merge volumes.

In their final conclusion, the authors discuss the operational effects of ramp grade, and suggest that the improved field of view at a ramp leading down onto a depressed freeway has a beneficial effect on traffic operations. This conclusion is supported empirically by a recent study at Northwestern University (8) which found that merge sight distance, expressed as a function of ramp grade and convergence angle, was the most significant single factor influencing the efficiency of ramp-freeway merge operations. Serious limitations on visibility were found to exist, particularly for merging trucks, at ramps with convergence angles of 2 deg or more and for ramps approaching the mainstream lanes either on an upgrade or from the left-hand side of the traveled way.

[4] A word of caution is in order here. These simple coefficients reflect the dimensions of the original variables; they do not reflect the comparative contribution of each variable to the value of Y unless they are first standardized. Hence the discussion following Table 3 is somewhat deceptive.

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JAMES D. BLACKBURN, City Traffic Engineer, Raleigh, North Carolina—The research being conducted at the Texas Transportation Institute and reported in this paper is valuable. It allows a fresh look at some of the design practices which have resulted in entrance ramp geometrics providing less than desirable traffic operation.

The study measured operational characteristics including the speed of ramp vehicles at the ramp nose and merge point, the change in the speed of ramp vehicles moving along the acceleration lane, the difference in speeds between freeway and ramp vehicles at the ramp nose and merge point, and the gap number accepted by merging vehicles and the distribution of points of entrance onto the freeway. The report relates those operational characteristics to three elements of geometric design: acceleration lane length, angle of convergence, and ramp grade.

One of the more significant findings of the study was in revealing that entrance ramps having significant downgrades as they approach the ramp nose provide traffic operation superior to what would be expected, based on a ramp's angle of convergence, length of acceleration lane, and volume of traffic being handled. This superior operation was explained in a simple and logical manner, i.e., motorists approaching the freeway on a downgrade have a field of view of the freeway lanes, allowing them to select a gap for merging prior to reaching the nose and then accelerate to meet the gap immediately beyond the ramp nose. I do not believe that designers have commonly taken this aspect into consideration when designing entrance ramp elements varying from rather steep upgrades approaching the freeway to desirable downgrades commonly found on depressed freeways.

Although the report states that at some locations the large volume of ramp traffic resulted in data that were not comparable to other locations or could not be reconciled with data from other locations, no specific correlation was made between the total volume of merging traffic and operational characteristics. Poor operation occurs when the total volume of ramp traffic and traffic in the outside freeway lane approaches the capacity of that lane. Differences in that total volume from location to location may explain some of the variability of the data presented.

Common design practice has based necessary acceleration lane length on the distance required to accelerate from the ramp design speed up to the freeway design speed. I believe this approach may be inadequate. It is presumed that many of the ramps studied had acceleration lane lengths meeting the above criteria but showed less than acceptable operational characteristics, whereas others with relatively short acceleration lanes exhibited good operational characteristics.

The reported change in speed of ramp vehicles proceeding from the ramp nose to the point of merging is significant. At those locations having acceleration lanes at least 450 ft long and angles of convergence less than 8 deg, the mean speed change along the acceleration lane was never greater than 6 mph. This seems to indicate that, although long acceleration lanes are quite necessary, the term acceleration lane may be a misnomer with good design. At all those locations having shorter acceleration lanes or larger angles of convergence, the mean speed changes were greater than 6 mph and ranged upwards to 17.5 mph. Drivers approaching well-designed entrance ramps and long acceleration lanes apparently feel it is not necessary to pass the nose

at a low speed for they have considerable distance beyond the nose to accept a gap and merge. On the other hand, short acceleration lanes force the driver to approach the nose at a low speed, select his gap and be prepared to immediately merge; otherwise, he may find himself at the end of the acceleration lane and no acceptable gap available. Although ramp vehicles must certainly accelerate up to the operating speed of freeway traffic, I believe that more significant determinates of acceleration lane lengths might be ramp grades approaching the nose and volume of traffic on both the ramp and the outside freeway lane.

ADOLF D. MAY, JR., Associate Professor of Civil Engineering, Institute of Transportation and Traffic Engineering, University of California, Berkeley—The subject of this paper is one of considerable importance to design engineers, and the consequences of such analyses are essential in adopting sound design standards, designing specific ramp configurations, and evaluating existing ramps. Rather than briefly covering several parts of the paper, this discussion will concentrate on one particular aspect—that of statistical analysis and interpretation. The major theme of this discussion is to stress that this is a multivariate problem and techniques such as multiple regression analysis should be considered.

