# A Nationwide Study of Freeway Merging Operations

JOHANN H. BUHR, DONALD R. DREW, JOSEPH A. WATTLEWORTH, and THOMAS G. WILLIAMS, Texas Transportation Institute, Texas A and M University

This paper introduces the research project entitled "Gap Acceptance and Traffic Interaction in the Freeway Merging Process" which forms a part of a four-year program on freeway merging undertaken by the Bureau of Public Roads. Field studies for the collection of data were performed on a nationwide basis at a number of selected entrance ramps, utilizing an aerial photographic technique. This technique, the data reduction methods and the study sites selected are described in detail.

Data editing routines and the analysis of the data for basic traffic parameters are discussed and some of these parameters are used to illustrate the merging operation at each study site. The qualitative effect of various geometric elements on the operation, as mirrored by the traffic parameters of volume, density, speed and acceleration noise, is noted. The paper further serves to demonstrate not only the nature of the data available, but also the vast quantity of data involved.

•THE engineer's problem in freeway design is basically one of estimating the parameters defining the traffic demand, capacity, and level of service of the facility. However, as a chain is only as strong as its weakest link, so the overall level of service on a freeway is highly subject to the operation in critical sections, manifest by either sudden increases in traffic demand or the creation of intervehicular conflicts within the traffic stream, or a combination of both. Such regions of more restrictive vehicular operation often occur in the vicinity of entrance ramps. It is therefore imperative that these regions be considered when determining the design volume and capacity of a facility. A knowledge of the operational characteristics and traffic requirements at such locations is essential for proper planning, design and control.

To this end the Texas Transportation Institute was awarded a research contract entitled "Gap Acceptance and Traffic Interaction in the Freeway Merging Process" by the U. S. Bureau of Public Roads. This research problem forms part of the program of Traffic Systems research undertaken by the Bureau.

## OBJECTIVES

Generally, the objective of this project is the development of detailed criteria on traffic stream interaction and geometric features pertaining to the freeway merging process, so as to develop methods for increasing capacity and safety through effective control and functional design. While primary emphasis is on gap acceptance characteristics, the system under study includes the freeway from a point upstream to a point downstream of the entrance ramp proper and takes due regard of other traffic characteristics, geometric features, and environmental conditions. The ultimate purpose of the research is the application of this information in traffic design and operation and in computer simulation.

Field studies for the gathering of data used in the testing and evaluation of existing and developed criteria were carried out at a large number of selected entrance ramps

Paper sponsored by Committee on Freeway Operations and presented at the 46th Annual Meeting.

between freeway and entering vehicles. These relationships were derived by means of a one-variable probit analysis. This analysis is of a more specialized nature and is further explored in another paper. On some of these figures presented later in this report, only one of the relative speed lines is shown. This is due to either extremely low sample sizes in one of the relative speed groups causing the results to be unreliable or otherwise the probit analysis did not converge.

A number of other computer programs have been written for the more specialized analysis of the merging operation. These specialized programs will not be discussed in this report apart from listing them in Table 8, which shows the library of computer programs written, all using the simple data format obtained by the time-oriented analysis of the films.

## TYPICAL RESULTS

The following is a discussion of the traffic operation at some of the study locations with emphasis on the effects of geometrics as mirrored by the contour diagrams.

### No Geometric Effect

Figures 42 and 43 illustrate the operation at two ramps in California. These two ramps are quite similar in the geometric features of acceleration lane length and shape, angles of convergence, grades, curvature, number of lanes and others. Furthermore, these two ramps are located in the same geographic area and both studies were made at about the same time of day. It is therefore reasonable to expect that the difference in operation at these two locations was caused by the traffic demand.

By comparing the two volume contours, it can be seen that the demand on the freeway was about the same at both locations but that the ramp volume was higher at the Ashby Avenue ramp. This may be the cause for the concentration of higher acceleration noise in the area near the nose of the Ashby ramp. This feature was also evidenced at other high-volume ramps. Although the range in magnitude of acceleration noise is about the same at both ramps, the noise is more evenly spread out at the Broadway ramp except for a high acceleration noise spot that coincides with a sudden peak in average speed and decrease in density. Another such peak in acceleration noise is unexplained but occurred at the end of the study period, perhaps before it was reflected by the other parameters. A region of low acceleration noise also coincides with a high-density, low-speed area. None of these peaks and dips in acceleration noise are reflected in the volume contours. As can be expected, the patterns of the contours showing the probability of a gap greater than 3 seconds resemble those of the volume contours. The probability seems to be lower generally at Broadway than at Ashby, although the volume levels in the Broadway merging area are generally lower. This may be caused by the bunching of vehicles which could cause the number of gaps greater than 3 seconds to remain essentially the same as volume increases slightly, while the total number of gaps increase directly with the number of vehicles.

Another situation in which traffic demand completely overshadows the effect of geometric variables, and which the reader of the contour diagrams should be watchful for, is when forced flow exists. Such a condition is illustrated in Figure 44. From an inspection of the volume and acceleration noise contours one could easily conclude, in view of the low acceleration noise, that this ramp is of an excellent design. That may well be so, but the speed and density contours reveal that conditions of forced flow exist, overshadowing any effect that geometrics might have. Note that again the regions of higher acceleration noise correspond to the regions of lower density and higher speed. This observation bears a distinct implication regarding the use of acceleration noise as a measure of the level of service on a facility. Another such example of congested flow is demonstrated by Figure 45. It is clear that in view of the low speeds, no observations on gap acceptance at high relative speeds were made and therefore only the low relative speed lines can be exhibited on the diagrams of gap acceptance characteristics.

These effects of traffic demand on operations in the merging area, as displayed by the contour diagrams, should be kept in mind when reading the figures for the effects of geometrics.

and the rows showing the distribution of speeds for different levels of gap sizes (volume levels). Similarly, Table 6 displays speed and space headway (density) distributions of volumes against densities. It should be noted that volumes are calculated by inverting gaps and densities by inverting space headways. Note the emergence of the volume-density curve in Table 7.

Further output of this program consists of one-minute and five-minute averages of volume counts, one- and five-minute space and time mean speeds and one- and five-minute average densities calculated first as the inverse of the mean space headway, second as the mean of the inverse space headways and third as defined by Lighthill and Whitham: the total travel time over the section divided by the product of the length of the study section and the time intervals used in averaging. As stated earlier, the program can compute this information for any or all of the sections in the study area, giving rise to output far too bulky for inclusion in this report.

Other programs used to extract basic traffic parameters describing the merging operation include programs to investigate ramp vehicle speeds and accelerations, freeway gap distributions over shorter time intervals, and ramp arrival distributions. Another program investigates the averages of a number of traffic parameters measured over short time intervals at each consecutive space interval. These parameters include: volume, density, speed, energy, shock wave speeds, speed noise, acclerations, acceleration noise, expected length of queue, and probability of a gap less than the critical gap. The program further proceeds to plot contour maps of each of these variables using a digital incremental plotter, thus effectively demonstrating their variation in both time and space. For the purpose of illustrating the merging operation in this report, only five of these contour maps were selected and drawn up on a figure. One such figure was prepared for each film taken, illustrating the merging operation during that period. Figure 41 is such a figure displaying the parameters of volume, speed, density, acceleration noise and probability of a gap of greater than 3 seconds on a continuous basis in both time and space. This figure was derived from one of the films taken at the Dempster Street northbound entrance ramp on Edens Expressway, illustrated earlier in Figure 35. The figures are read in exactly the same manner as a conventional contour level map with which civil engineers are more familiar. For example, a horizontal section through the volume contours gives a profile of volumes along the length of the study area at the instant in time at which the section is taken. Similarly, a vertical section through this figure gives a profile of volume levels over the time length of the study period at a point in space on the study area. The contour figure as a whole is an excellent way of demonstrating the variation of such a parameter in both dimensions and therefore effectively illustrates the overall operation in the study area.

All these parameters were computed by averaging over the time interval indicated on the ordinates of the figures (2 minutes in this case) and over the distance intervals indicated on the abscissae. The volume is computed by simply counting the number of arrivals at each station during the averaging interval and expanding it to hourly volumes. The speed is calculated by averaging the travel times over each interval for each averaging period and then dividing the distance by this average travel time. It is therefore the time mean speed. The density is not calculated from the volume and the speed, but is computed by summing the travel times of vehicles traversing the 200-ft section during the averaging time interval and then dividing this sum by the product of the distance interval over which the travel times were computed (200 ft) and the time interval (2 minutes). The acceleration noise is computed as the standard deviation of the accelerations of consecutive vehicles over two adjacent distance intervals and is therefore based on a 100 percent sample rather than on a single vehicle as has been conventionally done. The probability of a gap of greater than 3 seconds is computed by taking the ratio of the number of gaps greater than 3 seconds to the total number of gaps. The values thus calculated were considered to be the value of the parameter at the midpoint of the time and distance interval over which it was computed, and contour lines drawn through it in the conventional manner.

The sixth diagram on the figure illustrates the gap acceptance characteristics observed at the entrance ramp during the study period. It shows the cumulative probability of a certain size gap being accepted under conditions of high and low relative speeds

TABLE 8

COMPUTER PROGRAMS FOR THE ANALYSIS OF ENTRANCE RAMP OPERATIONS

| Program Number | Descriptive Title |
|---|---|
| 1 | Check for obvious errors |
| 2 | Plot time-space diagram |
| 3 | Analysis of speed-density relations |
| 4 | Speeds and accelerations of ramp vehicles |
| 5 | Analysis of gap availability |
| 6 | Analysis of gap stability |
| 7 | Analysis of gap acceptance characteristics |
| 8 | Probit analysis of gap acceptance characteristics |
| 9 | Effect of following gap on gap acceptance |
| 10 | Effect of time waiting on gap acceptance |
| 11 | Deviation of ramp speed distributions |
| 12 | Deviation of arrival distributions |
| 13 | Distributions of relative speeds |
| 14 | Distributions of point of entry |
| 15 | Distributions of number of gaps rejected |
| 16 | Analysis of vehicle travel times |

makes use of a digital incremental plotter to plot a time-space diagram of the operation on the study section during the study period. A sample from such a time-space plot is shown on Figure 40.

The solid lines on the diagram represent vehicle paths in time and space on the freeway and the dashed lines represent vehicles on the ramp. The dashed line of a ramp vehicle changes to a solid line at the first marked station after it enters the freeway.

The time-space traces begin where vehicles enter the study section, either at the beginning of the section or when a vehicle weaves into the outside freeway lane from the second lane. Similarly, traces terminate when a vehicle leaves the study area either at the end or by weaving into the second lane from the outside lane. A dashed line that terminates without changing to a solid line indicates that a ramp vehicle entered the freeway and then changed lanes before it reached the next reference mark.

The uses of the time-space diagram are many and varied. In the first place, it was used for detecting errors in the data that could not be found by the first error routine. Such errors are usually evidenced by sudden increases or decreases in speed (sharp changes in the slope of the time-space line) or by two lines coming very close together at certain points without actually crossing. (If it did cross, it would have been found by the first error program.) These probable errors were revealed by the time-space diagram and could then be checked by referring back to the film.

A second use of the time-space diagram was in simulating missing data points. These missing data points were usually at the ends of the study section, as explained earlier. As the computer cannot recognize the difference between a missing data point and a weaving vehicle, it was essential that these points be filled in. This was easily achieved by extrapolating the time-space path, taking due regard of the preceding and following vehicle. It was felt that this technique introduced only negligible error and was to be preferred to either shortening the study section by at least 400 ft or to breaking the continuous study period up into a number of shorter intervals.

The digital plotter plots to an accuracy of 0.01 inches, that is, an accuracy of $\frac{1}{10}$ second on the time scale used. Although this accuracy is adequate for taking most measurements directly off the time-space plot, it was not used in this capacity. It did, however, further prove its use in revealing the general operating conditions on the study section at a glance and was also found to be an almost indispensable aid in the writing and debugging of further programs.

## Basic Traffic Parameters

Several programs were written to extract a number of basic traffic parameters from the data. One of these programs computes the speed-volume-density relationships of the traffic stream in three different ways, based on individual vehicles, based on one-minute averages, and based on five-minute averages. These relationships can be computed over any or all 100-ft or 200-ft intervals in the study section. Some typical examples of the computer output on the microscopic relationships, that is, based on individual vehicles, are shown in Tables 5, 6, and 7 for the 200-ft section located between 400 ft and 200 ft upstream of the nose. These tables not only display the basic traffic parameters measured during the study period, but also present frequency tables of each parameter for different levels of any of the other parameters in a fashion appropriate for the further analysis of the stochastic properties of the interrelationships between speed, volume and density. For example, Table 5 is a two-way frequency table, the columns showing the distribution of gaps (volumes) for different speed levels

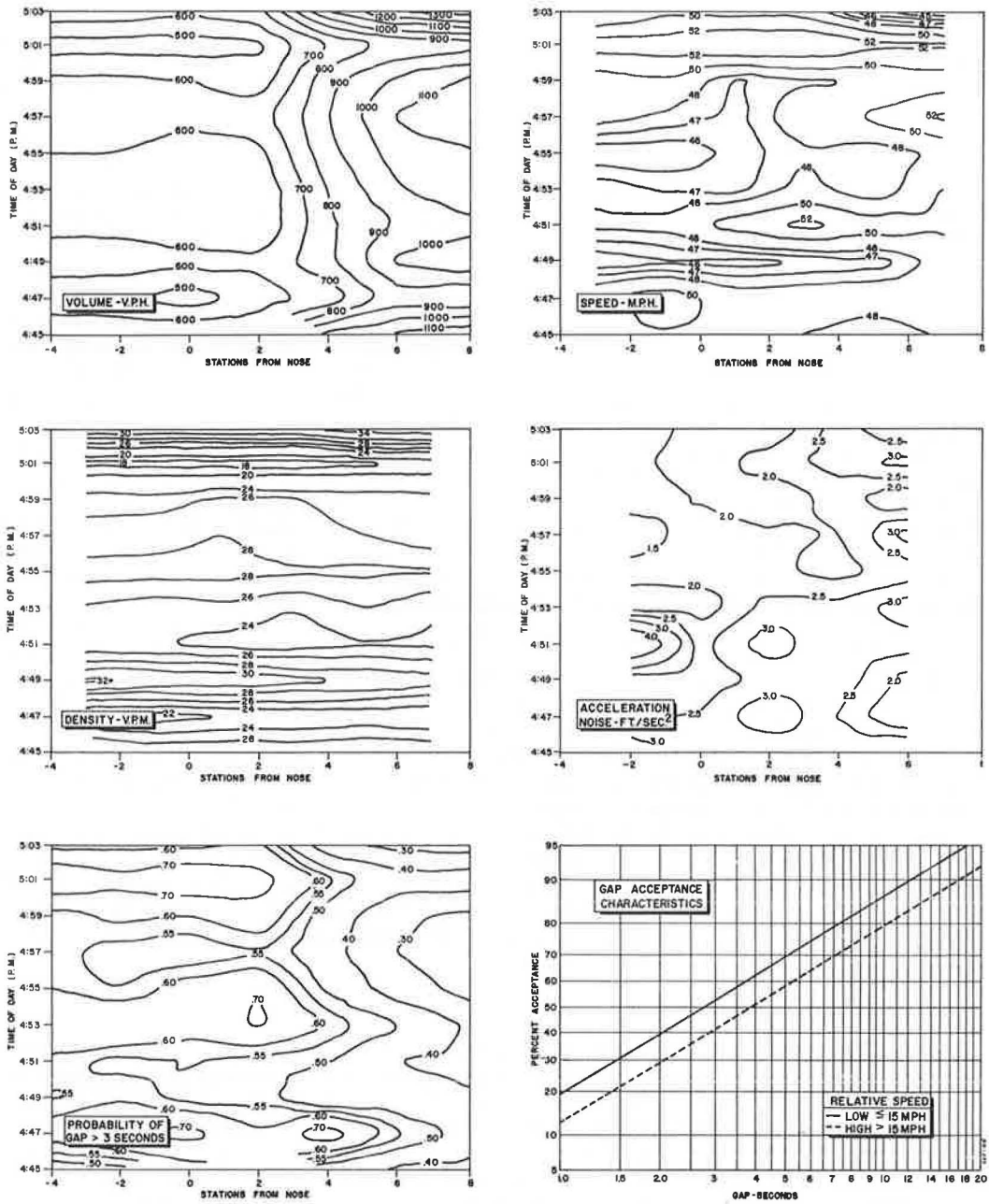



Figure 41. Traffic characteristics of Dempster Street northbound entrance ramp to Edens Expressway, Chicago.

TABLE 5

FREQUENCY TABLE OF GAPS AND SPEEDS, STATION -4 TO -2,
MONUMENT JUNCTION SOUTHBOUND ENTRANCE RAMP ON 1680,
PLEASANT HILL, SAN FRANCISCO

| Gaps | Speeds | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| | 0-25 | 25-35 | 35-40 | 40-45 | 45-50 | 50-55 | 55-60 | 60-65 | 65-75 | 75-99 | Totals |
| 0-1 | 0 | 2 | 1 | 8 | 3 | 2 | 4 | 1 | 0 | 0 | 21 |
| 1-2 | 0 | 0 | 13 | 18 | 41 | 17 | 6 | 4 | 2 | 0 | 101 |
| 2-3 | 0 | 5 | 7 | 20 | 25 | 14 | 5 | 2 | 1 | 1 | 80 |
| 3-4 | 0 | 0 | 5 | 8 | 23 | 10 | 4 | 3 | 2 | 3 | 58 |
| 4-5 | 0 | 1 | 3 | 5 | 8 | 5 | 6 | 5 | 1 | 0 | 34 |
| 5-6 | 0 | 0 | 2 | 4 | 12 | 6 | 10 | 5 | 3 | 0 | 42 |
| 6-7 | 0 | 0 | 1 | 5 | 10 | 3 | 4 | 4 | 0 | 2 | 29 |
| 7-8 | 0 | 0 | 0 | 4 | 13 | 5 | 4 | 2 | 0 | 0 | 28 |
| 8-9 | 0 | 0 | 1 | 2 | 7 | 1 | 5 | 1 | 0 | 1 | 18 |
| 9-10 | 0 | 0 | 1 | 0 | 5 | 1 | 1 | 3 | 1 | 0 | 12 |
| 10-11 | 0 | 0 | 1 | 3 | 0 | 2 | 2 | 1 | 1 | 0 | 10 |
| 11-12 | 0 | 0 | 0 | 1 | 4 | 1 | 2 | 1 | 0 | 0 | 9 |
| 12-13 | 0 | 0 | 0 | 0 | 2 | 1 | 0 | 4 | 1 | 0 | 8 |
| 13-14 | 0 | 0 | 1 | 0 | 1 | 1 | 1 | 2 | 0 | 0 | 6 |
| 14-15 | 0 | 0 | 0 | 1 | 1 | 1 | 1 | 0 | 0 | 0 | 4 |
| 15-99 | 0 | 0 | 0 | 1 | 7 | 0 | 1 | 3 | 0 | 0 | 12 |
| Totals | 0 | 8 | 36 | 80 | 162 | 70 | 56 | 41 | 12 | 7 | 472 |

TABLE 6

FREQUENCY TABLE OF SPACE HEADWAYS AND SPEEDS, STATION -4 TO -2,
MONUMENT JUNCTION SOUTHBOUND ENTRANCE RAMP ON 1680,
PLEASANT HILL, SAN FRANCISCO

| Space Headway | Speeds | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| | 0-25 | 25-35 | 35-40 | 40-45 | 45-50 | 50-55 | 55-60 | 60-65 | 65-75 | 75-99 | Totals |
| 0-40 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| 40-60 | 0 | 2 | 2 | 6 | 2 | 0 | 0 | 0 | 0 | 0 | 12 |
| 60-80 | 0 | 0 | 3 | 4 | 7 | 2 | 2 | 0 | 0 | 0 | 18 |
| 80-100 | 0 | 0 | 6 | 12 | 7 | 3 | 3 | 4 | 0 | 0 | 35 |
| 100-120 | 0 | 2 | 3 | 4 | 12 | 1 | 2 | 0 | 0 | 0 | 24 |
| 120-140 | 0 | 2 | 3 | 13 | 13 | 3 | 0 | 1 | 1 | 0 | 36 |
| 140-160 | 0 | 1 | 3 | 3 | 10 | 10 | 3 | 0 | 1 | 0 | 31 |
| 160-180 | 0 | 0 | 2 | 4 | 9 | 2 | 0 | 0 | 0 | 0 | 17 |
| 180-200 | 0 | 0 | 2 | 3 | 5 | 7 | 1 | 1 | 0 | 0 | 19 |
| 200-240 | 0 | 1 | 4 | 3 | 16 | 7 | 4 | 0 | 1 | 0 | 36 |
| 240-280 | 0 | 0 | 1 | 4 | 10 | 6 | 0 | 1 | 0 | 0 | 22 |
| 280-320 | 0 | 0 | 2 | 4 | 5 | 2 | 3 | 1 | 0 | 1 | 18 |
| 320-360 | 0 | 0 | 1 | 2 | 6 | 2 | 2 | 2 | 1 | 0 | 16 |
| 360-400 | 0 | 0 | 0 | 3 | 6 | 3 | 4 | 1 | 1 | 0 | 18 |
| 400-440 | 0 | 0 | 0 | 4 | 6 | 4 | 5 | 4 | 0 | 2 | 25 |
| 440-500 | 0 | 0 | 1 | 3 | 11 | 3 | 5 | 2 | 1 | 1 | 27 |
| 500-560 | 0 | 0 | 1 | 2 | 13 | 3 | 3 | 4 | 3 | 0 | 29 |
| 560-620 | 0 | 0 | 1 | 1 | 2 | 4 | 3 | 3 | 0 | 0 | 14 |
| 620-999 | 0 | 0 | 1 | 5 | 22 | 8 | 16 | 17 | 3 | 3 | 75 |
| Totals | 0 | 8 | 36 | 80 | 162 | 70 | 56 | 41 | 12 | 7 | 472 |

TABLE 7

FREQUENCY TABLE ON VOLUMES AND DENSITIES, STATION -4 TO -2,
MONUMENT JUNCTION SOUTHBOUND ENTRANCE RAMP ON 1680,
PLEASANT HILL, SAN FRANCISCO

| Density | Volume | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | 0-10 | 10-20 | 20-25 | 25-30 | 30-35 | 35-40 | 40-45 | 45-50 | 50-55 | 55-60 | 60-99 | Totals |
| 0-10 | 101 | 4 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 105 |
| 10-20 | 35 | 88 | 1 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 124 |
| 20-30 | 0 | 41 | 26 | 5 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 72 |
| 30-40 | 0 | 1 | 15 | 23 | 17 | 3 | 2 | 0 | 0 | 0 | 0 | 61 |
| 40-50 | 0 | 0 | 1 | 9 | 13 | 12 | 5 | 1 | 0 | 0 | 0 | 41 |
| 50-60 | 0 | 0 | 0 | 0 | 6 | 8 | 6 | 1 | 3 | 4 | 1 | 29 |
| 60-70 | 0 | 0 | 0 | 0 | 0 | 0 | 6 | 0 | 4 | 3 | 2 | 15 |
| 70-80 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 4 | 2 | 4 | 10 |
| 80-90 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 3 | 3 |
| 90-100 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 1 | 6 | 7 |
| 100-110 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| 110-120 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 3 | 3 |
| 120-130 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 2 | 2 |
| 130-140 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| 140-999 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| Totals | 136 | 134 | 43 | 37 | 36 | 23 | 19 | 2 | 11 | 10 | 21 | 472 |

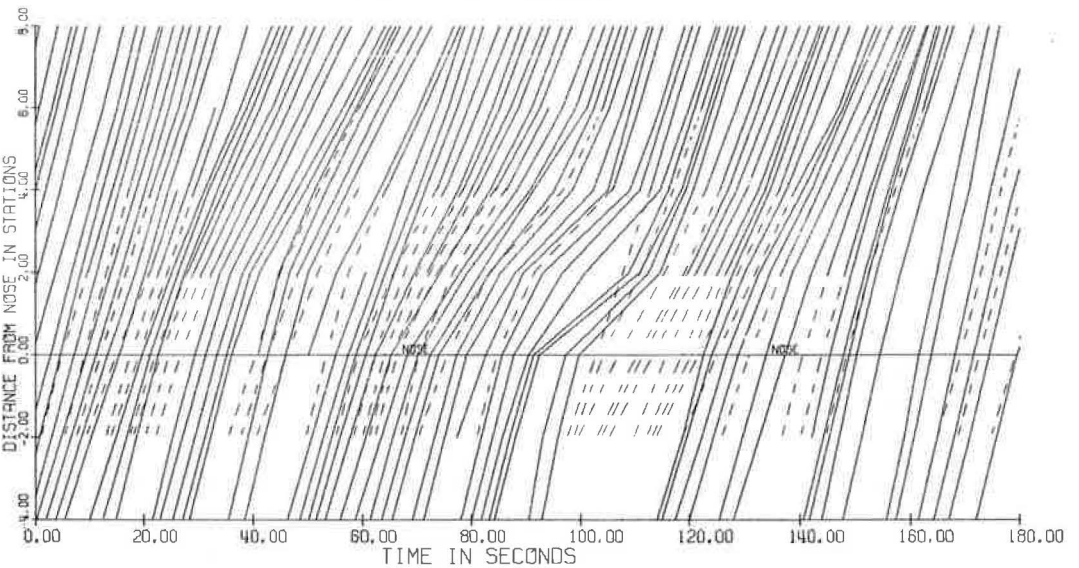



Figure 40. Time-space diagram: Broadway northbound entrance ramp, Bayshore Freeway, San Francisco. Dashed lines represent vehicles on ramp, solid lines represent vehicles on freeway.

on the rate of filming or camera speed. The vehicles were also classified into trucks and passenger cars. At the peak of the data reduction, for a period of about two months, nine analysis crews were working three 8-hr shifts per day. These data were then punched into computer cards for further processing by an electronic computer. This produced a library of traffic data on entrance ramp operation of such magnitude and scope as has been heretofore unavailable.

