HIGHWAY RESEARCH BOARD

Bulletin 235

Traffic Behavior on Freeways

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Bulletin 235

Traffic Behavior on Freeways

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Contents

Effect of Freeway Medians on Traffic Behavior

CHARLES J. KEESE, Research Engineer, and
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Texas Transportation Institute, Texas A & M College System

This paper presents a portion of the material developed during a series of traffic behavior studies conducted on freeways in Texas. The research was conducted by the Texas Transportation Institute for the Texas Highway Department and was designed to obtain data which would be useful in evaluating freeway median design.

The field studies utilized the Bureau of Public Roads' electronic traffic behavior equipment which permitted the recording of data on volume, speed, and vehicle placement for each of several freeway lanes. Studies were made on six different sections of freeways located in Houston, Dallas, and Fort Worth, Texas. Approximately 50,000 observations were analyzed.

Statistical analyses were made to determine the effect of various types of median designs on traffic behavior. Vehicle placements were used as a criterion of traffic behavior and the variations in these placements were compared for various median designs.

Studies were also made before and after the erection of a barrier fence on the 4-ft median of the Gulf Freeway in Houston to determine the effect of this fence on traffic behavior. This study utilizes data obtained by use of the Bureau of Public Roads' equipment and from motion picture studies conducted by the Texas Transportation Institute.

The analysis of the data indicated that average vehicle placements did not vary greatly, but that different type and width medians had some effect on traffic behavior. The wider medians reduced the effects of opposing flows and high volumes.

● NUMEROUS TYPES of medians, differing in width and in design, have been used on existing highways in Texas and throughout the country. Although various median studies have been performed in recent years, additional information regarding the effect of freeway median design on traffic behavior was felt to be of value. The purpose of this study was to develop additional knowledge of this type.

Volume, speed, and placement data were recorded as a possible criterion of median effect on traffic behavior. These data were obtained from a number of traffic behavior studies conducted by the Bureau of Public Roads and from motion picture studies performed by personnel of the Texas Transportation Institute.

The field studies utilized the Bureau of Public Roads' electronic traffic analyzer equipment. A. Taragin of the Bureau of Public Roads supervised the installation and operation of the equipment. Personnel of the Bureau of Public Roads and of the Texas Highway Department conducted the surveys.

Segmented placement tubes and air impulse speed tubes were placed across the pavement as shown in Figure 1. These tubes transmitted impulses to the electronic recording equipment housed in a special truck which was concealed from the motorists as shown in Figure 2. A speed meter, decimal timer, and four coding machines capable of handling any four traffic lanes were used to record time of passing, speed and placement data on each vehicle. These data were placed on punch cards and high-speed electronic computers were used in the analyses.

Figure 1. Speed trap tubes and placement tapes—Bureau of Public Roads Study.

For this study, six different sections of freeways located in or near Houston, Dallas, and Fort Worth, Texas, were selected to provide data on various designs of medians presently being used on freeways in Texas. The different types of medians studied (Figs. 3 and 4) ranged from a 4-ft concrete median to a 40-ft grassed median.

The studies performed are listed below with a brief description of median type for each study:

Study	Location	Date	Median Type	Fig. No.
00	Houston - Gulf Freeway	May 1958	4-ft concrete with barrier curb	4A
01	Fort Worth - East West Freeway	July 1957	12-ft asphalt with concrete barrier curb	3A
03	Dallas - Central Expressway	July 1957	12-ft concrete with mountable curb	3B

Study	Location	Date	Median Type	Fig. No.
04	Dallas - Central Expressway	July 1957	27-ft grassed with mountable curb	3C
05	Dallas - US 80 (rural)	July 1957	40-ft grassed, no curb	3D
07	Houston - Gulf Freeway	July 1957	4-ft concrete with barrier curb and barrier fence	4B
08	Houston - Eastex Freeway	July 1957	4-ft concrete with concrete barrier	4C

The daytime studies were conducted during the period of 7:00 A.M. to 7:00 P.M. and the night studies from 8:00 P.M. to 12:00 P.M. The data on speed, volume, and placement were tabulated by 6-min periods for each hour.

Data on average vehicle placements for all Bureau of Public Roads studies are shown in Table 1. These data include only passenger vehicles and are subdivided by lane and day-night tabulations. Placements were measured from the left lane line to the centerline of the vehicles.

The data shown in Table 1 represent a total of 46,968 observations of vehicle placements. The actual number of placement observations was greater than this but some data were invalidated by inclement weather and by unusual traffic conditions on the freeways such as accidents, stalled vehicles, etc.