The objective of this nationwide project was to study the effects of geometric variables on entrance ramp operation. The geometric variables quantitatively examined were as follows:

1. Acceleration lane length,
2. Angle of convergence at the ramp nose,
3. Angle of convergence 2 feet off pavement edge,
6. Length of ramp,
7. Ramp grade, and
8. Ramp lane width.

The measures of effectiveness of ramp operations included:

1. Speed of ramp vehicles at ramp nose (percent traveling < 30 mph),
2. Speed of ramp vehicles at merge point (mph),
3. Speed changes on the acceleration lane (mph),
4. Relative freeway-ramp vehicle speed at the merge point (mph),
5. Mean of accepted gap number, and
6. Standard deviation of accepted gap number.

These eight geometric variables and six measures of effectiveness of ramp operations were quantitatively determined for each of the 22 selected ramps in the study.

Sample multiple regression analyses were undertaken by the discusser utilizing the measurements contained in the paper. The intent of this sample analysis was to demonstrate the application of multiple regression analysis to the data given in the paper and to present the interpretations one can draw from such an analysis. A rather unique stepwise multiple regression program was utilized on an IBM 1620 computer for this problem.

The geometric features were considered as the independent variables while each individual measure of effectiveness was considered as the dependent variable. The authors did not report on the results of any test to determine the independence of the geometric features studied. A t-test was applied to the geometric features studied by the discusser and the correlation coefficients between (a) acceleration lane length and convergence angle at nose, (b) acceleration lane length and convergence angle at the

$$Y_1 = -7.80 + 6.87X_3 + 8.71X_4$$

$$Y_2 = 43.8 - 0.715X_2$$

$$Y_3 = -0.115 + 0.954X_3$$

$$Y_4 = 11.6 - 0.00915X_1$$

$$Y_5 = 3.94 + 0.0618X_3 - 0.00037X_6 - 0.224X_8$$

$$Y_6 = 5.13 + 0.0937X_3 - 0.408X_8$$

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where

Y_1 = speed of ramp vehicles at ramp nose (percent traveling <30 mph)

Y_2 = speed of ramp vehicles at merge point (mph)

Y_3 = speed changes on the acceleration lane (mph)

Y_4 = relative freeway-ramp vehicle speed at the merge point (mph)

Y_5 = mean of accepted gap number

Y_6 = standard deviation of accepted gap number

X_1 = acceleration lane length

X_2 = angle of convergence at the ramp nose

X_3 = angle of convergence 2 feet off pavement edge

X_4 = grade at nose

X_5 = curb offset at nose

X_6 = length of ramp

X_7 = ramp grade

X_8 = ramp lane width

Figure 30. Multiple regression equations.

2-ft offset point, and (c) the convergence angle at the nose and the convergence angle at the 2-ft offset point were significant at the 0.05 level. The authors may wish to consider these results if multiple regression analysis techniques are pursued further.

Only linear relationships were considered in this sample analysis, although the stepwise multiple regression program did permit nonlinear equations. The general equation format is

$$Y_i = A + B_1 X_1 + B_2 X_2 + B_3 X_3 + \ldots\ldots + B_N X_N$$

Inspection of several independent variable vs selected dependent variable plots indicated that linear relationships were not unreasonable but nonlinear relationships may result in improved multiple regression analysis. Again the authors may wish to consider nonlinear relationships if the multiple regression analysis techniques are pursued further.

Six multiple regression analyses were undertaken, one for each measure of effectiveness. The resulting equations which include only the significant (at the 0.05 level) independent variables are shown in Figure 30. The following interpretations were drawn from these multiple regression analyses:

1. Decreasing the angle of convergence at the 2-ft offset point and reducing the ramp grade at the nose significantly reduces the percent of ramp vehicles traveling less than 30 mph at the ramp nose.
2. Decreasing the angle of convergence at the ramp nose significantly increases the speed of ramp vehicles at the merge point.
3. Decreasing the angle of convergence at the 2-ft offset point significantly decreases the speed changes on the acceleration lane.
4. Increasing the length of the acceleration lane significantly decreases the relative freeway-ramp vehicle speeds at the merge point.
5. Decreasing the angle of convergence at the 2-ft offset point increasing the length of the ramp, and increasing the ramp lane width, significantly decreases the accepted gap number.
6. Decreasing the angle of convergence at the 2-ft offset point and increasing the ramp lane width significantly decreases the standard deviation of accepted gap number.