## DATA ANALYSIS

The vast amount of data collected on this project could only be processed by electronic computer and to this end, use was made of the facilities of the Texas A and M University Data Processing Center, of which the principal computer is an IBM 7094. In order to extract the most possible information with the highest possible sample sizes from the data, extreme care had to be taken with data editing routines for removing all possible errors made during the film analysis and punching of the data cards.

### Error Routines

One such error-detecting program simply scans the data for such obvious errors as negative speeds, vehicle paths crossing or two vehicles at the same point at the same time. The latter seems to have been the most frequent mistake, caused by improper identification of vehicles from one picture to the next. This could easily happen under conditions of high density on the study section where, at the same time, the film image definition was less than ideal. The first editing program was written to detect these errors which could then easily be rectified by going back to the original film.

Due to the circling technique of filming, certain problems were experienced in the data analysis that must be immediately evident to a practical person—the problem of missing data points. This could occur in several ways. For example, the reference mark at either end of the study section could be momentarily out of the viewfinder of the camera because of a sudden movement of the airplane. Sometimes even the whole study section could momentarily disappear from view. Normally this would cause a drastic reduction in the sample size of continuous study and in the length of the study section. These problems were overcome by the second editing program. This program

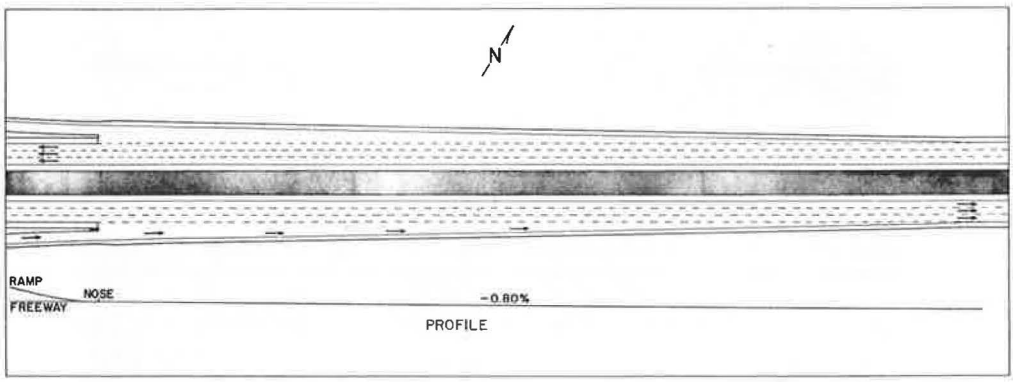
Figure 39. Film analysis in progress.

filmed on these trips are listed in Table 4. Drawings of most of these ramps, with tables listing the major geometric characteristics, appear as Figures 10, 12, and 26 through 38.

## DATA REDUCTION

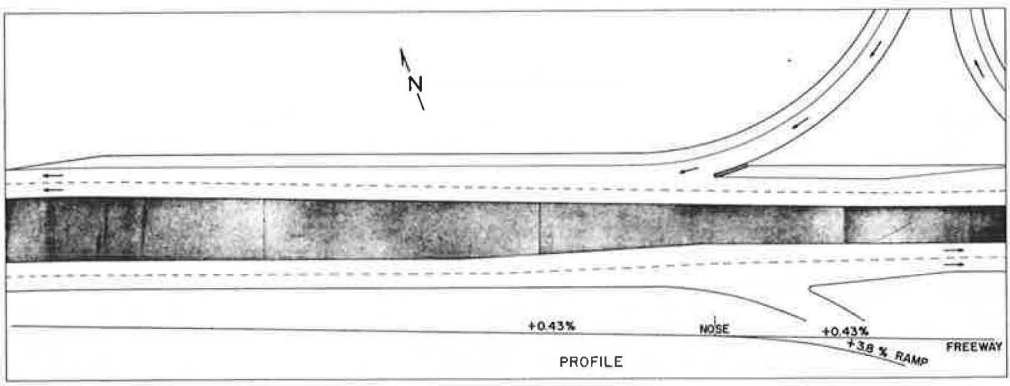
Before the data collection could be started, serious consideration had to be given the film analysis techniques and equipment to be used. The analyst of time-lapse photographs has the choice as to time orientation or space orientation, i. e., either measuring the time required for a certain fixed displacement or measuring the displacement over a certain fixed time interval. Either method has certain advantages and disadvantages over the other. Time-oriented analysis requires a higher rate of filming than space-oriented analysis for the same accuracy, but is usually considerably faster to perform. Specialized projectors with automatic X-Y coordinate readout equipment are available for space-oriented data reduction and these were considered for use on this project. However, because of the continuously changing space scale inherent in the technique of data collection used, space-oriented analysis was rejected in favor of time orientation. To this end, marks were made along the freeway and the ramp at fixed intervals both upstream and downstream of the ramp nose as described earlier. Time orientation, as used on this project, has the further advantage of eliminating the need for maintaining a strict altitude or flight pattern during filming. The data reduction was performed on three 35-mm projectors, two of which were Richardson Model 300 projectors (Fig. 39) and the third was a Vanguard projector, consisting of a Model M-35CD projection head and a Model M-13 projection case.

Data reduction consisted of following each vehicle on the outside freeway lane and each vehicle on the ramp through the study area, recording the frame number at which the vehicle crossed each reference mark. In this manner data were collected on the time-space trajectories of approximately 60, 000 vehicles. Further information taken off the films included the frame number at which each ramp vehicle entered the freeway and frame numbers at fixed time intervals so as to determine and keep a running check



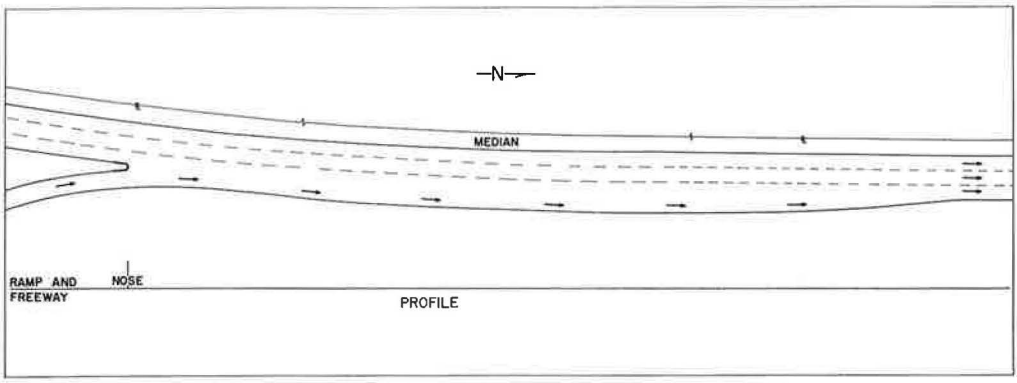

| GEOMETRIC CHARACTERISTICS | DATA |
|---|---|
| LENGTH OF ACCELERATION LANE | 1500 FEET |
| SHAPE OF ACCELERATION LANE | TAPER |
| ANGLE OF CONVERGENCE AT RAMP NOSE | 2° |
| ANGLE OF CONVERGENCE 2 FT. OFF PAVEMENT EDGE | 1½° |
| RAMP GRADE AT NOSE | -0.80% |
| FREEWAY GRADE AT NOSE | -0.80% |
| NUMBER OF FREEWAY LANES | 3 |
| NUMBER OF RAMP LANES | 1 |
| FREEWAY CURVATURE | TANGENT |
| RAMP CURVATURE | TANGENT |
| CURB OFFSET AT NOSE | 10 FEET |
| LENGTH OF RAMP | 900 FEET |

Figure 37. Geometric characteristics of Pulaski Road eastbound entrance ramp, Southwest Expressway, Chicago.



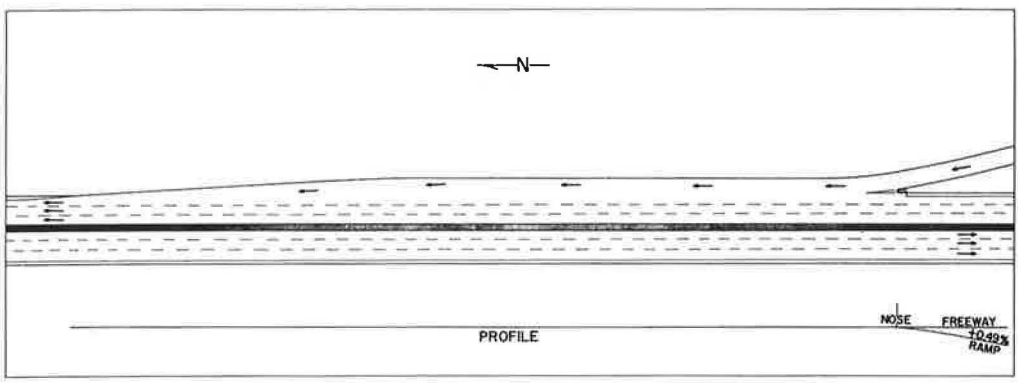

| GEOMETRIC CHARACTERISTICS | DATA |
|---|---|
| LENGTH OF ACCELERATION LANE | 593 FEET |
| SHAPE OF ACCELERATION LANE | PARALLEL |
| ANGLE OF CONVERGENCE AT RAMP NOSE | 14½° |
| ANGLE OF CONVERGENCE 2 FT. OFF PAVEMENT EDGE | 14½° |
| RAMP GRADE AT NOSE | +0.43% |
| FREEWAY GRADE AT NOSE | +0.43% |
| NUMBER OF FREEWAY LANES | 2 |
| NUMBER OF RAMP LANES | 1 |
| FREEWAY CURVATURE | TANGENT |
| RAMP CURVATURE | SLIGHT RIGHT |
| CURB OFFSET AT NOSE | 2 FEET |
| LENGTH OF RAMP | 600 FEET |

Figure 38. Geometric characteristics of Brentwood Avenue westbound entrance ramp, Daniel Boone Expressway, St. Louis.



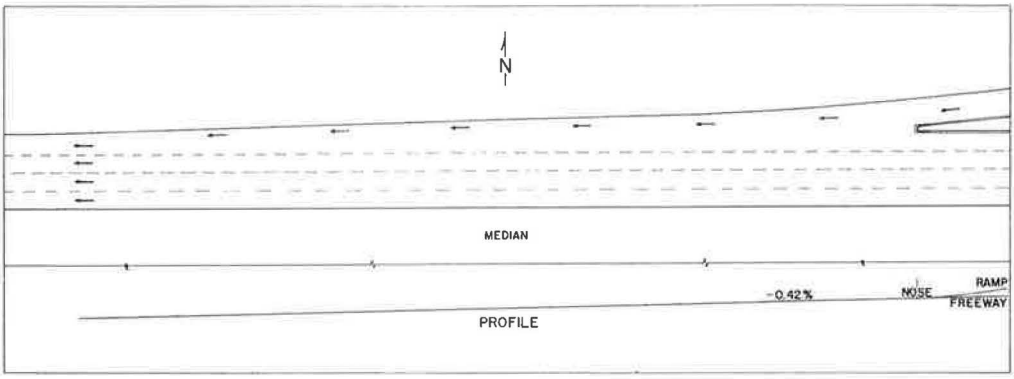

| GEOMETRIC CHARACTERISTICS DATA | |
|---|---|
| LENGTH OF ACCELERATION LANE | 785 FEET |
| SHAPE OF ACCELERATION LANE | PARALLEL |
| ANGLE OF CONVERGENCE AT RAMP NOSE | 11° |
| ANGLE OF CONVERGENCE 2 FT. OFF PAVEMENT EDGE | 11° |
| RAMP GRADE AT NOSE | LEVEL |
| FREEWAY GRADE AT NOSE | LEVEL |
| NUMBER OF FREEWAY LANES | 3 |
| NUMBER OF RAMP LANES | 1 |
| FREEWAY CURVATURE | TANGENT |
| RAMP CURVATURE | SLIGHT RIGHT |
| CURB OFFSET AT NOSE | 2 FEET |
| LENGTH OF RAMP | 925 FEET |

Figure 35. Geometric characteristics of Dempster Avenue northbound entrance ramp, Edens Expressway, Chicago.



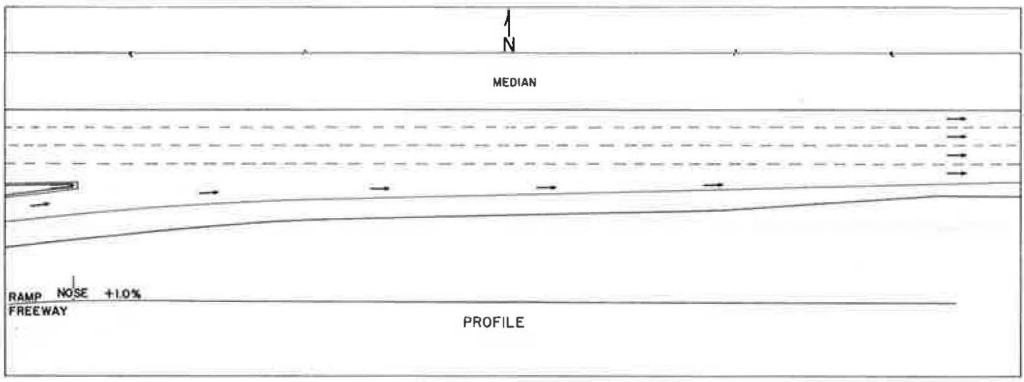

| GEOMETRIC CHARACTERISTICS DATA | |
|---|---|
| LENGTH OF ACCELERATION LANE | 468 FEET |
| SHAPE OF ACCELERATION LANE | PARALLEL |
| ANGLE OF CONVERGENCE AT RAMP NOSE | 11° |
| ANGLE OF CONVERGENCE 2 FT OFF PAVEMENT EDGE | 11° |
| RAMP GRADE AT NOSE | +0.49% |
| FREEWAY GRADE AT NOSE | LEVEL |
| NUMBER OF FREEWAY LANES | 3 |
| NUMBER OF RAMP LANES | 1 |
| FREEWAY CURVATURE | TANGENT |
| RAMP CURVATURE | SLIGHT RIGHT |
| CURB OFFSET AT NOSE | 2 FEET |
| LENGTH OF RAMP | 1020 FEET |

Figure 36. Geometric characteristics of Peterson Avenue northbound entrance ramp, Edens Expressway, Chicago.



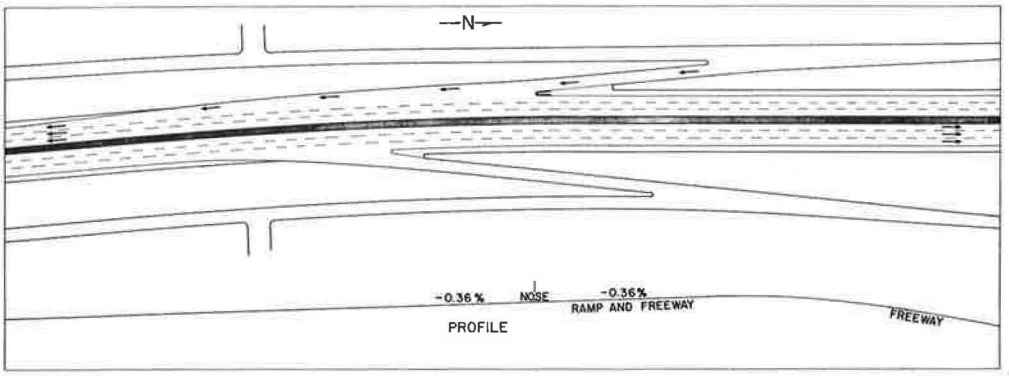

| GEOMETRIC CHARACTERISTICS | DATA |
|---|---|
| LENGTH OF ACCELERATION LANE | 738 FEET |
| SHAPE OF ACCELERATION LANE | TAPER |
| ANGLE OF CONVERGENCE AT RAMP NOSE | 6° |
| ANGLE OF CONVERGENCE 2 FT. OFF PAVEMENT EDGE | 6° |
| RAMP GRADE AT NOSE | -0.42% |
| FREEWAY GRADE AT NOSE | -0.42% |
| NUMBER OF FREEWAY LANES | 4 |
| NUMBER OF RAMP LANES | 1 |
| FREEWAY CURVATURE | TANGENT |
| RAMP CURVATURE | TANGENT |
| CURB OFFSET AT NOSE | 2 FEET |
| LENGTH OF RAMP | 432 FEET |

Figure 33. Geometric characteristics of Independence Avenue westbound entrance ramp, Eisenhower Expressway, Chicago.



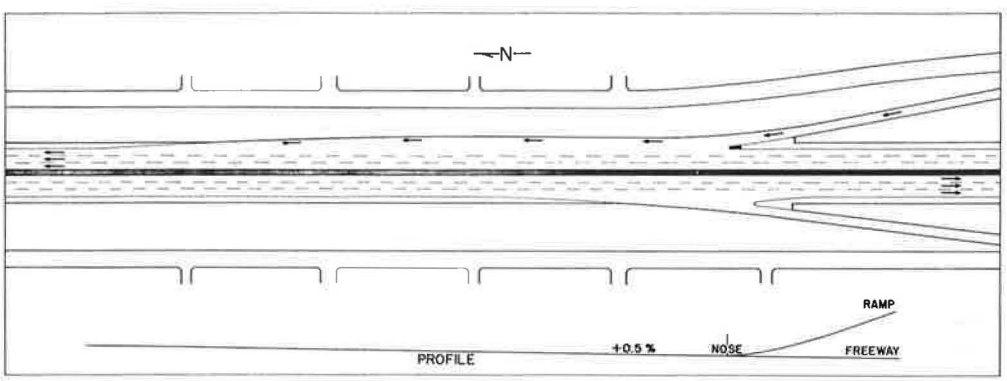

| GEOMETRIC CHARACTERISTICS | DATA |
|---|---|
| LENGTH OF ACCELERATION LANE | 712 FEET |
| SHAPE OF ACCELERATION LANE | TAPER |
| ANGLE OF CONVERGENCE AT RAMP NOSE | 6° |
| ANGLE OF CONVERGENCE 2 FT. OFF PAVEMENT EDGE | 6° |
| RAMP GRADE AT NOSE | +1.0% |
| FREEWAY GRADE AT NOSE | +1.0% |
| NUMBER OF FREEWAY LANES | 4 |
| NUMBER OF RAMP LANES | 1 |
| FREEWAY CURVATURE | SLIGHT RIGHT |
| RAMP CURVATURE | SLIGHT RIGHT |
| CURB OFFSET AT NOSE | 2 FEET |
| LENGTH OF RAMP | 350 FEET |

Figure 34. Geometric characteristics of Kostner Avenue eastbound entrance ramp, Eisenhower Expressway, Chicago.



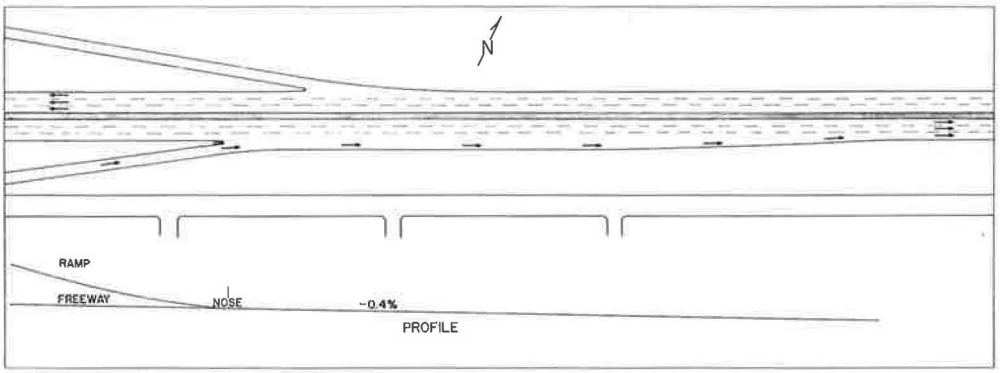

| GEOMETRIC CHARACTERISTICS | DATA |
|---|---|
| LENGTH OF ACCELERATION LANE | 660 FEET |
| SHAPE OF ACCELERATION LANE | TAPER |
| ANGLE OF CONVERGENCE AT RAMP NOSE | 3° 30' |
| ANGLE OF CONVERGENCE 2 FT. OFF PAVEMENT EDGE | 3° 30' |
| RAMP GRADE | -0.36% |
| FREEWAY GRADE | -0.36% |
| NUMBER OF FREEWAY LANES | 3 |
| NUMBER OF RAMP LANES | 1 |
| FREEWAY CURVATURE | TANGENT |
| RAMP CURVATURE | TANGENT |
| CURB OFFSET AT NOSE | 2 FEET |
| LENGTH OF RAMP | 50 FEET |

Figure 31. Geometric characteristics of Warren eastbound entrance ramp, Southfield Expressway, Detroit.



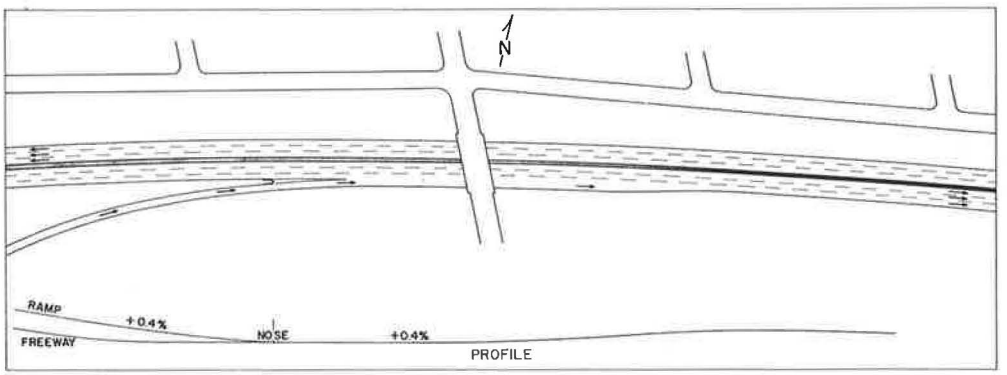

| GEOMETRIC CHARACTERISTICS | DATA |
|---|---|
| LENGTH OF ACCELERATION LANE | 515 FEET |
| SHAPE OF ACCELERATION LANE | PARALLEL |
| ANGLE OF CONVERGENCE AT RAMP NOSE | 4° 45' |
| ANGLE OF CONVERGENCE 2 FT. OFF PAVEMENT EDGE | 4° 45' |
| RAMP GRADE AT NOSE | +0.5% |
| FREEWAY GRADE AT NOSE | +0.5% |
| NUMBER OF FREEWAY LANES | 3 |
| NUMBER OF RAMP LANES | 1 |
| FREEWAY CURVATURE | TANGENT |
| RAMP CURVATURE | TANGENT |
| CURB OFFSET AT NOSE | 2 FEET |
| LENGTH OF RAMP | 550 FEET |

Figure 32. Geometric characteristics of Linwood northbound entrance ramp, John Lodge Expressway, Detroit.



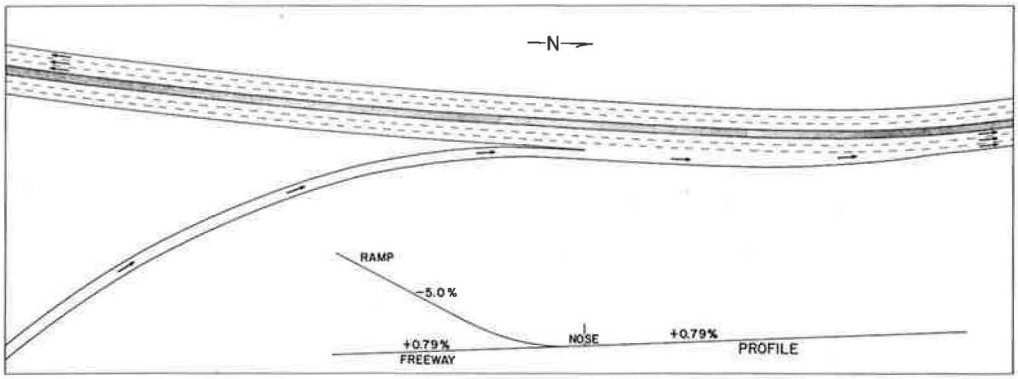

| GEOMETRIC CHARACTERISTICS DATA | |
|---|---|
| LENGTH OF ACCELERATION LANE | 693 FEET |
| SHAPE OF ACCELERATION LANE | TAPER |
| ANGLE OF CONVERGENCE AT RAMP NOSE | 6°15' |
| ANGLE OF CONVERGENCE 2 FT. OFF PAVEMENT EDGE | 6°15' |
| RAMP GRADE | -0.3% |
| FREEWAY GRADE | -0.4% |
| NUMBER OF FREEWAY LANES | 3 |
| NUMBER OF RAMP LANES | 1 |
| FREEWAY CURVATURE | TANGENT |
| RAMP CURVATURE | TANGENT |
| CURB OFFSET AT NOSE | 2 FEET |
| LENGTH OF RAMP | 450 FEET |

Figure 29. Geometric characteristics of Chene eastbound entrance ramp, Edsel Ford Expressway, Detroit.



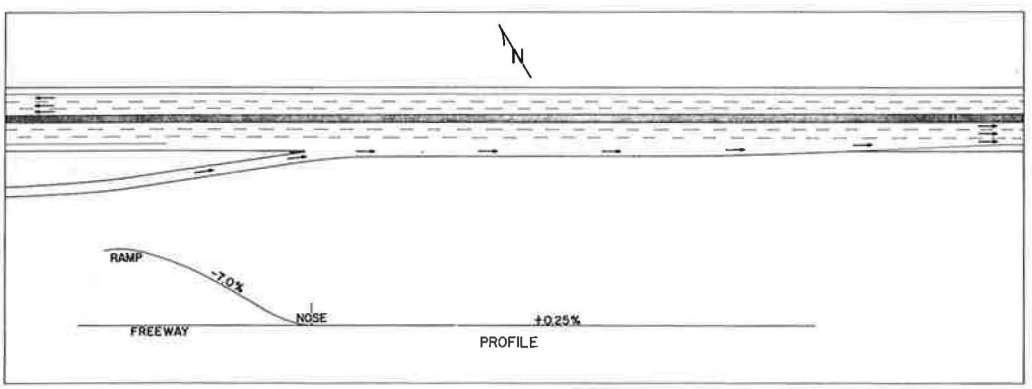

| GEOMETRIC CHARACTERISTICS DATA | |
|---|---|
| LENGTH OF ACCELERATION LANE | 500 FEET |
| SHAPE OF ACCELERATION LANE | TAPER |
| ANGLE OF CONVERGENCE AT RAMP NOSE | 7°15' |
| ANGLE OF CONVERGENCE 2 FT. OFF PAVEMENT EDGE | 7°15' |
| RAMP GRADE AT NOSE | +0.4 % |
| FREEWAY GRADE AT NOSE | +0.4 % |
| NUMBER OF FREEWAY LANES | 3 |
| NUMBER OF RAMP LANES | 1 |
| FREEWAY CURVATURE | TANGENT |
| RAMP CURVATURE | TANGENT |
| CURB OFFSET AT NOSE | 2 FEET |
| LENGTH OF RAMP | 600 FEET |

Figure 30. Geometric characteristics of Gratiot eastbound entrance ramp, Edsel Ford Expressway, Detriot.




| GEOMETRIC CHARACTERISTICS DATA | |
|---|---|
| LENGTH OF ACCELERATION LANE | 1200 FEET |
| SHAPE OF ACCELERATION LANE | PARALLEL |
| ANGLE OF CONVERGENCE AT RAMP NOSE | 1° |
| ANGLE OF CONVERGENCE 2 FT. OFF PAVEMENT EDGE | 1° |
| RAMP GRADE AT NOSE | +0.79 % |
| FREEWAY GRADE AT NOSE | +0.79 % |
| NUMBER OF FREEWAY LANES | 3 |
| NUMBER OF RAMP LANES | 1 |
| FREEWAY CURVATURE | SLIGHT LEFT |
| RAMP CURVATURE | SLIGHT LEFT |
| CURB OFFSET AT NOSE | 2 FEET |
| LENGTH OF RAMP | 1200 FEET |

Figure 27. Geometric characteristics of Long Island Expressway westbound entrance ramp to Cross Island Expressway, New York.




| GEOMETRIC CHARACTERISTICS DATA | |
|---|---|
| LENGTH OF ACCELERATION LANE | 500 FEET |
| SHAPE OF ACCELERATION LANE | PARALLEL |
| ANGLE OF CONVERGENCE AT RAMP NOSE | 5° |
| ANGLE OF CONVERGENCE 2 FT. OFF PAVEMENT EDGE | 5° |
| RAMP GRADE AT NOSE | +0.25% |
| FREEWAY GRADE AT NOSE | +0.25% |
| NUMBER OF FREEWAY LANES | 3 |
| NUMBER OF RAMP LANES | 1 |
| FREEWAY CURVATURE | TANGENT |
| RAMP CURVATURE | TANGENT |
| CURB OFFSET AT NOSE | 12 FEET |
| LENGTH OF RAMP | 520 FEET |

Figure 28. Geometric characteristics of 69th Road southbound entrance ramp, Grand Central Expressway, New York.

TABLE 4

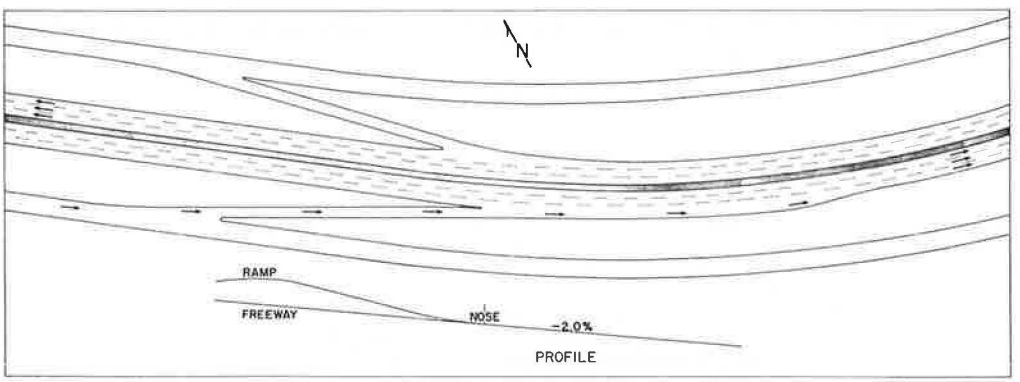
STUDY LOCATIONS IN NEW YORK, DETROIT, CHICAGO AND ST. LOUIS

| Location of Ramp | Number of Films |
|---|---|
| New York Area | |
| Jericho, eastbound on Long Island Expressway | 2 |
| Community Drive, eastbound on Long Island Expressway | 3 |
| Long Island Expressway, northbound on Cross Island Expressway | 3 |
| Broadway, eastbound on Northern State Parkway | 2 |
| Brush Hollow Road, eastbound on Northern State Parkway | 2 |
| 69th Road, southbound on Grand Central Parkway | 2 |
| Rockaway, northbound on Van Wyck Expressway | 2 |
| Detroit | |
| Chene, eastbound on Edsel Ford Expressway | 2 |
| Gratiot, eastbound on Edsel Ford Expressway | 2 |
| Warren Avenue, southbound on Southfield Expressway | 2 |
| Linwood, northbound on John Lodge Expressway | 2 |
| Chicago | |
| Independence Avenue, westbound on Eisenhower Expressway | 2 |
| Kostner, westbound on Eisenhower Expressway | 2 |
| Dempster Street, northbound on Edens Expressway | 3 |
| Peterson, northbound on Edens Expressway | 3 |
| Pulaski, eastbound on Southwest Expressway | |
| St. Louis | |
| Brentwood, westbound to Daniel Boone Expressway | 3 |

Circling at a quarter of a mile radius provided a better view of the study area, facilitating the analysis, and yet was wide enough that the pilot and plane could maintain the circle for long periods of time.

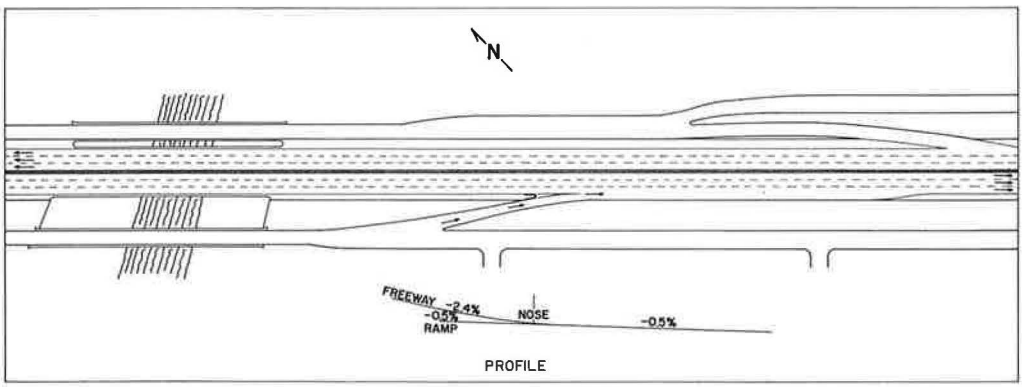
During this time, studies were carried out in Houston and the techniques and procedures perfected. The Houston studies were carried out at the eight ramps listed in Table 3. These ramps are illustrated in Figure 13 and Figures 20 through 25.

In May of 1966, the second out-of-state study was made in New York, Detroit and Chicago. This trip was a great success except for being marred by unfavorable weather, which made necessary a third trip, this time to Chicago and St. Louis. The ramps



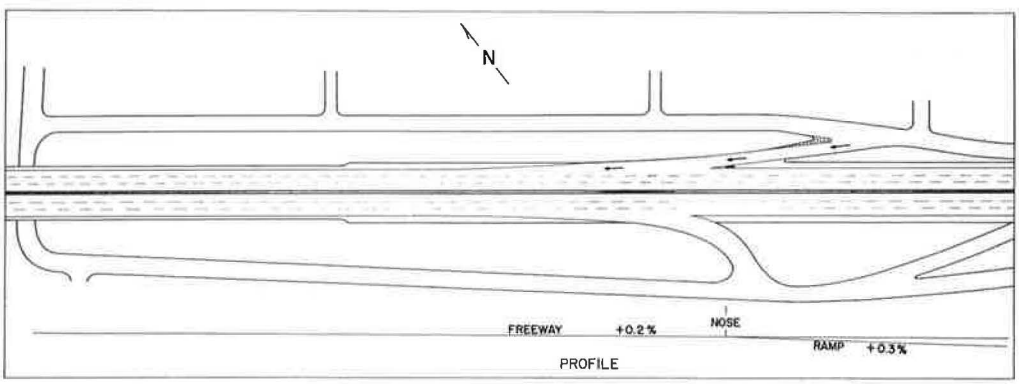

| GEOMETRIC CHARACTERISTICS | DATA |
|---|---|
| LENGTH OF ACCELERATION LANE | 700 FEET |
| SHAPE OF ACCELERATION LANE | PARALLEL |
| ANGLE OF CONVERGENCE AT RAMP NOSE | 3° |
| ANGLE OF CONVERGENCE 2 FT. OFF PAVEMENT EDGE | 3° |
| RAMP GRADE AT NOSE | -2.0% |
| FREEWAY GRADE AT NOSE | -2.0% |
| NUMBER OF FREEWAY LANES | 3 |
| NUMBER OF RAMP LANES | 1 |
| FREEWAY CURVATURE | SLIGHT LEFT |
| RAMP CURVATURE | SLIGHT LEFT |
| CURB OFFSET AT NOSE | 2 FEET |
| LENGTH OF RAMP | 660 FEET |

Figure 26. Geometric characteristics of Community Drive eastbound entrance ramp, Long Island Expressway, New York.



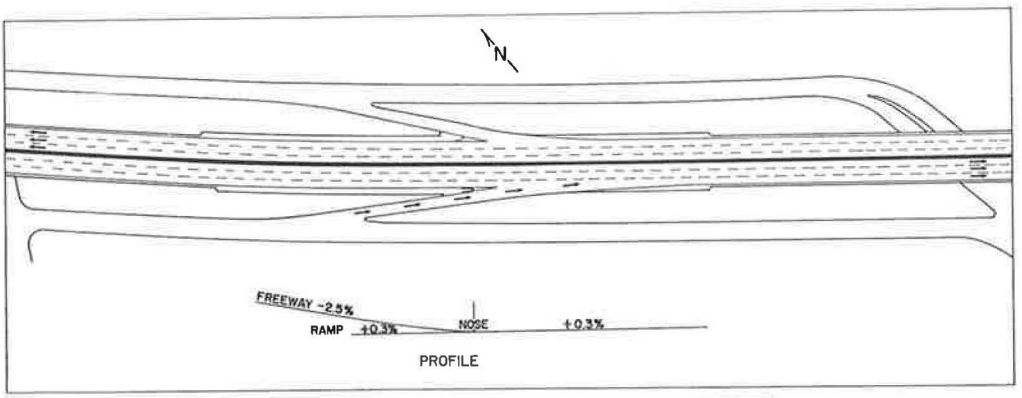

| GEOMETRIC CHARACTERISTICS | DATA |
|---|---|
| LENGTH OF ACCELERATION LANE | 680 FEET |
| SHAPE OF ACCELERATION LANE | PARALLEL |
| ANGLE OF CONVERGENCE AT RAMP NOSE | 10° |
| ANGLE OF CONVERGENCE 2 FT. OFF PAVEMENT EDGE | 10° |
| RAMP GRADE AT NOSE | -0.5% |
| FREEWAY GRADE AT NOSE | -0.5% |
| NUMBER OF FREEWAY LANES | 3 |
| NUMBER OF RAMP LANES | 1 |
| FREEWAY CURVATURE | TANGENT |
| RAMP CURVATURE | TANGENT |
| CURB OFFSET AT NOSE | 2 FEET |
| LENGTH OF RAMP | 380 FEET |

Figure 24. Geometric characteristics of Wayside eastbound entrance ramp, Gulf Freeway, Houston.



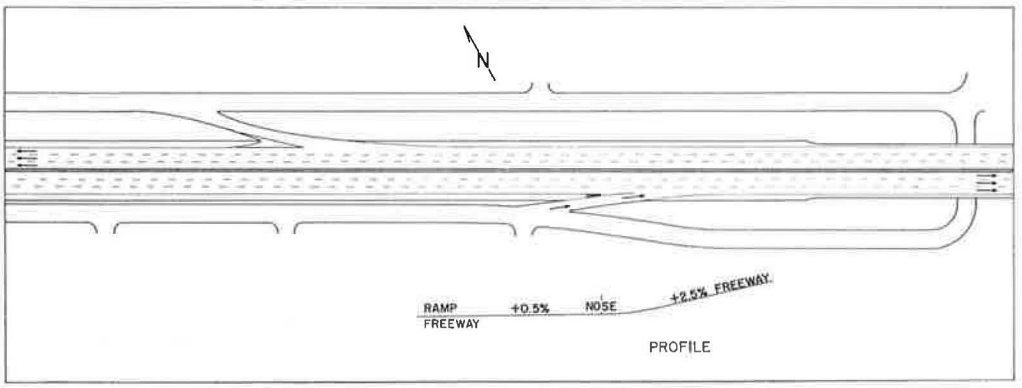

| GEOMETRIC CHARACTERISTICS | DATA |
|---|---|
| LENGTH OF ACCELERATION LANE | 310 FEET |
| SHAPE OF ACCELERATION LANE | TAPER |
| ANGLE OF CONVERGENCE AT RAMP NOSE | 10° |
| ANGLE OF CONVERGENCE 2 FT. OFF PAVEMENT EDGE | 10° |
| RAMP GRADE | +0.3% |
| FREEWAY GRADE | +0.2% |
| NUMBER OF FREEWAY LANES | 3 |
| NUMBER OF RAMP LANES | 1 |
| FREEWAY CURVATURE | TANGENT |
| RAMP CURVATURE | TANGENT |
| CURB OFFSET AT NOSE | 2 FEET |
| LENGTH OF RAMP | 150 FEET |

Figure 25. Geometric characteristics of Mossrose northbound entrance ramp, Gulf Freeway, Houston.



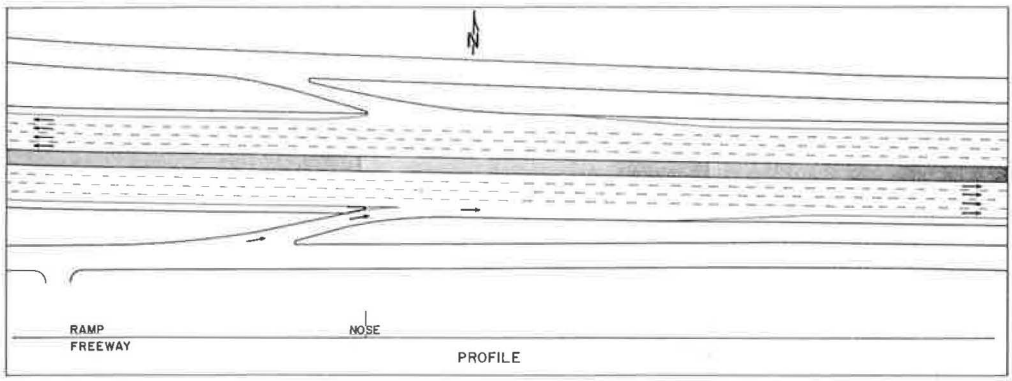

| GEOMETRIC CHARACTERISTICS DATA | |
|---|---|
| LENGTH OF ACCELERATION LANE | 340 FEET |
| SHAPE OF ACCELERATION LANE | TAPER |
| ANGLE OF CONVERGENCE AT RAMP NOSE | 10° |
| ANGLE OF CONVERGENCE 2 FT. OFF PAVEMENT EDGE | 10° |
| RAMP GRADE AT NOSE | +0.3% |
| FREEWAY GRADE AT NOSE | -0.3% |
| NUMBER OF FREEWAY LANES | 3 |
| NUMBER OF RAMP LANES | 1 |
| FREEWAY CURVATURE | TANGENT |
| RAMP CURVATURE | TANGENT |
| CURB OFFSET AT NOSE | 2 FEET |
| LENGTH OF RAMP | 1800FEET |

Figure 22. Geometric characteristics of Cullen eastbound entrance ramp, Gulf Freeway, Houston.