JOSEPH A. WATTLEWORTH, JOHANN H. BUHR, DONALD R. DREW, and FRANK A. GERIG, JR., Closure—The authors would like to express their appreciation to James D. Blackburn, Adolf D. May, and Richard D. Worrall for their fine and stimulating discussions.

It was interesting to note in these discussions the divergence in the views of the "operational world" as expressed by Blackburn and those of the "academic world" as expressed by May and Worrall. Blackburn, being an operating engineer, evaluated the results and conclusions in the framework of his experience, while the two distinguished academic representatives concentrated their discussions on the research

to the acid test of application or use by operating people. It was gratifying to note that the presently reported results and conclusions seem to agree with the experience of Blackburn.

Both May and Worrall have pointed out the fact that the paper was primarily descriptive rather than rigorously analytical, and this is certainly true. For additional analytical work on the same data set, the reader's attention is directed to the other seven reports on this project (10 to 16).

May and Worrall indicated the multivariate nature of the problem which, of course, is widely recognized. The research approach taken was that of selecting study sites at which the effects of other variables were a minimum. For example, the ramps were selected, as much as possible, to merge with freeways which were on a level, tangent section; an attempt was made to select study times to obtain traffic volumes near but not over capacity; study sites and time periods were selected so that the operation of the ramp itself was unaffected by downstream bottlenecks; of course, with an aerial photographic technique, all data were collected in good weather. This is not to say that there were no extraneous variables or that the rudimentary attempts to achieve some experimental control were entirely successful.

Experimental design is a function of several factors. Worrall discussed the experimental design from the viewpoint of the rigorous statistician. Other factors such as constraints on time and budget, frequently force the researcher to compromise in his research planning.

The concept of controlled experiments at one location rather than studying several sites has considerable merit, and to this end the Texas Transportation Institute is developing a test track to permit this type of work.

In the reported research, it would have been possible to have studied the effect of acceleration lane length at one site by varying the acceleration lane length there (if a

local operating agency could have been convinced to shorten temporarily the length of an acceleration lane so that studies could be made to determine the adverse effect of this action). Ramp grade and convergence angle could not have been so easily changed. In addition, this type of experimental design would not have fit easily within the time requirements of the project.

Worrall also expressed concern that differences in driver characteristics in different geographical areas might have increased "the level of residual statistical-noise." The authors will concede that driver characteristics might differ from one geographical area and also have a possible explanation for this. In conducting the field studies on this project, it soon became quite clear that the geometric designs also tended to be peculiar to the geographical areas. For example, in California, diamond interchanges of high type, standard designs are widely used; in Texas, most freeways are at grade and the "slip type" diamond interchange ramps are common, while in other areas the cloverleaf interchange is more usual. It could be argued quite strongly that the driving characteristics of the freeway motorist are quite a critical function of the type of geometrics on the freeways on which he learned to drive. In other words, the geographic differences in driver characteristics may be a function of the very ramps being studied.

Another interesting comment of Worrall's is that the conclusions are based on "a somewhat limited data set." This is interesting in light of the fact that the data set used and collected on this project probably represents the most complete set of data on freeway merging characteristics which has ever been assembled. To have followed some of Worrall's suggestions for increasing the sample size in each cell in the matrix and for increasing the number of variables (and hence the number of cells) would quickly have led to a study of monumental proportions. Again, the constraints of time and money provided some limitation on the sample sizes obtained. Within the budget constraint and a 20-month project duration, the project staff was successful in:

1. Developing a data acquisition system which met the requirements of (a) mobility, (b) low cost, (c) minimum interference to traffic, (d) minimum requirements for help from local agencies, and (e) necessary data;
2. Conducting studies on more than 30 entrance ramps in 8 cities from coast to coast;
3. Developing a data reduction and analysis system to obtain and process the large volume of data; and
4. Interpreting the results and preparing eight technical reports.

Both May and Worrall discuss the problem of non-independence of acceleration lane length and convergence angle and arrive at different conclusions regarding its statistical significance. Based on the geometry of merging areas and normal geometric design procedures, however, it would be surprising if the merging angle and acceleration lane length are entirely independent.

The authors would like to urge a great deal of reservation in accepting as final the results of May's regression analyses. In particular, the fact that entrance ramp grade failed to appear as a significant variable in the regression analyses should be interpreted with a great deal of caution. The authors choose to await the results of further research which is under way at the Texas Transportation Institute and which will document more completely the effects of ramp grades on merging operation, before accepting the suggestion that this geometric variable has little or no effect on merging operation.

The authors would once again like to express their thanks and gratitude to the three reviewers for their discussions of this paper. They raised many salient points which will certainly be of benefit to future research.

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