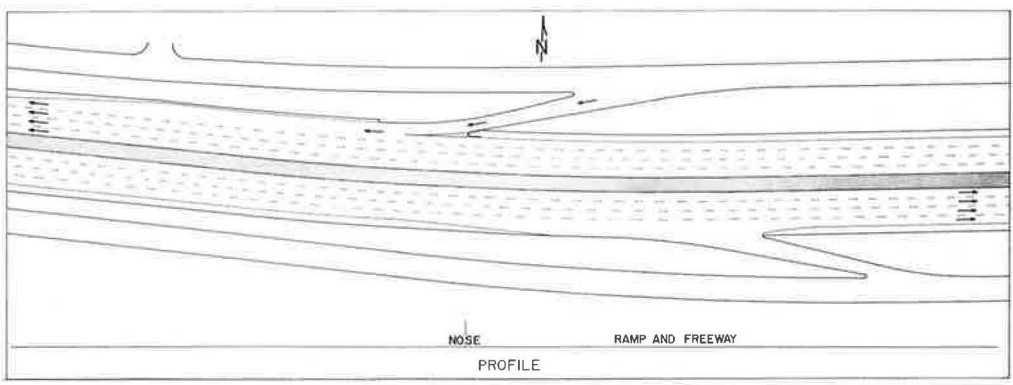

| GEOMETRIC CHARACTERISTICS DATA | |
|---|---|
| LENGTH OF ACCELERATION LANE | 240 FEET |
| SHAPE OF ACCELERATION LANE | TAPER |
| ANGLE OF CONVERGENCE AT RAMP NOSE | 7° |
| ANGLE OF CONVERGENCE 2FT. OFF PAVEMENT | 7° |
| RAMP GRADE AT NOSE | +0.5% |
| FREEWAY GRADE AT NOSE | +0.5% |
| NUMBER OF FREEWAY LANE | 3 |
| NUMBER OF RAMP LANES | 1 |
| FREEWAY CURVATURE | TANGENT |
| RAMP CURVATURE | TANGENT |
| CURB OFFSET AT NOSE | 2 FEET |
| LENGTH OF RAMP | 170 FEET |

Figure 23. Geometric characteristics of Dumble eastbound entrance ramp, Gulf Freeway, Houston.



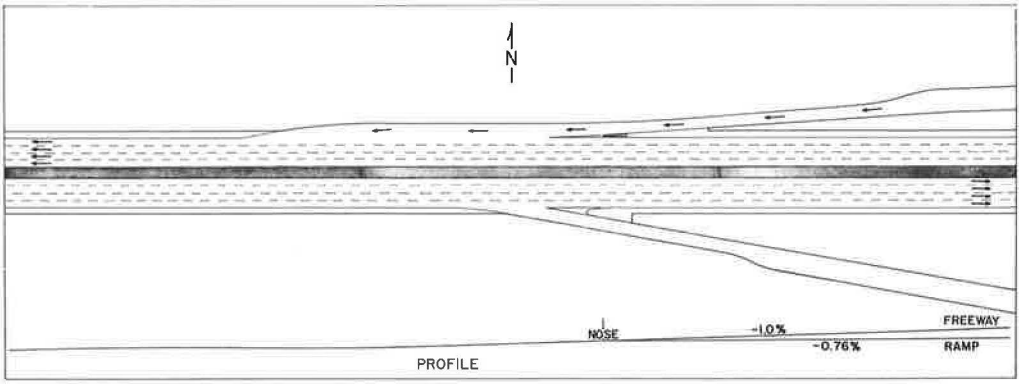

| GEOMETRIC CHARACTERISTICS | DATA |
|---|---|
| LENGTH OF ACCELERATION LANE | 610 FEET |
| SHAPE OF ACCELERATION LANE | PARALLEL |
| ANGLE OF CONVERGENCE AT RAMP NOSE | 12° 15' |
| ANGLE OF CONVERGENCE 2 FT. OFF PAVEMENT EDGE | 12° 15' |
| RAMP GRADE AT NOSE | LEVEL |
| FREEWAY GRADE AT NOSE | -0.40% |
| NUMBER OF FREEWAY LANES | 4 |
| NUMBER OF RAMP LANES | 1 |
| FREEWAY CURVATURE | TANGENT |
| RAMP CURVATURE | TANGENT |
| CURB OFFSET AT NOSE | 2 FEET |
| LENGTH OF RAMP | 103 FEET |

Figure 20. Geometric characteristics of Weslayan eastbound entrance ramp, Southwest Freeway, Houston.




| GEOMETRIC CHARACTERISTICS | DATA |
|---|---|
| LENGTH OF ACCELERATION LANE | 620 FEET |
| SHAPE OF ACCELERATION LANE | PARALLEL |
| ANGLE OF CONVERGENCE AT RAMP NOSE | 12° |
| ANGLE OF CONVERGENCE 2 FT. OFF PAVEMENT EDGE | 12° |
| RAMP GRADE AT NOSE | LEVEL |
| FREEWAY GRADE AT NOSE | LEVEL |
| NUMBER OF FREEWAY LANES | 4 |
| NUMBER OF RAMP LANES | 1 |
| FREEWAY CURVATURE | 1° RIGHT |
| RAMP CURVATURE | TANGENT |
| CURB OFFSET AT NOSE | 2 FEET |
| LENGTH OF RAMP | 160 FEET |

Figure 21. Geometric characteristics of Buffalo Speedway westbound entrance ramp, Southwest Freeway, Houston.




| GEOMETRIC CHARACTERISTICS | DATA |
|---|---|
| LENGTH OF ACCELERATION LANE | 970 FEET |
| SHAPE OF ACCELERATION LANE | PARALLEL |
| ANGLE OF CONVERGENCE AT RAMP NOSE | 6° |
| ANGLE OF CONVERGENCE 2FT. OFF PAVEMENT EDGE | 6° |
| RAMP GRADE AT NOSE | -0.8% |
| FREEWAY GRADE AT NOSE | -1.0% |
| NUMBER OF FREEWAY LANES | 3 |
| NUMBER OF RAMP LANES | 1 |
| FREEWAY CURVATURE | TANGENT |
| RAMP CURVATURE | TANGENT |
| CURB OFFSET AT NOSE | 2 FEET |
| LENGTH OF RAMP | 600 FEET |

Figure 19. Geometric characteristics of Coldwater Canyon Avenue westbound entrance ramp, Ventura Freeway, Los Angeles.

entry (Fig. 12) and a ramp with a short acceleration lane and a large angle of entry (Fig. 13).

After extensive correspondence with highway officials in many parts of the country and reviewing a multitude of plans and profiles, ramps were selected for study in Los Angeles, Sacramento, the San Francisco area, the New York metropolitan area, Detroit, Chicago, St. Louis, and Houston.

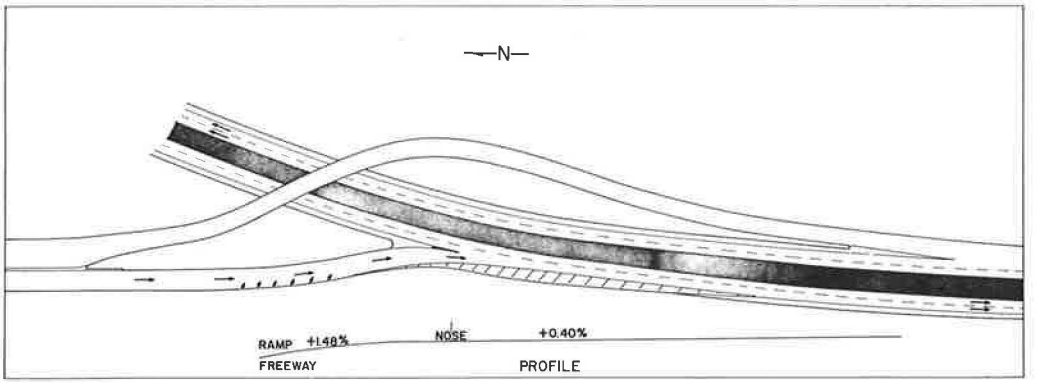
Experimental studies were first carried out in Houston, mainly for the purpose of checking out the equipment and techniques and developing the various procedures to be followed into a smoothly running organization. The first out-of-state study was done in California in November of 1965, where the ramps listed in Table 2 were filmed. The table also shows the number of films taken at each location. The study locations are listed according to the metropolitan area in which they are located, rather than by the exact suburb. Drawings of these study locations, with a table giving the major geometric characteristics, are shown in Figure 11 and Figures 14 through 19.

After the California study, it became clear that the study techniques and equipment had to be reevaluated. Some of the films taken at the locations listed and all of the films taken at some other locations were not usable. This reevaluation led to several improvements. In the first place, the camera, which until this time had a fixed shutter speed, was modified to have adjustable speeds as described earlier. Second, the camera mounting was slightly altered so as to further dampen the effect of vibrations. Third, the use of different kinds of film and different filters was investigated. Finally, the flight pattern was altered. Until this time circles were made at a radius of approximately half a mile. It was found desirable, however, that the circle be pulled tighter so that the films could be taken from more directly above the traffic.

TABLE 3

STUDY LOCATIONS IN HOUSTON

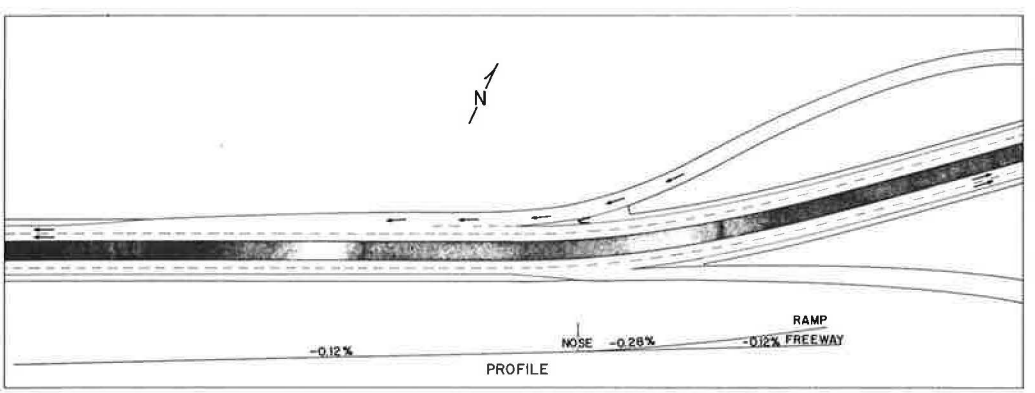
| Location of Ramp | Number of Films |
|---|---|
| Weslayan, eastbound on Southwest Freeway | 4 |
| Buffalo Speedway, westbound on Southwest Freeway | 2 |
| Cullen, eastbound on Gulf Freeway | 3 |
| Dumble, eastbound on Gulf Freeway | 5 |
| Telephone, eastbound on Gulf Freeway | 3 |
| Wayside, eastbound on Gulf Freeway | 4 |
| Broad Street, eastbound on Gulf Freeway | 4 |
| Mossrose, westbound on Gulf Freeway | 2 |




| GEOMETRIC CHARACTERISTICS | DATA |
|---|---|
| LENGTH OF ACCELERATION LANE | 600 FEET |
| SHAPE OF ACCELERATION LANE | TAPER |
| ANGLE OF CONVERGENCE AT RAMP NOSE | 4° |
| ANGLE OF CONVERGENCE 2 FT. OFF PAVEMENT EDGE | 4° |
| RAMP GRADE AT NOSE | +0.4% |
| FREEWAY GRADE AT NOSE | +0.4% |
| NUMBER OF FREEWAY LANES | 2 |
| NUMBER OF RAMP LANES | 1 |
| FREEWAY CURVATURE | SLIGHT LEFT |
| RAMP CURVATURE | SLIGHT RIGHT |
| CURB OFFSET AT NOSE | 2 FEET |
| LENGTH OF RAMP | 800 FEET |

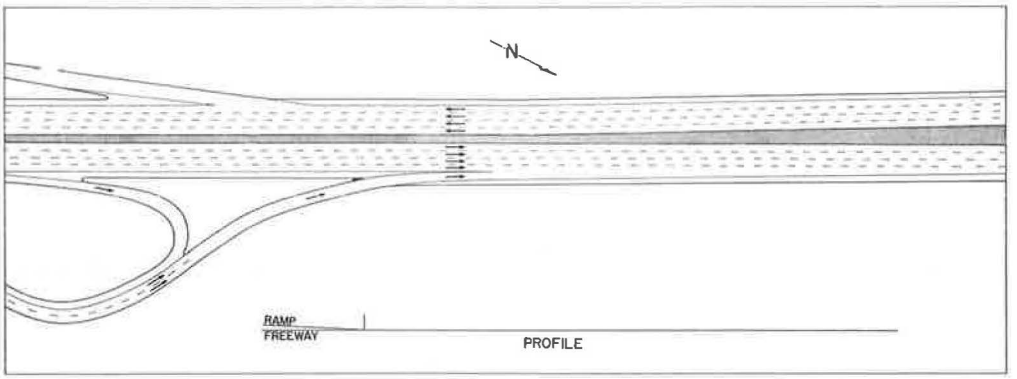
Figure 17. Geometric characteristics of Monument Junction southbound entrance ramp, I-680 in Pleasant Hill (San Francisco).

The coverage of these two geometric elements is perhaps better illustrated by Table 1 which shows the number of ramps studied that fall into each group of acceleration lane lengths and angles of entry. The range of ramp shapes studied is illustrated in Figures 10 through 13, showing the geometric characteristics of a ramp with a long acceleration lane and a small angle of entry (Fig. 10), a ramp with a long acceleration lane and a large angle of entry (Fig. 11), a ramp with a short acceleration lane and a small angle of




| GEOMETRIC CHARACTERISTICS | DATA |
|---|---|
| LENGTH OF ACCELERATION LANE | 690 FEET |
| SHAPE OF ACCELERATION LANE | PARALLEL |
| ANGLE OF CONVERGENCE AT RAMP NOSE | 4° |
| ANGLE OF CONVERGENCE 2 FT. OFF PAVEMENT EDGE | 4° |
| RAMP GRADE AT NOSE | -0.3% |
| FREEWAY GRADE AT NOSE | -0.12% |
| NUMBER OF FREEWAY LANES | 2 |
| NUMBER OF RAMP LANES | 1 |
| FREEWAY CURVATURE | SLIGHT RIGHT |
| RAMP CURVATURE | SLIGHT RIGHT |
| CURB OFFSET AT NOSE | 2 FEET |
| LENGTH OF RAMP | 500 FEET |

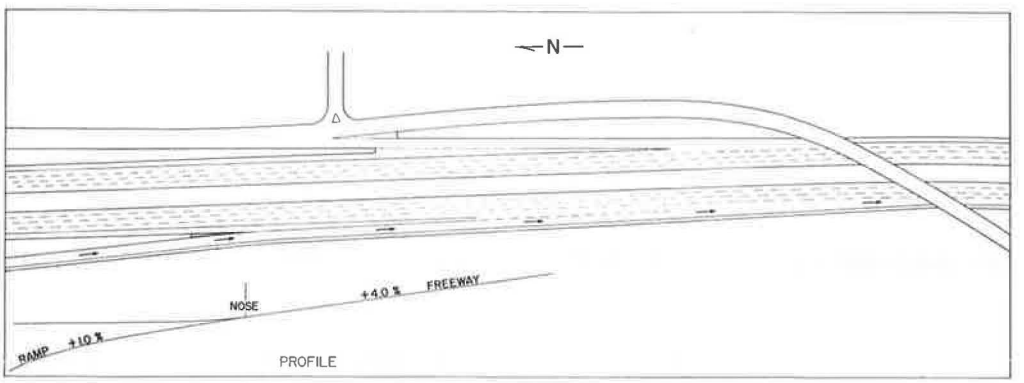
Figure 18. Geometric characteristics of Watt Avenue southbound entrance ramp, I-80, Sacramento.




| GEOMETRIC CHARACTERISTICS DATA | |
|---|---|
| LENGTH OF ACCELERATION LANE | 1025 FEET |
| SHAPE OF ACCELERATION LANE | TAPER |
| ANGLE OF CONVERGENCE AT RAMP NOSE | 7 ½ DEGREES |
| ANGLE OF CONVERGENCE 2FT. OFF PAVEMENT EDGE | 2 DEGREES |
| RAMP GRADE AT NOSE | SLIGHT DOWNGRADE |
| FREEWAY GRADE AT NOSE | LEVEL |
| NUMBER OF FREEWAY LANES | 4 |
| NUMBER OF RAMP LANES | 1 |
| FREEWAY CURVATURE | TANGENT |
| RAMP CURVATURE | SLIGHT RIGHT |
| CURB OFFSET AT NOSE | 10 FEET |
| LENGTH OF RAMP | 300 FEET + |

Figure 15. Geometric characteristics of Bayshore Freeway, Broadway entrance ramp, San Francisco.

Geometric considerations in the selection of study sites required the coverage of a wide range of geometrics in the ramps to be studied. Variations in acceleration lane length, angle of convergence and ramp grade were sought, primarily at locations where the freeway alignment was straight and fairly level. The considerable range of geometrics covered among the ramps selected can be seen in Figure 9, which illustrates the variation in acceleration lane lengths and angles of convergence of the ramps studied.




| GEOMETRIC CHARACTERISTICS DATA | |
|---|---|
| LENGTH OF ACCELERATION LANE | 700 FEET |
| SHAPE OF ACCELERATION LANE | TAPER |
| ANGLE OF CONVERGENCE AT RAMP NOSE | 5° |
| ANGLE OF CONVERGENCE 2 FT. OFF PAVEMENT EDGE | 2° |
| RAMP GRADE | +10% |
| FREEWAY GRADE | +4.0% |
| NUMBER OF FREEWAY LANES | 4 |
| NUMBER OF RAMP LANES | 1 |
| FREEWAY CURVATURE | TANGENT |
| RAMP CURVATURE | TANGENT |
| CURB OFFSET AT NOSE | 10 FEET |
| LENGTH OF RAMP | 450 FEET |

Figure 16. Geometric characteristics of Lakeshore southbound entrance ramp, MacArthur Freeway, Los Angeles.

TABLE 2

STUDY LOCATIONS IN CALIFORNIA

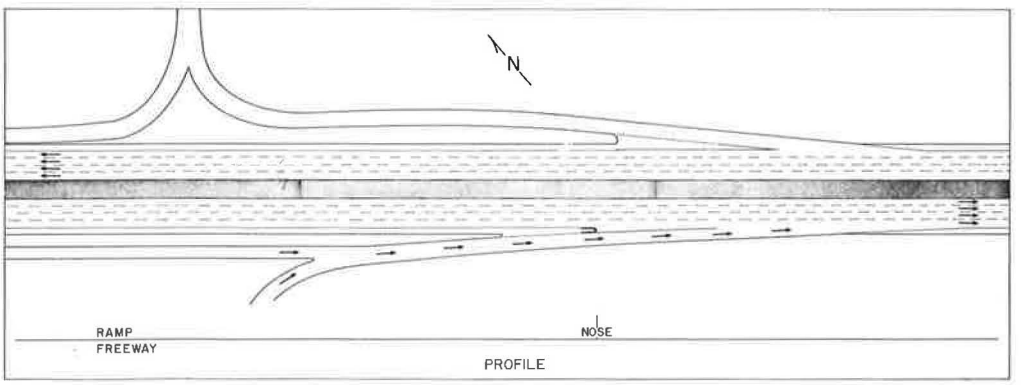
| Location of Ramp | Number of Films |
|---|---|
| San Francisco Area | |
| Milbrae, southbound on Bayshore Freeway | 1 |
| Broadway, southbound on Bayshore Freeway | 2 |
| Lakeshore, southbound on MacArthur Freeway | 1 |
| Ashby, southbound on Eastshore Freeway | 2 |
| Monument Junction, southbound on I-680 | 2 |
| Sacramento | |
| Watt Avenue, southbound on I-80 | 2 |
| Los Angeles | |
| Coldwater Canyon, westbound on Ventura Freeway | 2 |

The marking tape is first placed in position (Fig. 7) and is then cemented by rolling it down with a special roller applicator (Fig. 8). Upon completion of the study, the tape can easily be removed by simply peeling it from the pavement. It was found that for improved visibility from high altitudes, the most important dimension of the reference mark was its length rather than its width or shape.

Normally, reference marks were placed at 200-ft intervals radiating from the concrete nose of the ramp. However, on short ramps of 400 ft or less, marks were placed at 100-ft intervals.

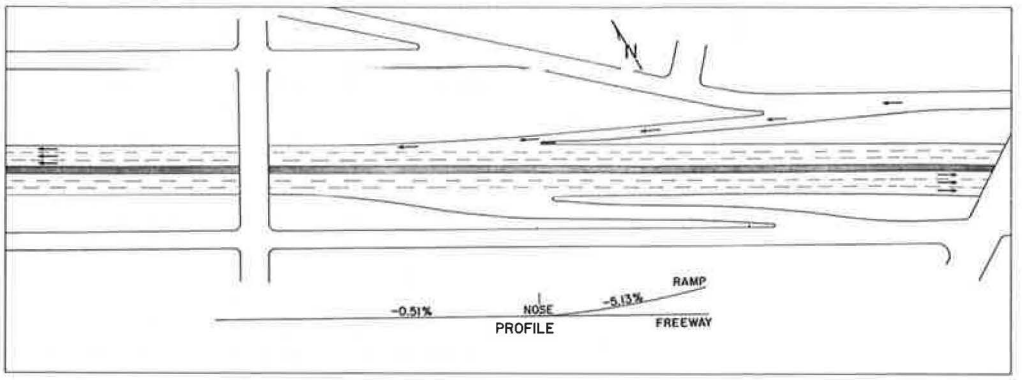
## STUDY LOCATIONS

The study locations were selected to meet several operational and geometric requirements. Operational considerations required the selection of study sites operating at or near capacity while unaffected by upstream or downstream conditions, so that a pure merging situation existed. Local authorities were extremely helpful in suggesting study sites and providing volume data to aid 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 effect of any downstream restrictions. Based on the traffic operations during the time of the field observation, the study period was selected so that a free flow merging operation prevailed and so that the merging volume was near capacity. In spite of this careful checking of the study sites, the operation during the film studies was not always the same as during the field checks due to changes in traffic patterns, accidents, or some other temporary situation, with the result that the operational requirements were not always successfully met.




| GEOMETRIC CHARACTERISTICS DATA | |
|---|---|
| LENGTH OF ACCELERATION LANE | 675 FEET |
| SHAPE OF ACCELERATION LANE | TAPER |
| ANGLE OF CONVERGENCE AT RAMP NOSE | 3° |
| ANGLE OF CONVERGENCE 2FT OFF PAVEMENT EDGE | 2° |
| RAMP GRADE AT NOSE | LEVEL |
| FREEWAY GRADE AT NOSE | LEVEL |
| NUMBER OF FREEWAY LANES | 4 |
| NUMBER OF RAMP LANES | 1 |
| FREEWAY CURVATURE | TANGENT |
| RAMP CURVATURE | TANGENT |
| CURB OFFSET AT NOSE | 10 FEET |
| LENGTH OF RAMP | 350 FEET |

Figure 14. Geometric characteristics of Milbrae Avenue southbound entrance ramp, Bayshore Freeway, San Francisco.

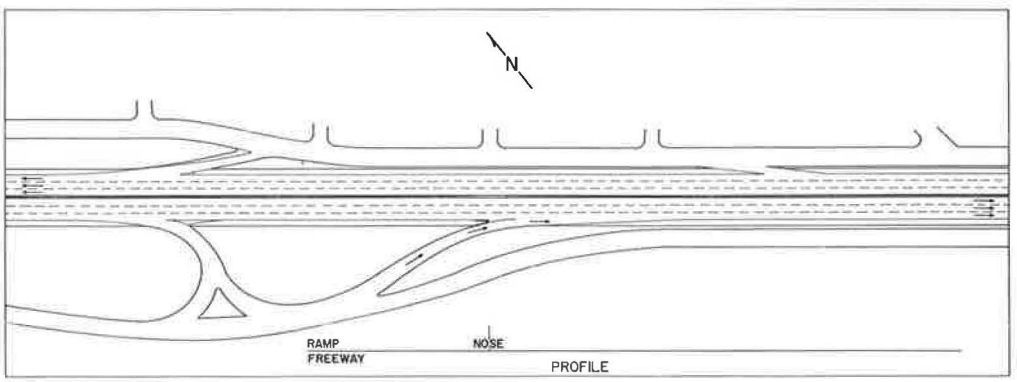



| GEOMETRIC CHARACTERISTICS DATA | |
|---|---|
| LENGTH OF ACCELERATION LANE | 435 FEET |
| SHAPE OF ACCELERATION LANE | TAPER |
| ANGLE OF CONVERGENCE AT RAMP NOSE | 2° |
| ANGLE OF CONVERGENCE 2 FT. OFF PAVEMENT EDGE | 2° |
| RAMP GRADE AT NOSE | -0.51 % |
| FREEWAY GRADE AT NOSE | -0.51 % |
| NUMBER OF FREEWAY LANES | 3 |
| NUMBER OF RAMP LANES | 1 |
| FREEWAY CURVATURE | TANGENT |
| RAMP CURVATURE | TANGENT |
| CURB OFFSET AT NOSE | 2 FEET |
| LENGTH OF RAMP | 380 FEET |

Figure 12. Geometric characteristics of Rockaway northbound entrance ramp, Van Wyck Expressway, New York.

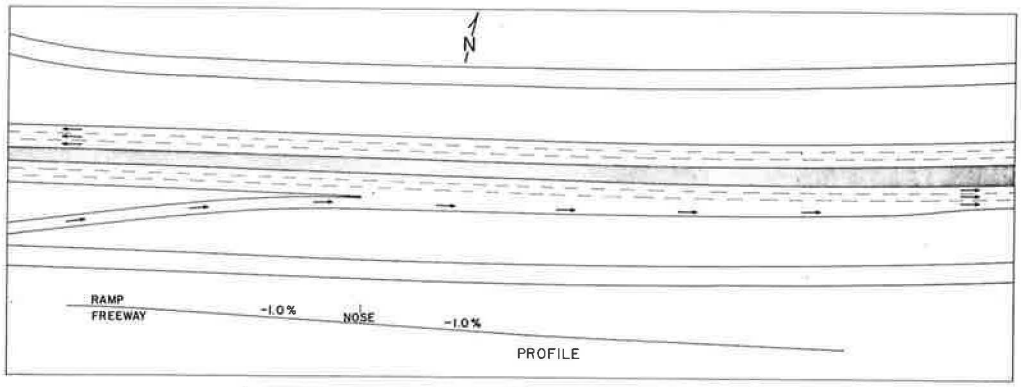
## Ground Control Stations

As ground control stations for referencing the position of vehicles as they traverse the study area, marks were made on the shoulder of the freeway and the ramp. Experimentation with various marking materials and mark designs led to the use of 3M Lane Marking Tape in an alternating pattern of arrowhead-shaped and parallel line marks (Fig. 6). The marking tape is a white nonreflective 6-in.-wide tape with a bituminous adhesive on one side, making its application and removal extremely easy and convenient.




| GEOMETRIC CHARACTERISTICS DATA | |
|---|---|
| LENGTH OF ACCELERATION LANE | 335 FEET |
| SHAPE OF ACCELERATION LANE | TAPER |
| ANGLE OF CONVERGENCE AT RAMP NOSE | 14° |
| ANGLE OF CONVERGENCE 2 FT. OFF PAVEMENT EDGE | 14° |
| RAMP GRADE AT NOSE | LEVEL |
| FREEWAY GRADE AT NOSE | LEVEL |
| NUMBER OF FREEWAY LANES | 3 |
| NUMBER OF RAMP LANES | 1 |
| FREEWAY CURVATURE | TANGENT |
| RAMP CURVATURE | TANGENT |
| CURB OFFSET AT NOSE | 2 FEET |
| LENGTH OF RAMP | 225 FEET |

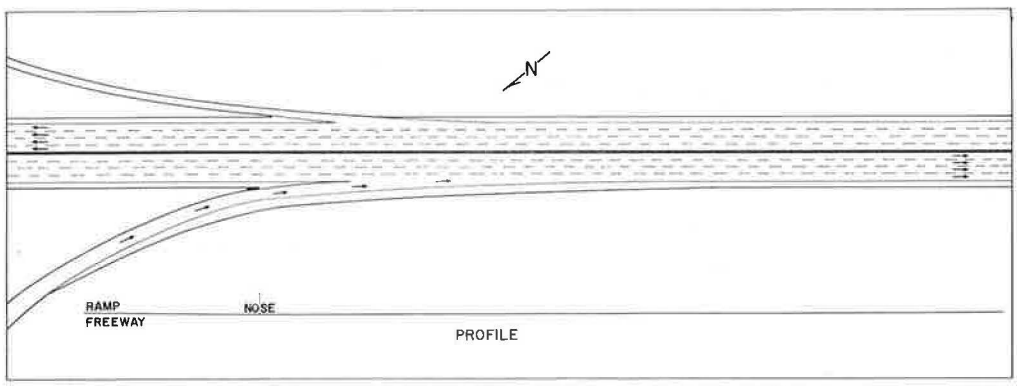
Figure 13. Geometric characteristics of Broad Street southbound entrance ramp, Gulf Freeway, Houston.




| GEOMETRIC CHARACTERISTICS DATA | |
|---|---|
| LENGTH OF ACCELERATION LANE | 1200 FEET |
| SHAPE OF ACCELERATION LANE | PARALLEL |
| ANGLE OF CONVERGENCE AT RAMP NOSE | 1° |
| ANGLE OF CONVERGENCE 2 FT. OFF PAVEMENT EDGE | 1° |
| RAMP GRADE AT NOSE | -1.0% |
| FREEWAY GRADE AT NOSE | -1.0% |
| NUMBER OF FREEWAY LANES | 3 |
| NUMBER OF RAMP LANES | 1 |
| FREEWAY CURVATURE | TANGENT |
| RAMP CURVATURE | SLIGHT RIGHT |
| CURB OFFSET AT NOSE | 2 FEET |
| LENGTH OF RAMP | 600 FEET |

Figure 10. Geometric characteristics of Jericho (Rt. 25) eastbound entrance ramp, Long Island Expressway, New York.

International, New York's Kennedy and La Guardia, Chicago's O'Hare and Houston's International. As an additional safety precaution, it was sometimes deemed desirable to have a third person in the airplace as an observer to keep a sharp lookout for other aircraft.




| GEOMETRIC CHARACTERISTICS DATA | |
|---|---|
| LENGTH OF ACCELERATION LANE | 1120 FEET |
| SHAPE OF ACCELERATION LANE | TAPER |
| ANGLE OF CONVERGENCE AT RAMP NOSE | 7°30' |
| ANGLE OF CONVERGENCE 2 FT. OFF PAVEMENT EDGE | 2° |
| RAMP GRADE AT NOSE | LEVEL |
| FREEWAY GRADE AT NOSE | LEVEL |
| NUMBER OF FREEWAY LANES | 4 |
| NUMBER OF RAMP LANES | 1 |
| FREEWAY CURVATURE | TANGENT |
| RAMP CURVATURE | TANGENT |
| CURB OFFSET AT NOSE | 10 FEET |
| LENGTH OF RAMP | 500 FEET |

Figure 11. Geometric characteristics of Ashby Avenue southbound entrance ramp, Eastshore Freeway, San Francisco.

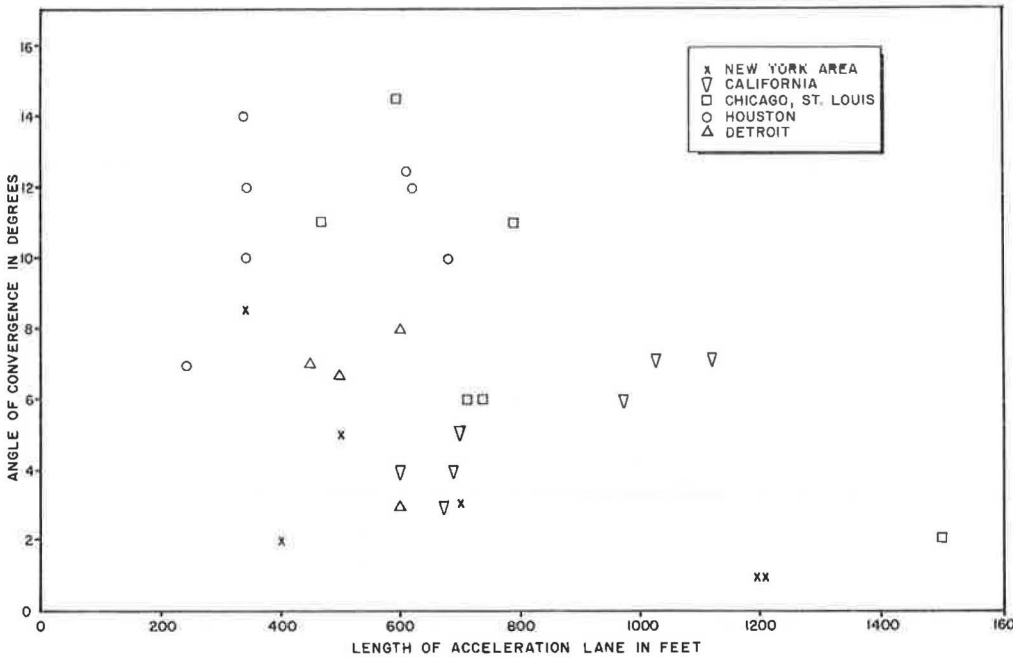



Figure 9. Range of geometrics of ramps studied.

Exposure settings were obtained using a Weston Master V Universal Exposure Meter model 748. It was found desirable to obtain light readings on the ground before filming since exposure settings determined at altitudes above 1000 ft could differ as much as 3 f-stops from that determined at ground level on days of extreme haze conditions, resulting in overexposure of the film. The best image definition was obtained by filming just after a frontal passage or following a rain shower when there is little atmospheric haze.

After the initial teething troubles, this filming technique proved extremely satisfactory. A crew of two, consisting of pilot and cameraman, could take off in the morning, fly several hundred miles, film a location or two and return to home base with minimum disturbance to the local authorities and negligible preparational furor. This mobility, plus the substantially reduced cost involved originally, led to the choice of a light airplane over a helicopter. One problem encountered in the circling technique was that of changing light conditions when the sun is close to the horizon or when the study area is located close to a large body of water. This could lead to the film being overexposed when the camera is in a certain phase of the orbit and then underexposed when it is on the opposite side. This problem could, however, be overcome with a camera equipped with an "electric eye" that automatically adjusts the aperture, or with a camera which allows this adjustment to be made during filming. Interference with other air traffic did not present much of a problem, mainly through the cooperation of the personnel of the Federal Aviation Agency Air Traffic Control Center in each area filmed. Information regarding approach and departure routes of aircraft and safe altitudes for filming was provided by the local air traffic controller. The fine service rendered by the local radar and control tower personnel permitted the filming of study sites in such high-density air traffic areas as Los Angeles' International, San Francisco's

TABLE 1

NUMBER OF RAMPS STUDIED IN EACH CELL OF ACCELERATION LANE LENGTH AND ANGLE OF ENTRY

| Angle of Entry (deg) | Acceleration Lane Length (ft) | | | |
|---|---|---|---|---|
| | 0-400 | 400-600 | 600-800 | Above 800 |
| 0-4 | 1 | 2 | 3 | 3 |
| 4-8 | 1 | 4 | 3 | 4 |
| Above 8 | 4 | 2 | 4 | 0 |

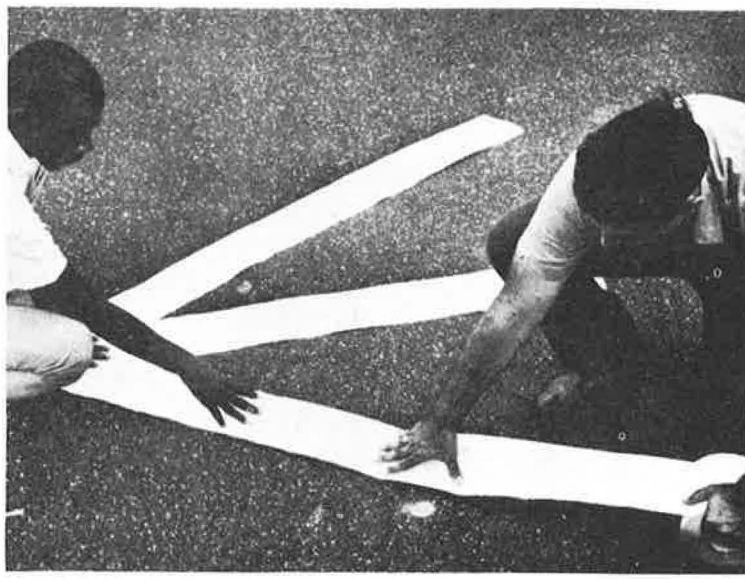


Figure 7. Placing of marker tape.

Figure 8. Tape being rolled down.

In the data collection on this project, three 400-ft magazines were used, while filming was done at a rate of 5 frames per second. This allowed three filming periods of approximately 22 minutes each. Figure 5 shows a sequence of four photographs taken from a film, showing the study area from different positions in the orbit.

Both color and black and white film were used in some of the initial studies, but it was soon found that, at twice the price, color film had little if any advantage over black and white. Kodak Plus-X Panchromatic Type 4231 film having a speed rating of ASA 80 was used mostly, but on overcast days or on days when light readings were low, such as during the peak hours in the winter months, a somewhat faster film, Kodak Double-X Panchromatic Type 5222, with a speed rating of ASA 250, was used. The slower speed film is finer grained than the high-speed film and was therefore preferred whenever light conditions permitted its use.

The filters used to reduce the veiling effect of atmospheric haze, present at all times to a greater or lesser degree, were Wratten No. 8 (K-2), No. 15 (G) or No. 23 (A), depending on the degree of air pollution.

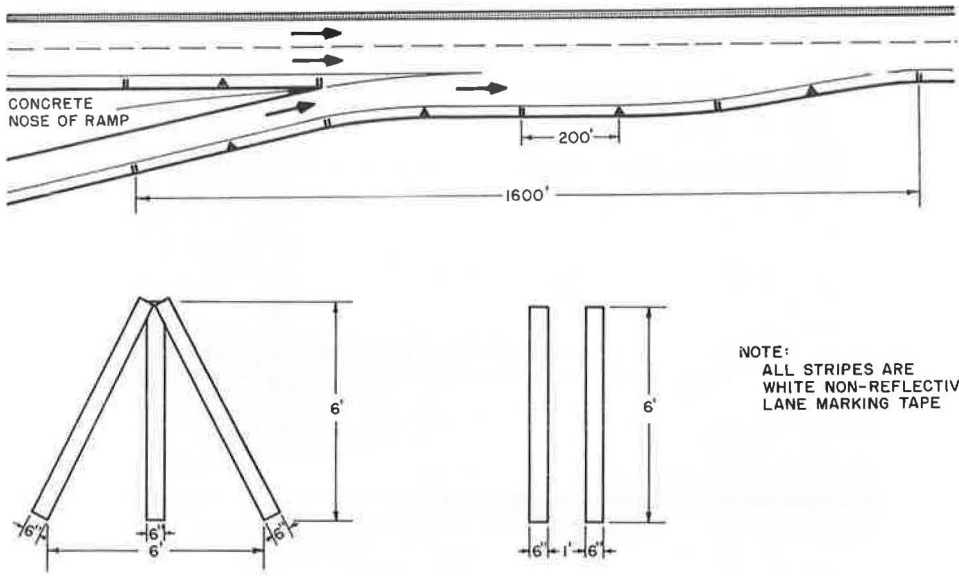



Figure 6. Typical study section.

## Aerial Technique and Equipment

The flight pattern consisted of orbiting the study area in a circular or elliptical pattern with a light airplane while training the camera on the center of the study area, usually the nose of the entrance ramp. The aircraft used was a Cessna 206 with the baggage door of the rear passenger compartment modified to accept a large, clear plexiglass window. The left rear seat was removed to permit mounting of the camera inside the aircraft. This allowed filming through the plexiglass window without any noticeable glare or distortion. Figure 2 shows the modification, which has proven quite satisfactory, and Figure 3 shows the camera mounted inside the aircraft.

The camera used was a 35-mm Automax G-2 data recording camera, fitted with Automax Model 250 control head and an Automax 25 intervalometer which could pulse the camera at the rate of ½, 1, 3, 5, or 10 frames per second and with a setting for cine operation at 16 frames per second. Power was supplied to the camera by two 12-volt DC batteries, connected in series to provide sufficient voltage to drive the camera, which maintained a constant speed through a voltage range of 18 to 36 volts DC. The camera has interchangeable lenses, is adaptable to a 400-ft or a 1000-ft film magazine and has a variable shutter speed ranging from $\frac{1}{64}$ to $\frac{1}{1000}$ second. The camera also has a data chamber containing a clock with a sweep-second hand, a frame counter and a data slate, all of which is projected as an image on each frame of the film being taken.

The camera was mounted inside the aircraft on a small tripod fitted with a Miller fluid head. The tripod was mounted on special rubber "shoes" to dampen vibrations and secured to the floor of the aircraft with adaptable wires fitted with turnbuckles. To further dampen vibrations, a piece of medium density rubber was installed between the fluid head and the top of the tripod.

Experimentation with lenses of different focal lengths used at different flight altitudes led to the development of the chart shown in Figure 4. This chart was used throughout the study to avoid conflict with other air traffic. It was found that when a distance on the freeway of more than 1800 ft was covered, the film analysis became extremely cumbersone because it was difficult to follow a single vehicle through the study area under conditions of high traffic density. This difficulty was due to shadows, vehicle image size and general lack of definition, caused mainly by atmospheric haze.

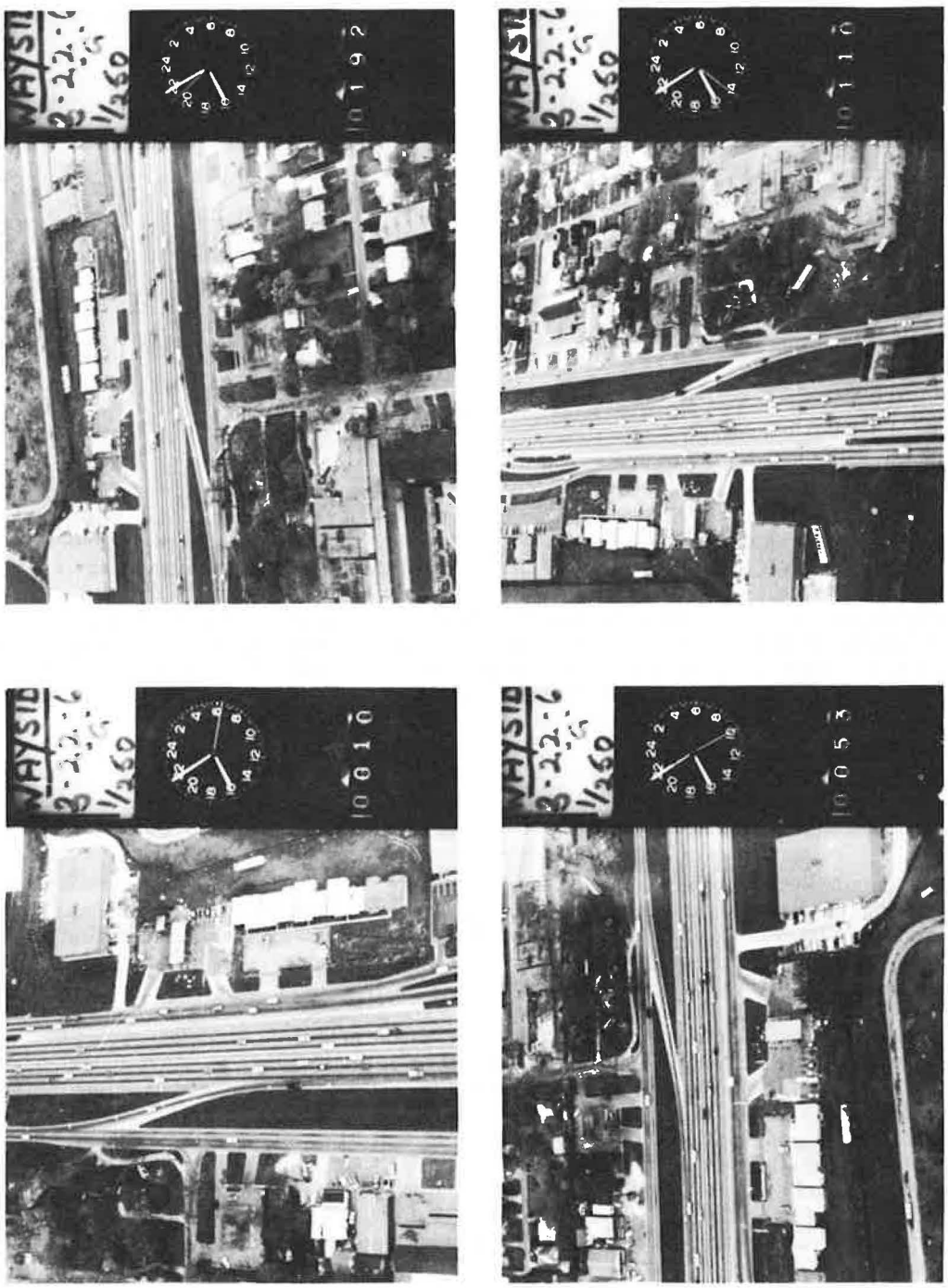



Figure 5. Typical frames from data film.

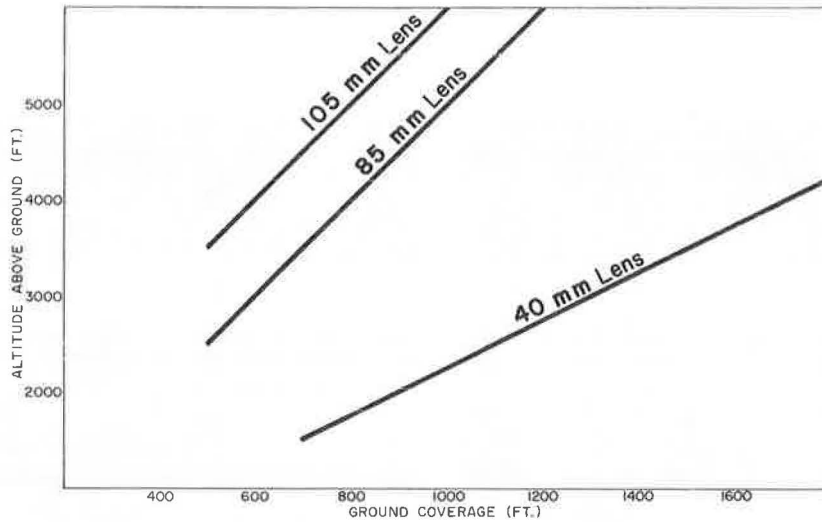



Figure 4. Altitude-ground coverage curves.

ranging over the length and breadth of the continental United States. The study had to be completed in the relatively short time of 18 months, with the result that close attention had to be paid to proper scheduling of the many activities involved in order to attain the wide-ranging objectives. Figure 1 shows the critical path scheduling envisioned at the start of the project.

The objectives of this project are so varied in scope and comprehensive in nature as to prohibit their being covered in their entirety in this report. The main purpose of this paper is to report on the data collection and reduction techniques employed, to describe the ramps under study and to indicate the nature of the data available for purposes of future reference. Furthermore, the authors wish to report on the editing and preliminary analysis of the data to present a comprehensive summary of merging operations at 32 ramp-freeway connections specially chosen to include diverse geometric, geographic, environmental and operating conditions.

## DATA COLLECTION

The data collection phase of this study was carried out at 32 entrance ramps located in 8 major metropolitan areas in 6 states. Data were collected on a continuous basis at each ramp to provide the researchers with information on all the variables that could possibly influence the merging maneuver. The many variables involved clearly necessitated the need for a permanent record of the operation, making continual back-reference feasible. Perhaps the best such permanent record is provided by photographic techniques, and the decision to use time-lapse photography was therefore almost a foregone conclusion. Furthermore, the need for collecting data at many different locations, in different parts of the country, made the use of one or more stationary cameras impractical. The data collection procedure had to be independent of the availability of vantage points such as conveniently located tall buildings or overhead structures, and had to be extremely mobile, requiring little equipment and few personnel. Since the studies were to be carried out in areas under the jurisdiction of various highway authorities another requirement of the procedure was that it should interfere as little as possible with the day-to-day operation of the organization concerned. All these considerations led to the development of an aerial photographic technique for the continuous study of a length of highway.

Figure 2. Aircraft door modification.

Figure 3. Camera mounted in aircraft.

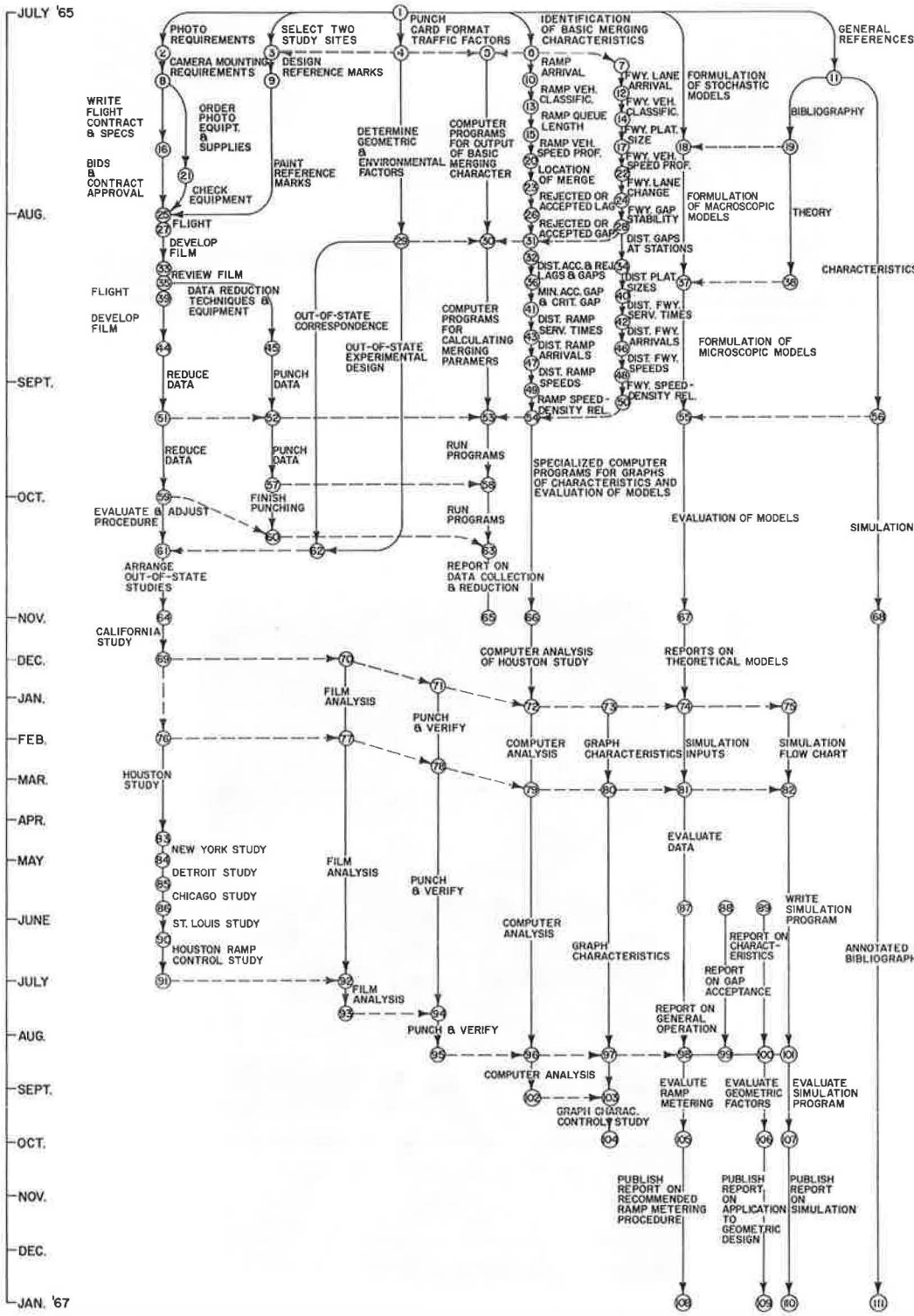



Figure 1. CPM network diagram for ramp merging research project.

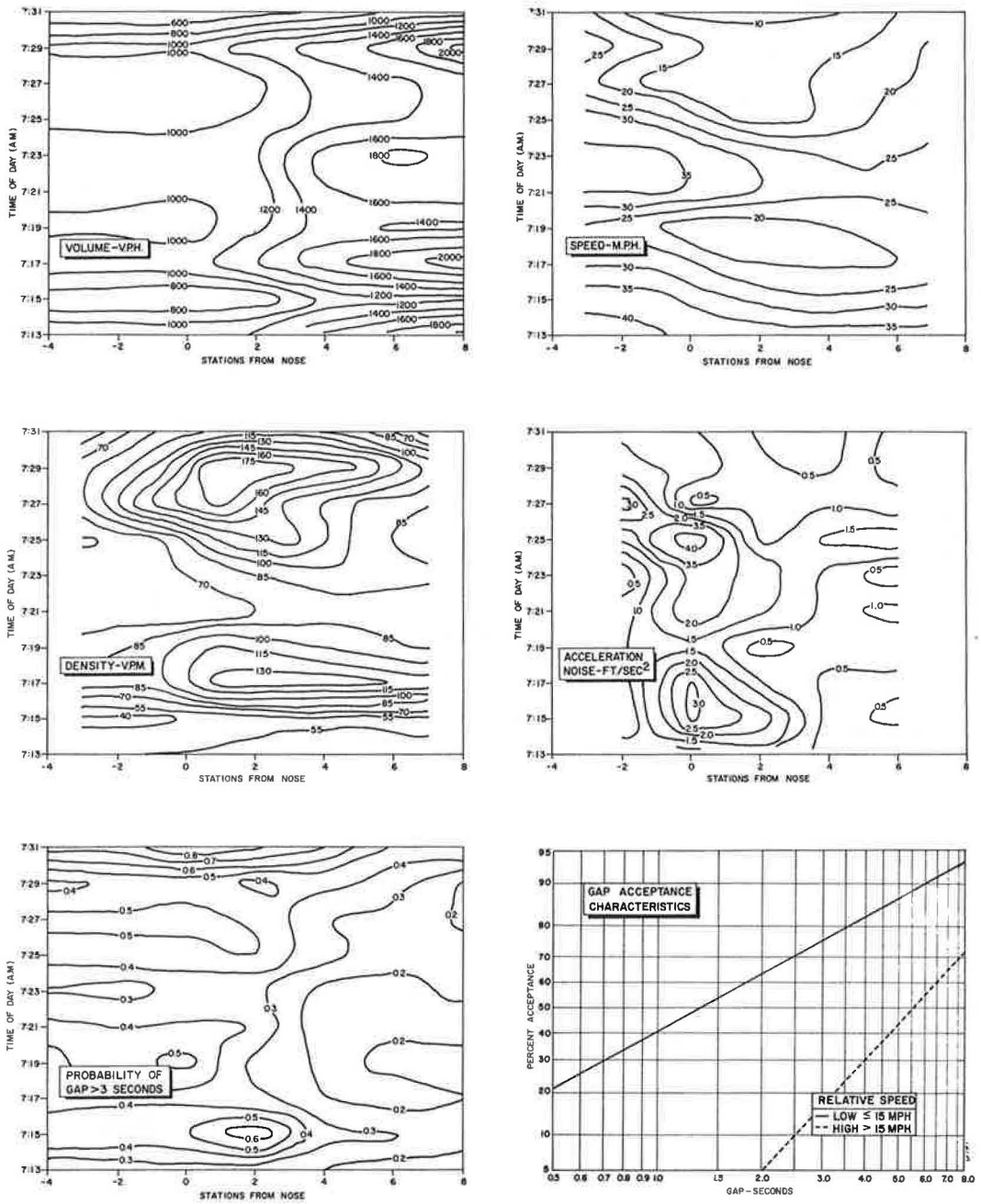



Figure 42. Traffic characteristics of Ashby Avenue southbound entrance ramp, Eastshore Freeway, San Francisco.

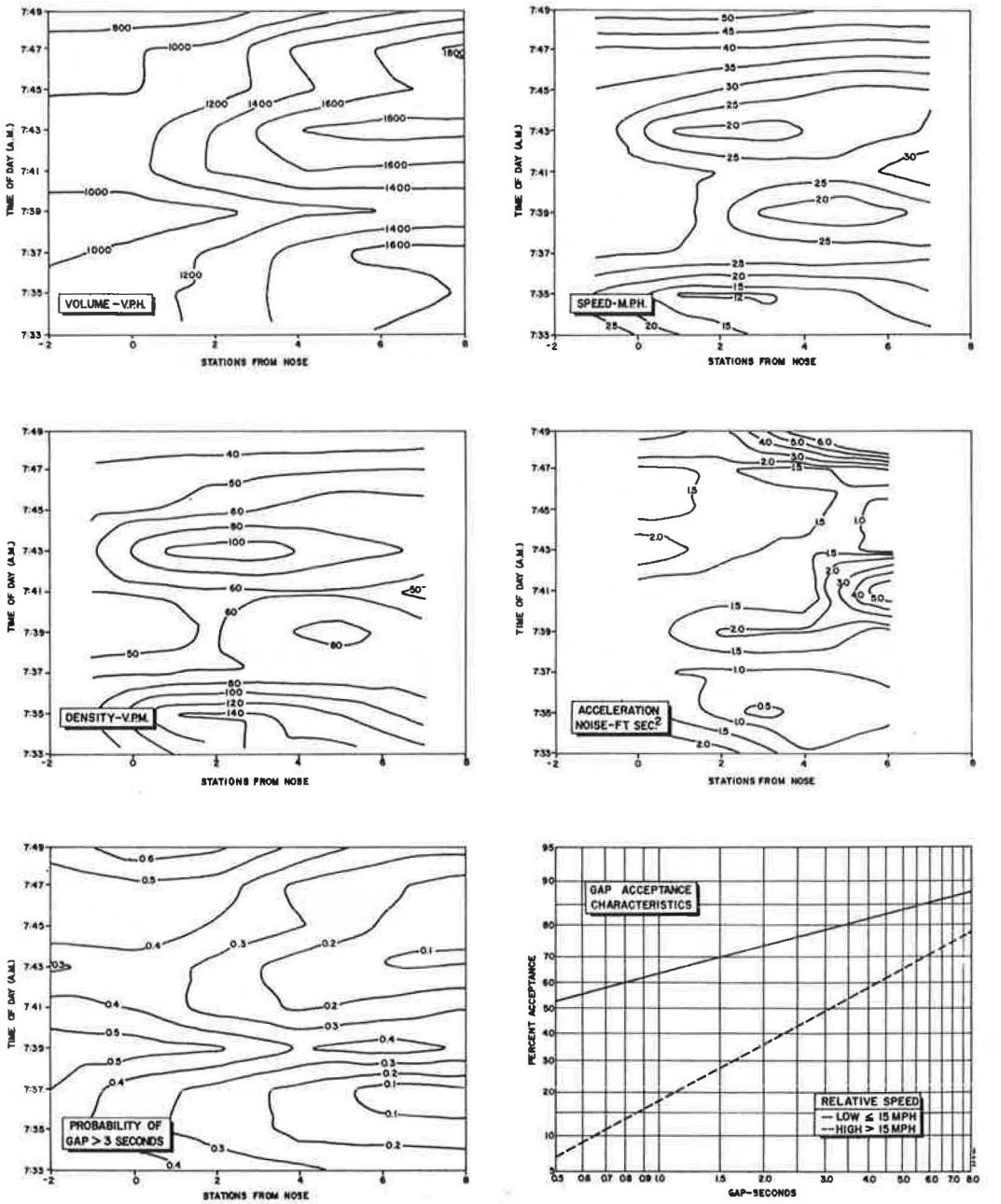



Figure 43. Traffic characteristics of Broadway northbound entrance ramp, Bayshore Freeway, San Francisco.

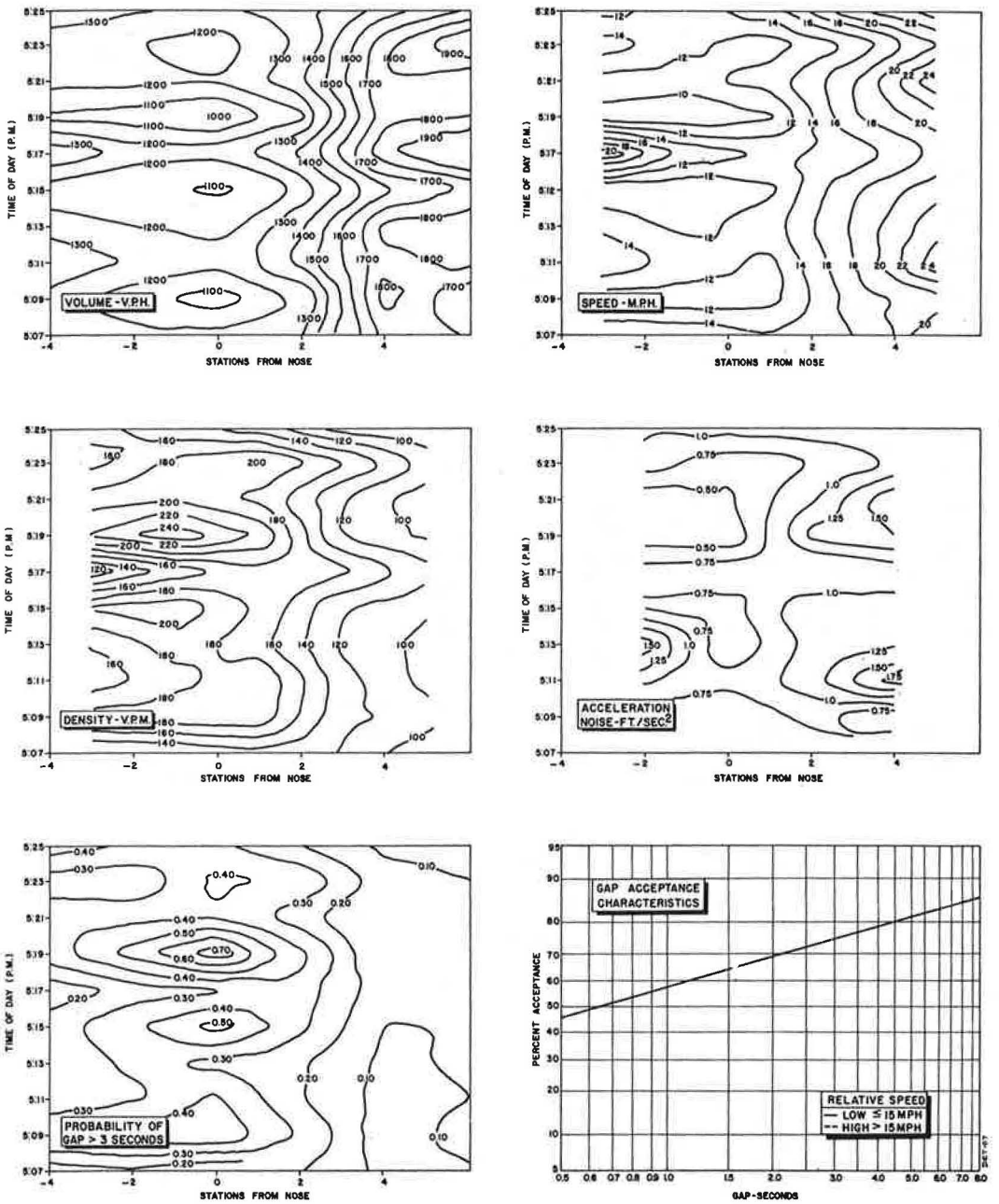



Figure 44. Traffic characteristics of Linwood northbound entrance ramp on the John Lodge Expressway, Detroit.

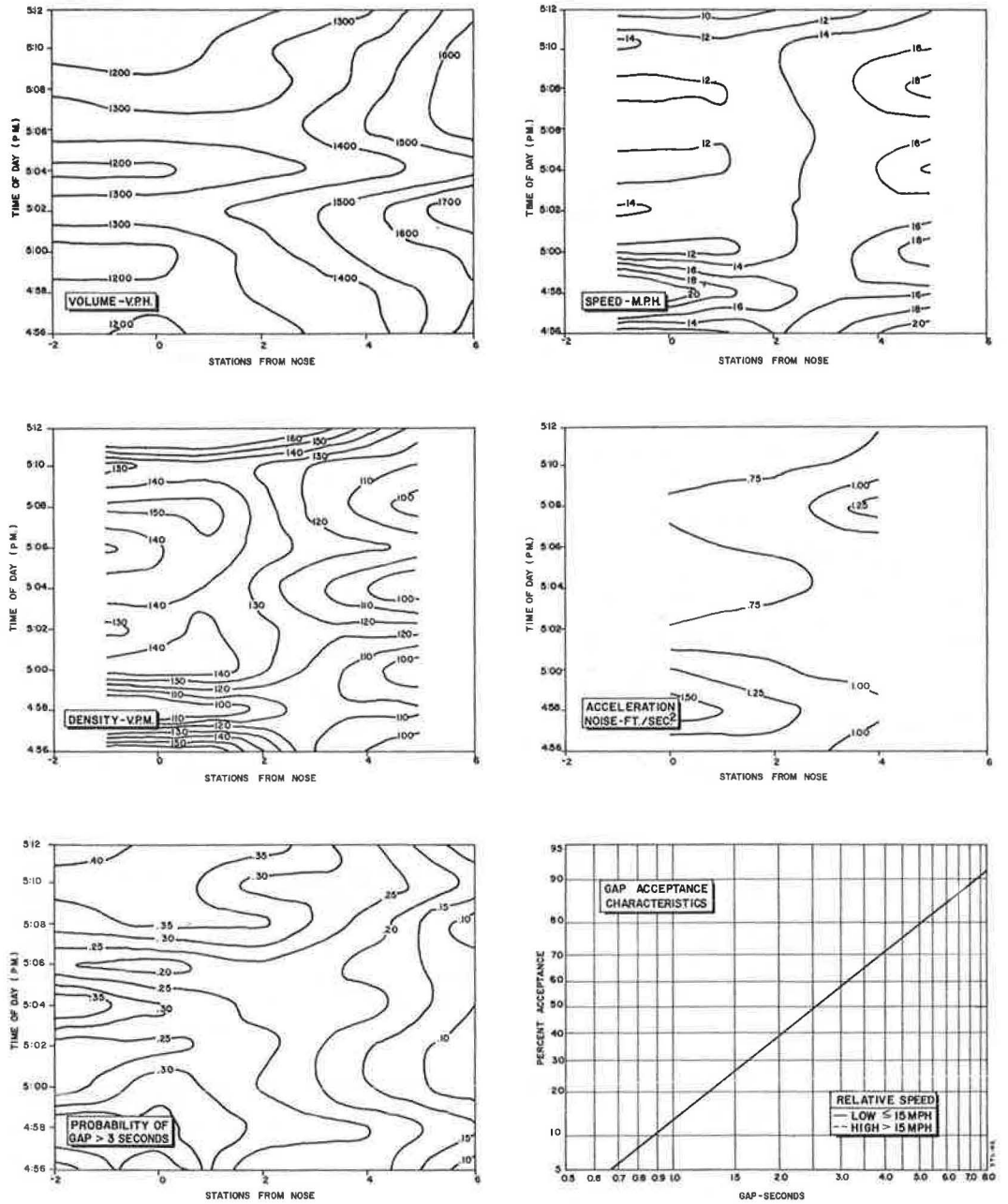



Figure 45. Traffic characteristics of Brentwood westbound entrance ramp to Daniel Boone Expressway, St. Louis.

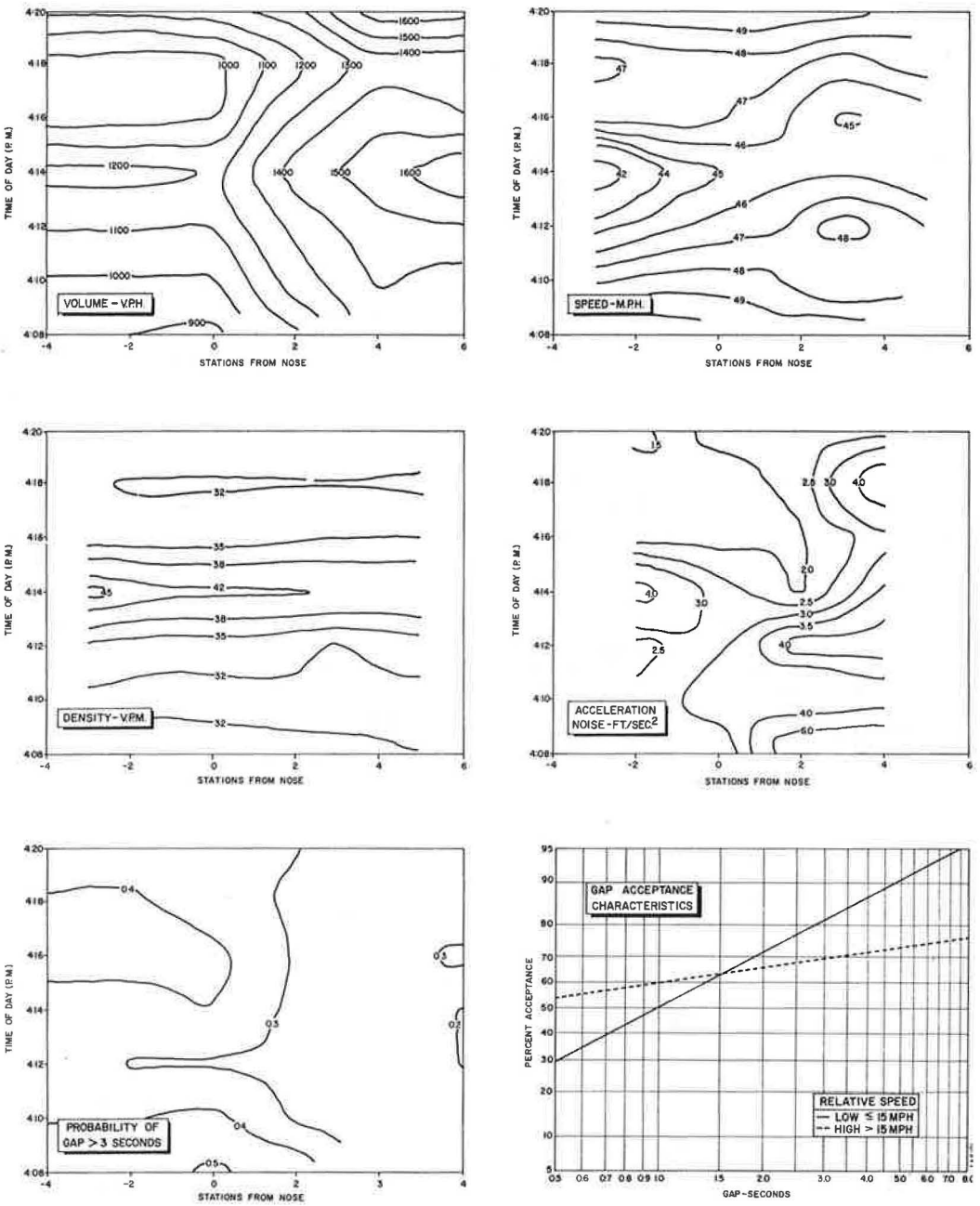



Figure 46. Traffic characteristics of Coldwater Canyon Avenue westbound entrance ramp, Ventura Freeway, Los Angeles.

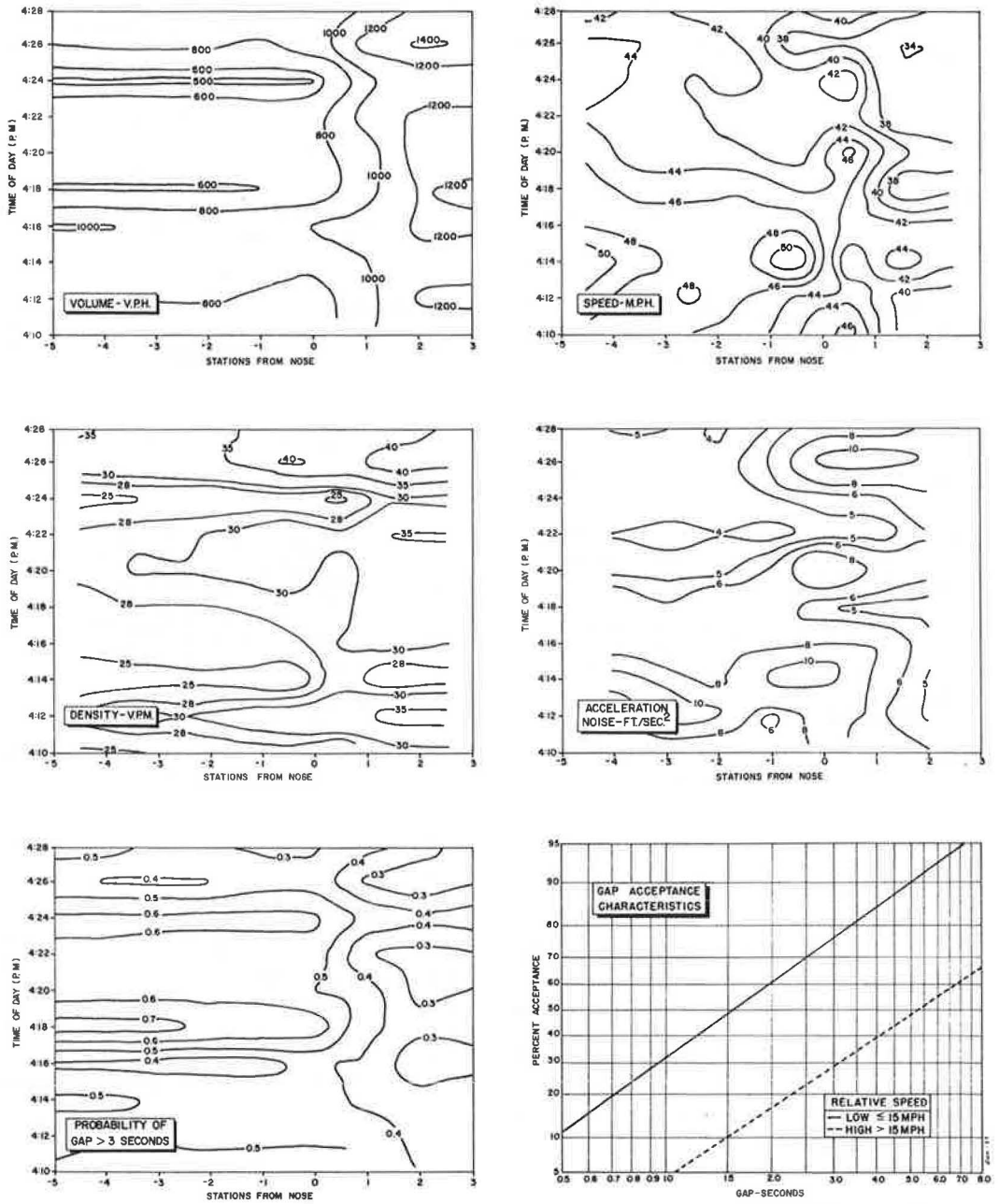



Figure 47. Traffic characteristics of Dumble eastbound entrance ramp on the Gulf Freeway, Houston.

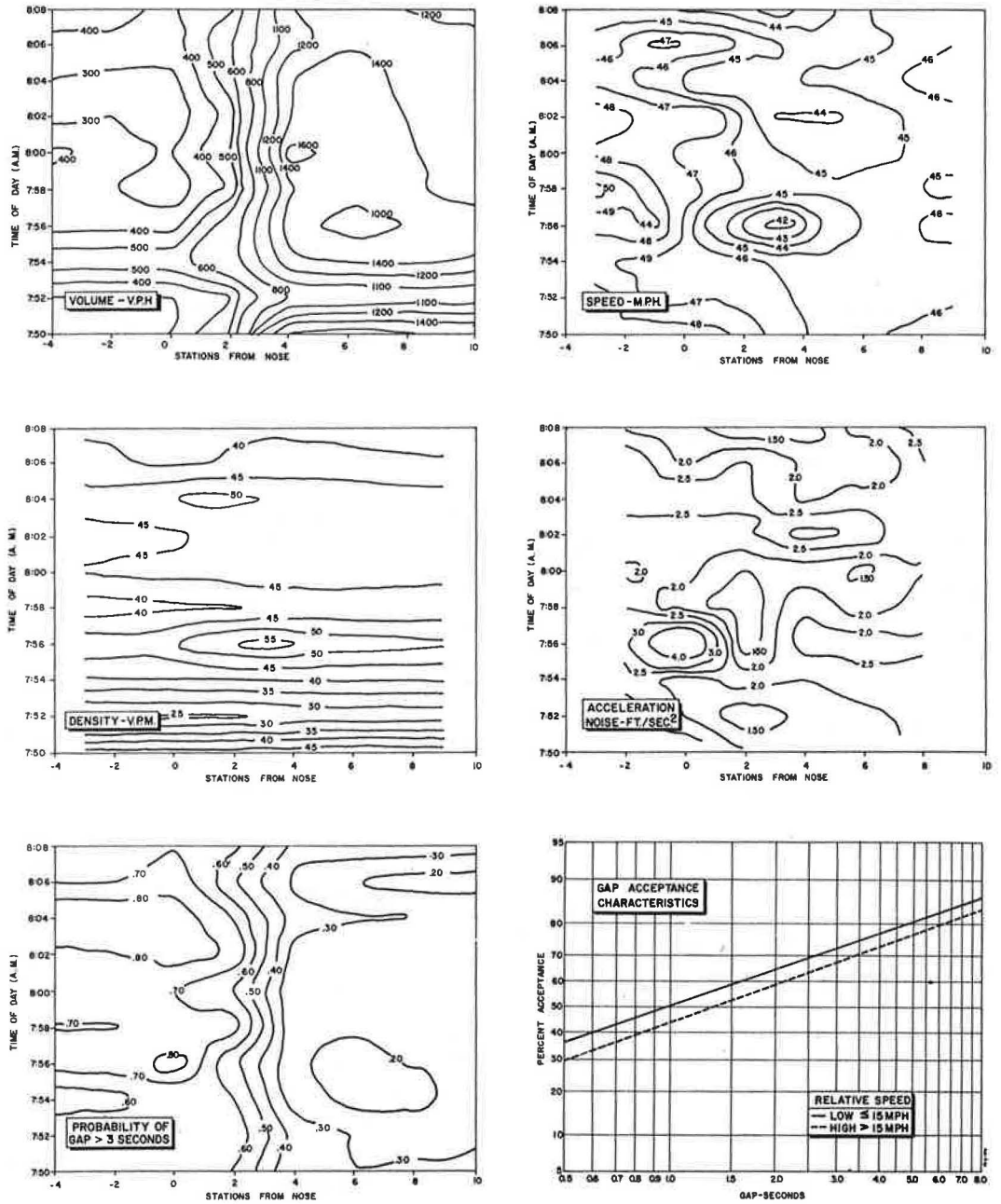



Figure 48. Traffic characteristics of Long Island Expressway northbound entrance ramp to Cross Island Expressway, New York.

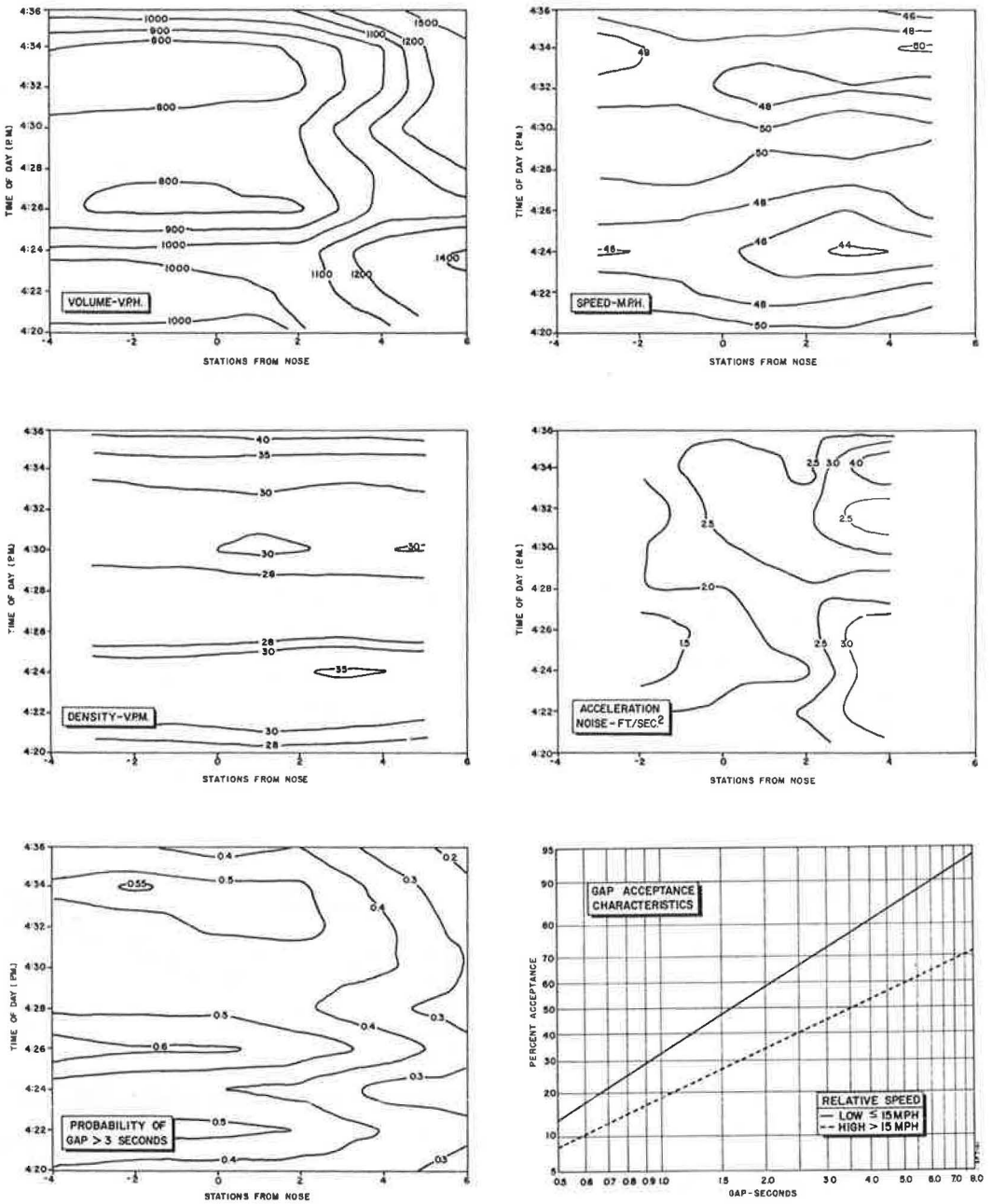



Figure 49. Traffic characteristics of Milbrae Avenue southbound entrance ramp, Bayshore Freeway, San Francisco.

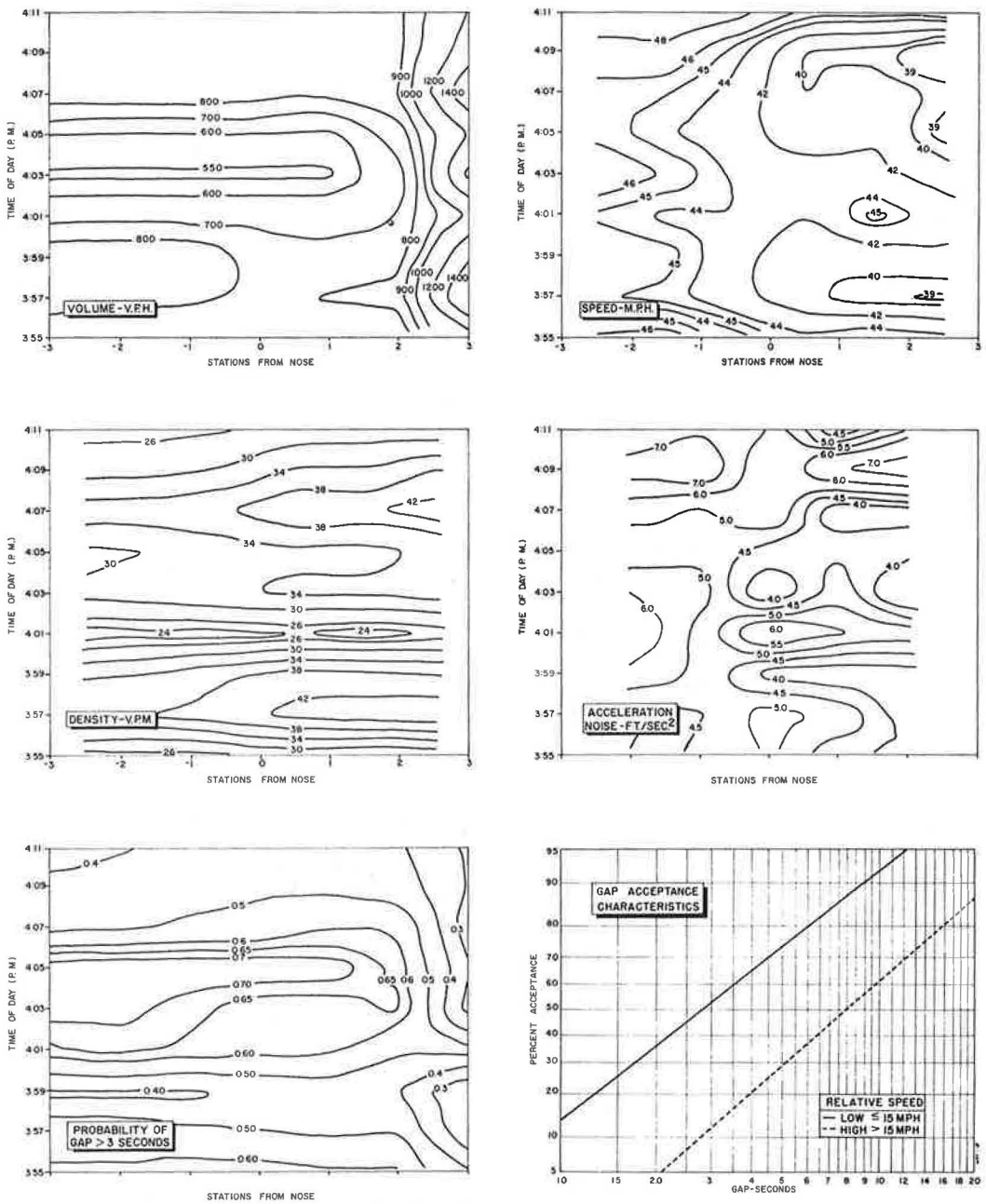



Figure 50. Traffic characteristics of Wayside eastbound entrance ramp on the Gulf Freeway, Houston.

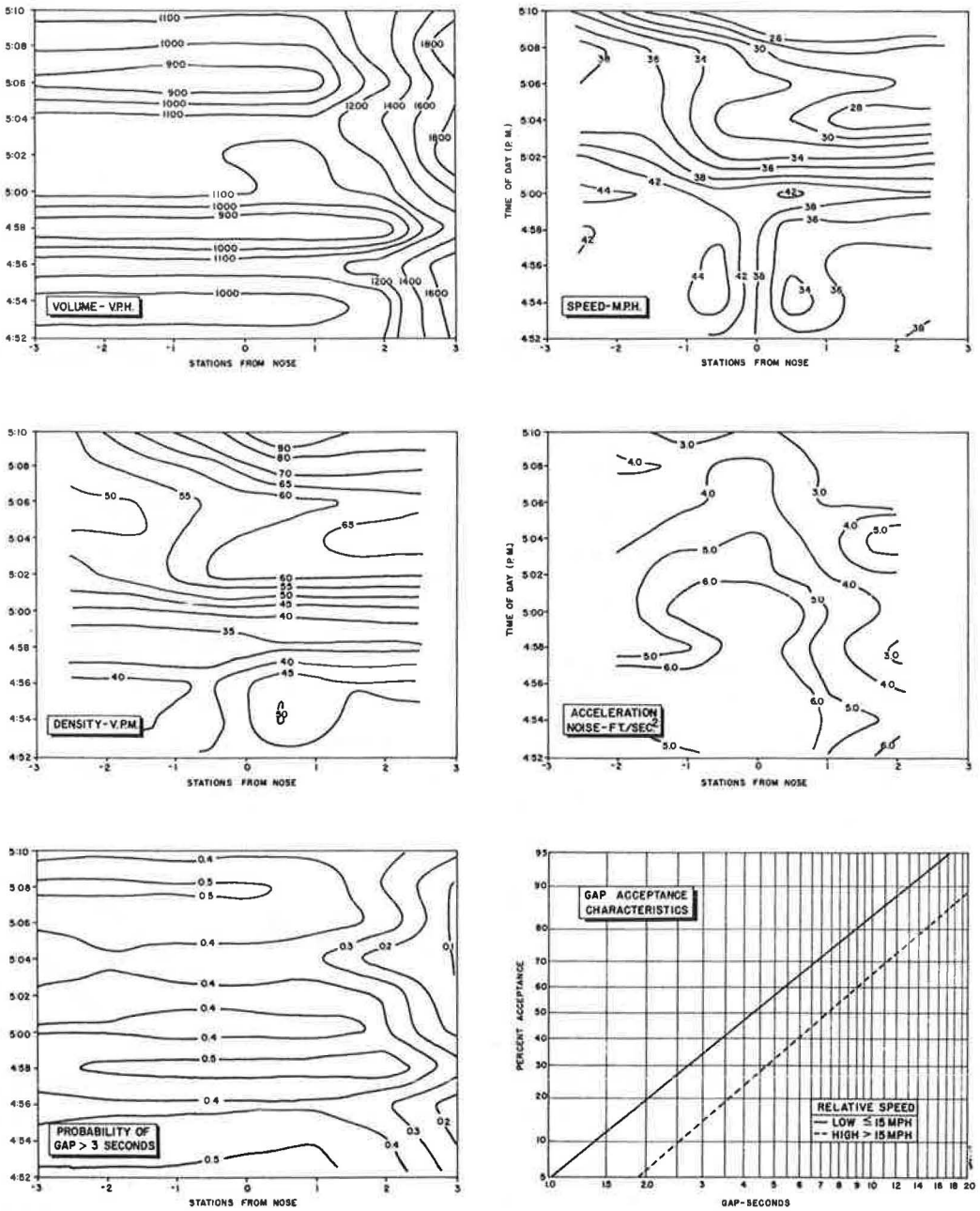



Figure 51. Traffic characteristics of Wayside eastbound entrance ramp on the Gulf Freeway, Houston.

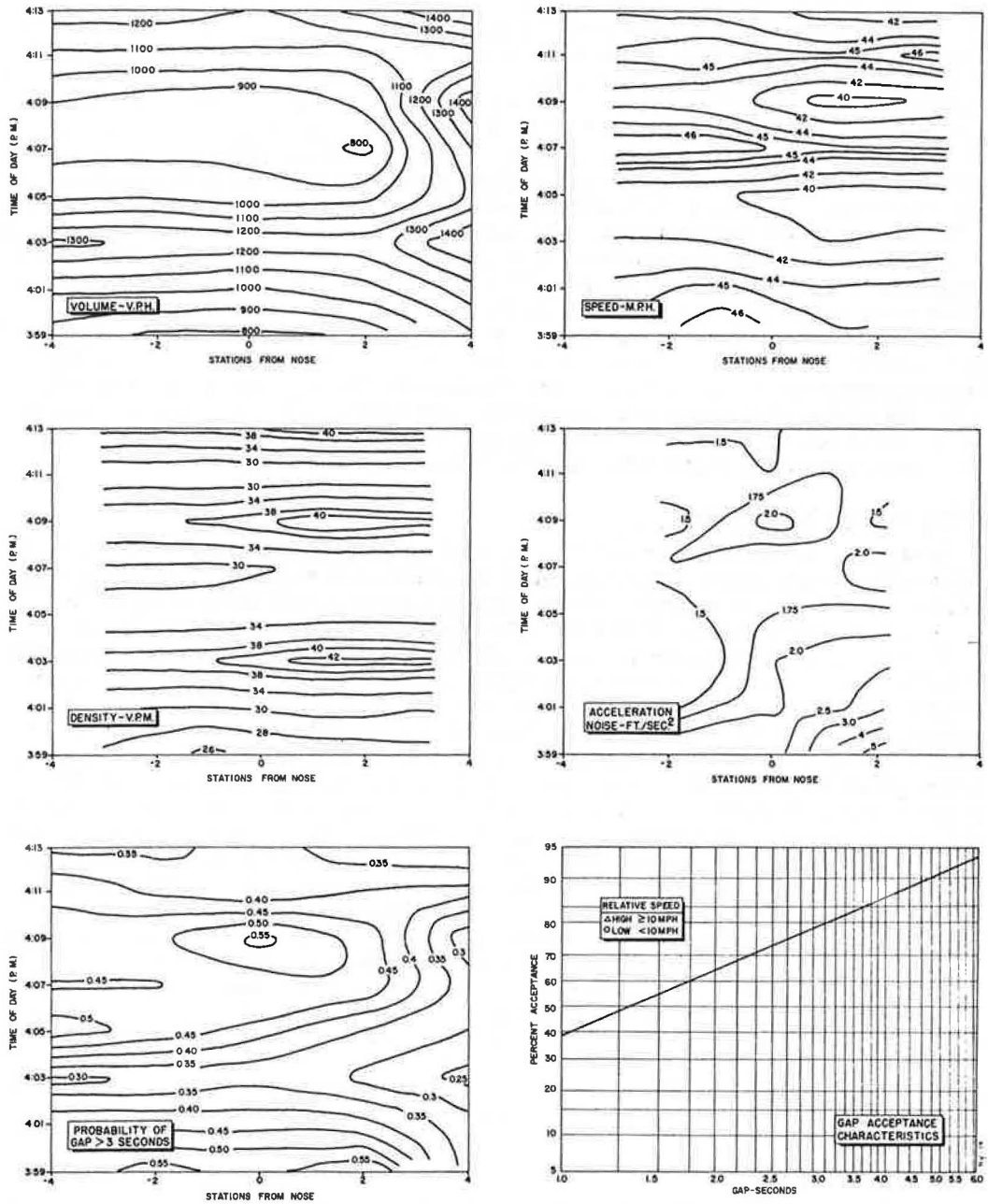



Figure 52. Traffic characteristics of 69th Road southbound entrance ramp on the Grand Central Parkway, New York.

## Effect of Acceleration Lane Length

The effect of the length of acceleration lane is illustrated by Figures 46 and 47. These two figures were selected not only for the similarity of general geometric features other than acceleration lane lengths of the ramps to which they apply, but also for the similarity in the ranges of speeds and densities. The freeway volume was lighter but since both merging areas were operating at similar speeds and densities, the effects of the traffic demand on the acceleration noise are minimized. Perhaps the most striking difference in the operations of the merging areas is the general smoothness of flow at the ramp with the larger acceleration lane as exhibited by all the contour diagrams. A comparison of the volume contours clearly reveals the gradual increase in volume level over the length of the acceleration lane of the Coldwater Canyon ramp as compared to the sudden increase over a short distance at the Dumble ramp, resulting in considerable turbulence in speeds and densities. This turbulence caused the higher acceleration noise observed at the Dumble ramp. Even the probability contours display this smoother operation at the Coldwater Canyon ramp. These two figures form a good demonstration of the desirability of the longer acceleration lane.

The operation at a high-volume ramp with a very long acceleration lane is illustrated by Figure 48. Notice that although the acceleration lane is 1200 ft long, by far the largest proportion of ramp vehicles chose to enter the freeway within the first 400 ft. This type of operation was also evidenced by other studies at this and another similar ramp. However, in spite of the extremely high entrance ramp volume, high speeds were maintained and the acceleration noise remained at a low level.

## Effect of Angle of Convergence

In order to demonstrate the effect of the angle of convergence two sets of data were selected that were gathered at ramps with geometrics that differed mainly in the angle of convergence, during periods when speeds and densities were fairly comparable. These are shown in Figures 49 and 50. The Wayside entrance ramp with the higher angle of entry seems to cause a more sudden increase in volume levels over a shorter distance than the Milbrae ramp with the smaller angle of convergence. This causes a greater turbulence in speeds and densities resulting in a generally higher level of acceleration noise at the Wayside ramp. This may be partially caused by the traffic demand since the freeway volume upstream of the nose is generally lower at the Wayside ramp, giving a higher ratio of ramp volume. However, comparisons with a study period at Wayside when the freeway volumes were higher, such as in Figure 51, show that speeds generally decreased and densities increased, resulting in a slightly lower acceleration noise but which was still generally higher than that at the Milbrae ramp.

Figures 52 and 53 serve as another illustration of the effects of the angle of convergence. In this case the ramp geometrics differ again mainly in the angle of convergence, but both are of such high type designs that the value of 5 degrees, as against 11 degrees, perhaps gives a wrongful impression of the actual difference.

By inspection of the contour diagrams, it can be seen that volumes, speeds and densities were comparable during the study periods at these two ramps. The resulting acceleration noise at the 69th Road ramp with the lower angle of entry seems to be generally lower than at the Peterson Avenue ramp. However, the difference in ramp profiles should be noted and may lead one to conclude that the effect of the difference in angle of convergence at these two ramps is not noticeable in the contour diagrams.

## Effect of Grades

Figures 54 and 55 demonstrate the operation at two ramps that are remarkably similar in most geometric aspects. Both have 1200-ft long parallel lane type acceleration lanes with ramps converging at one degree at the nose. They differ only slightly in the grades along the acceleration lane, in that the Jericho ramp is slightly downgrade and the Long Island Expressway ramp slightly uphill.

The general pattern of operation is also remarkably similar at the two ramps, as evidenced by the contour diagrams. At both locations, most of the ramp vehicles

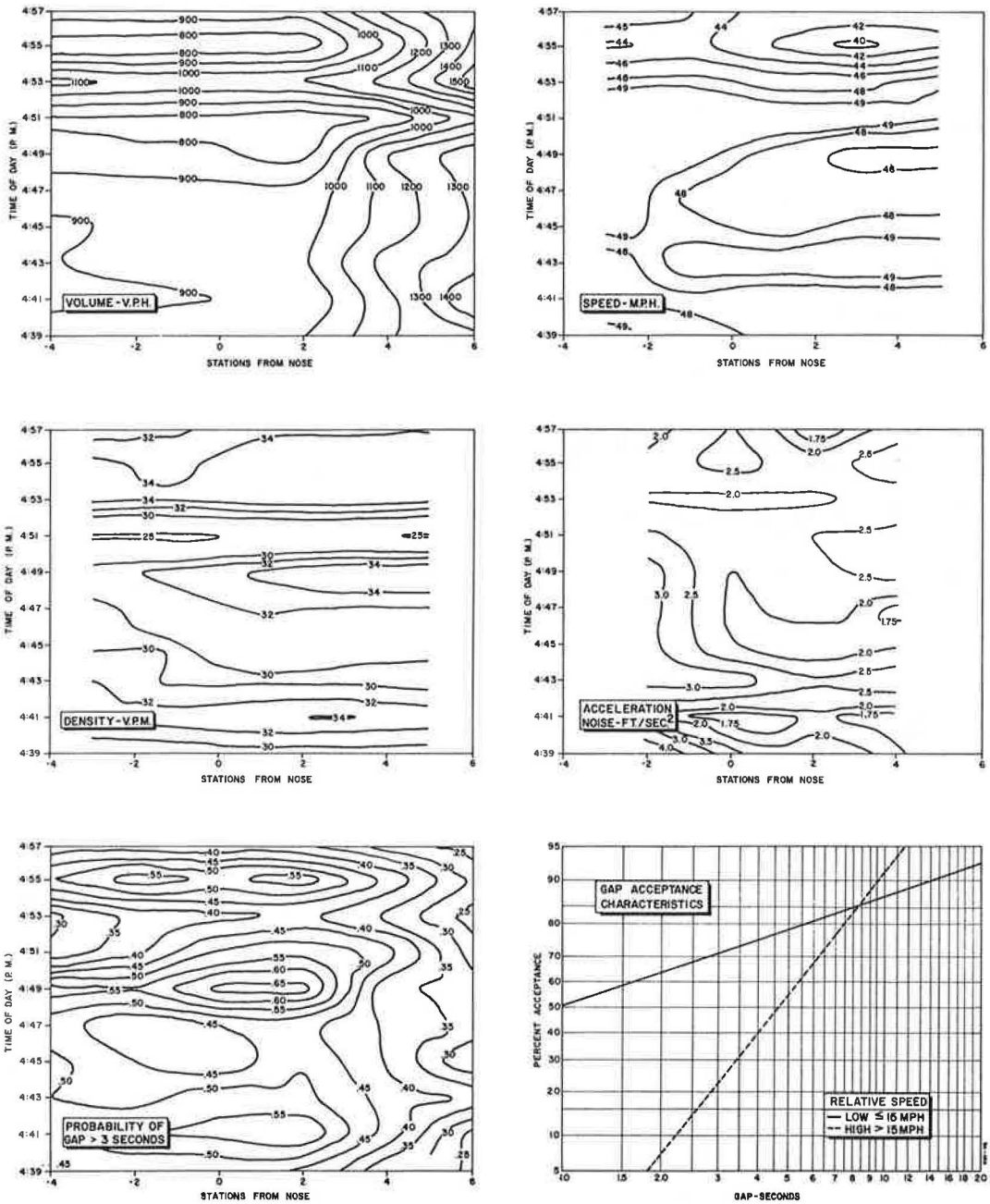



Figure 53. Traffic characteristics of Peterson Avenue northbound entrance ramp to Edens Expressway, Chicago.

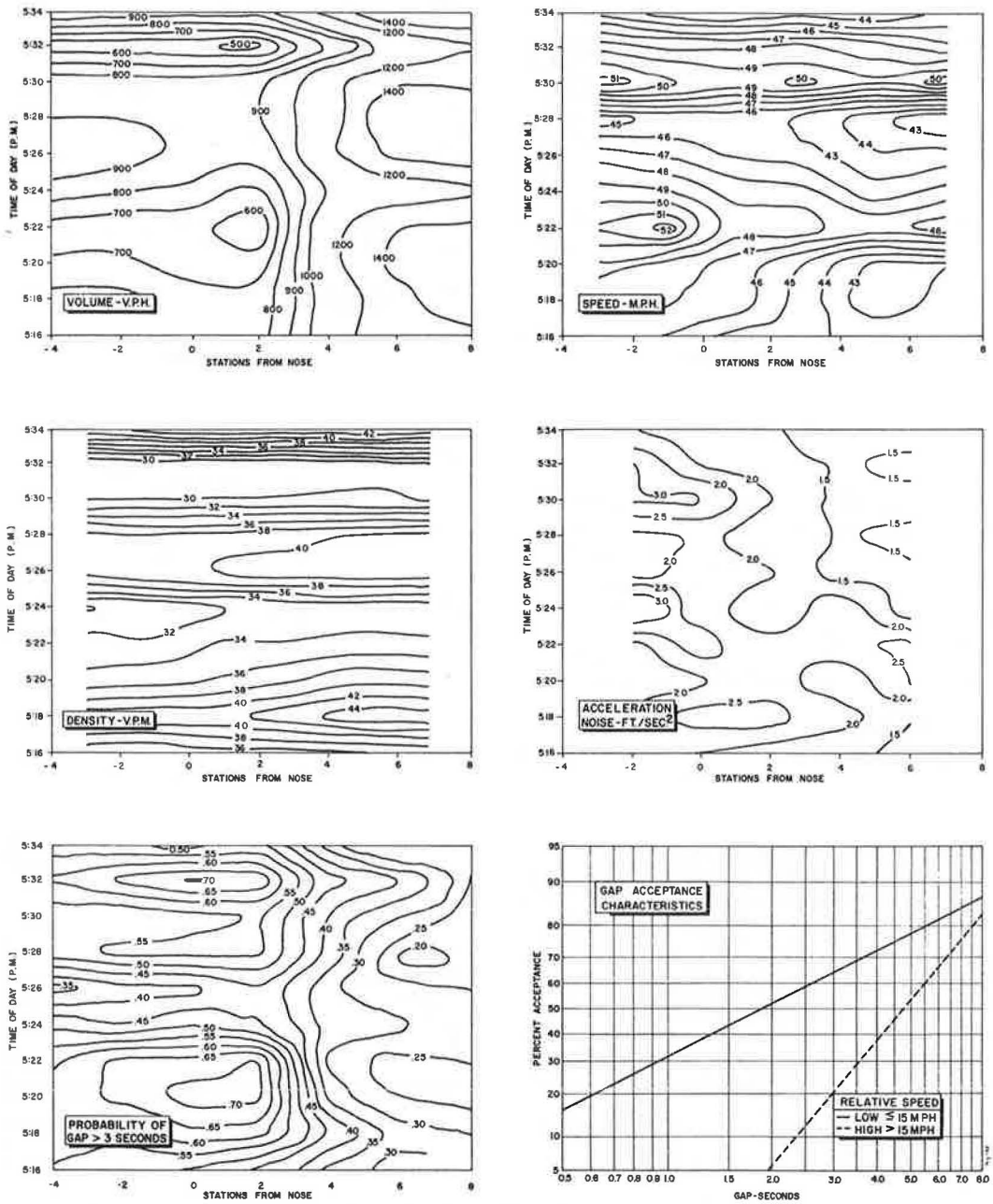



Figure 54. Traffic characteristics of Jericho (Rt. 25) eastbound entrance ramp on Long Island Expressway, New York.

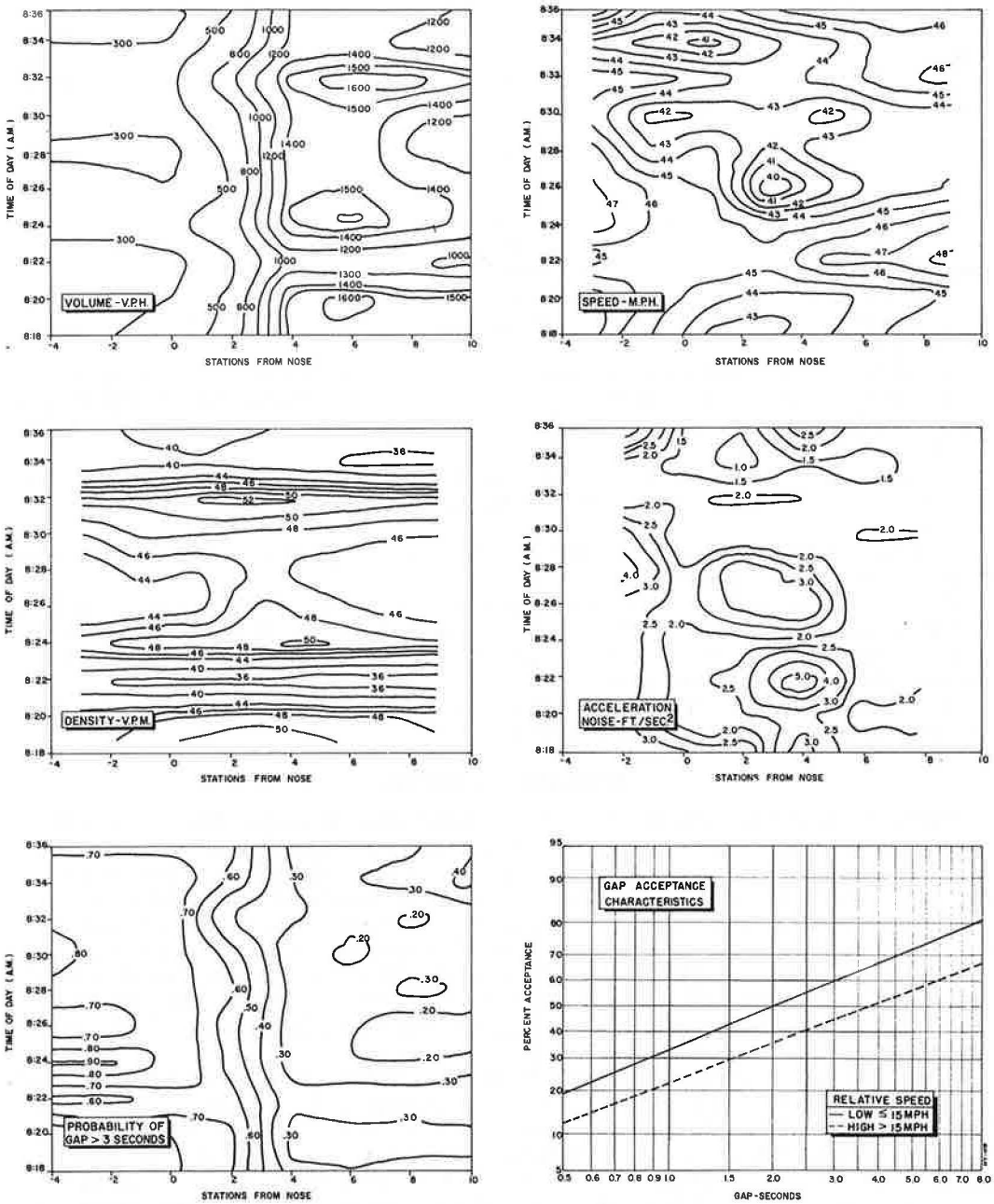



Figure 55. Traffic characteristics of Long Island Expressway northbound entrance ramp to Cross Island Expressway, New York.

entered the freeway within the first 500 to 600 ft of the acceleration lane length. The total merging volumes at the two locations were comparable, but the ramp volume at the Long Island ramp far exceeded that at the Jericho ramp, giving rise to slightly lower speeds and higher densities, resulting in a higher level of acceleration noise. Because of this uneven split in the traffic demands, it is difficult to isolate the effect, if any, of the slight difference in grades. It does seem, however, that at the upgrade ramp, vehicles entered the freeway generally sooner than at the Jericho ramp, which may well have been caused by the grade.

## COMMENTS

1. An aerial photographic technique has been developed for collecting large masses of comprehensive traffic data with relative economy.
2. The manner and mobility of the photographic technique make it generally applicable to almost any study site located anywhere.
3. Since no distances are measured off the films, the study technique is not dependent on maintaining a strict flight altitude or flight path and is not affected by highway elevation changes.
4. Problems encountered in the filming studies included the mounting of the equipment in the aircraft, development of the proper flight path, evaluation and acquiring of the proper hardware and software, and coping with the changing light conditions during circling.
5. Problems encountered in the data reduction included the careful training of film analysis personnel, lack of definition in some films and the problem of missing data points.
6. In the study of the effects of geometrics on traffic operation, care should be taken to avoid periods of forced flow.
7. Time-space diagrams of vehicle paths, such as illustrated in Figure 40, not only reveal the operation on the facility at a glance, but also are an invaluable aid in the editing of data, the writing and debugging of more complicated computer programs and meeting the problem of missing data points.
8. Contour diagrams are an effective way of illustrating the operation of a facility on a continuous basis in both time and space.

## ACKNOWLEDGMENTS

The success of this phase of the project with the national scope of its field studies is due to a large extent to the cooperation of the Federal government, six State governments, and many local governmental agencies. The aid of the following personnel, their staffs and agencies is noted: James E. Wilson, Karl Moskowitz and Leonard Newman of the California Division of Highways; Charles H. McLean of the Illinois Division of Highways; Joseph Marlowe of the Michigan State Highway Department; James Little and James Roberts of the Missouri Highway Department; Dale D. Marvel, John N. Lipscomb and William V. Ward of the Texas Highway Department; Alger F. Malo of the Detroit Department of Traffic; and Edward Bonelli of the New York City Department of Traffic.

Deserving special mention is Joseph W. Hess, Acting Leader, Improved Utilization of High Speed Highways Task Group of the U. S. Bureau of Public Roads. Mr. Hess, who was instrumental in defining the scope and direction of the project in the prospectus, has helped greatly in making contracts with local agencies and selecting study sites. Also greatly appreciated is the work of W. R. McCasland in making preparations for many of the Houston studies, and James Bradley, motion picture production technician, whose fine work meant a great deal to the success of the project.