The maximum variations in average placements are shown in Figures 5 and 6. These data indicate that for all of the medians studied there was a relatively small amount of variation in average vehicle placement. The average placements for the inside and middle lanes were close to the centerline of the lane with the maximum difference being 0.85 ft for the inside lane and 0.82 ft for the middle lane during the daytime. The average placements in the outside lane were generally further to the left of the lane centerline and were more variable than the inside and middle placements.

METHOD OF STUDY

Because the variations in average placements for the different type medians were relatively small, a statistical analysis was performed to study the variance of the data. With this type of analysis, it was possible to determine significant differences among the data and to infer possible conclusions from these differences. Two separate studies were made: a study to determine the effect of a barrier fence on traffic behavior and a general study to determine the effect of various width medians on traffic behavior.

After consideration of the data and the method of analysis it was decided to use only placement and volume data in the analysis. Because vehicle speeds were affected by such factors as volume, speed limits, type of area, enforcement level, etc., the application of speed data to statistical analysis was impractical in these studies. Data on average speeds are presented in Table 2 as an indication of the character of operation on each of the facilities.

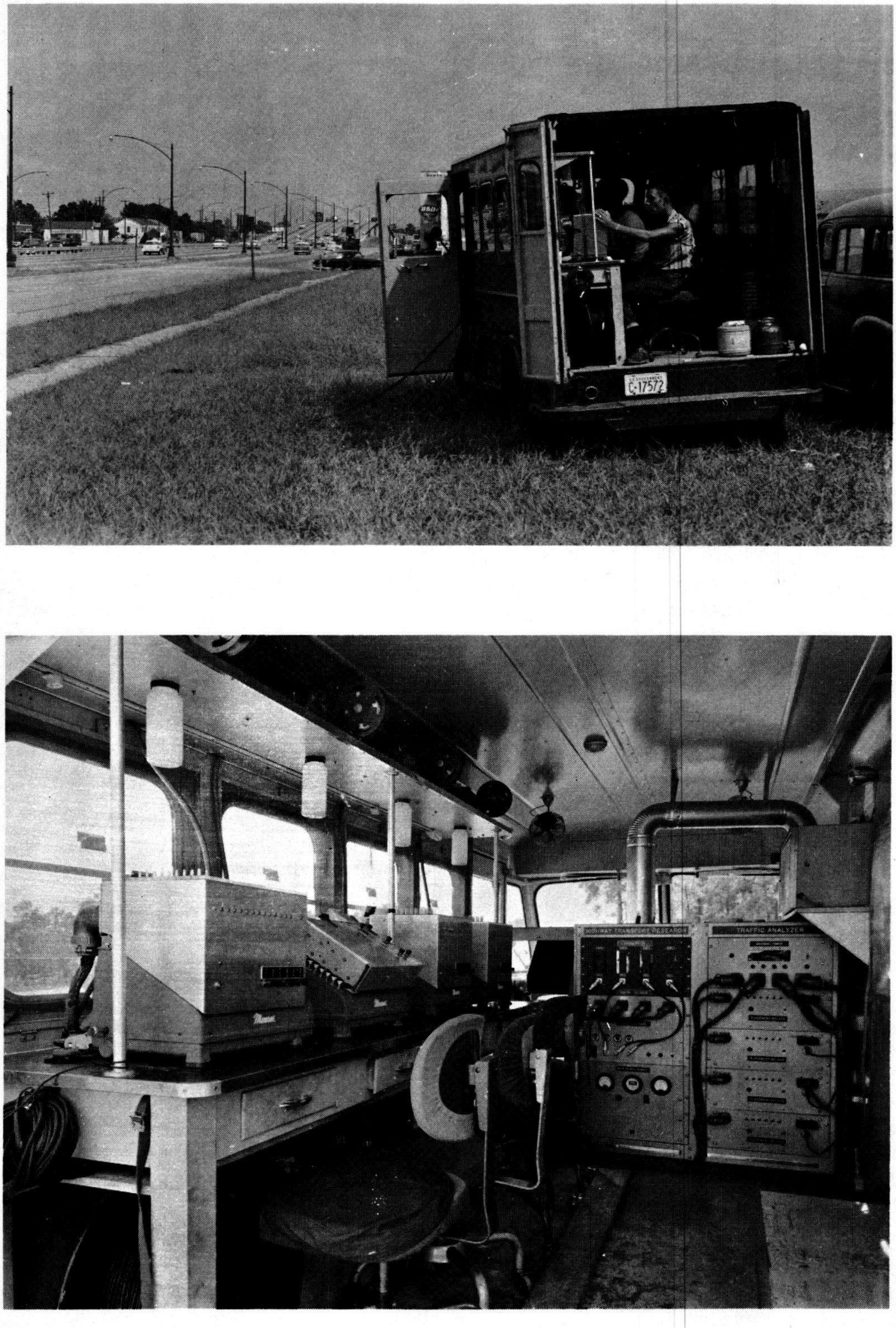
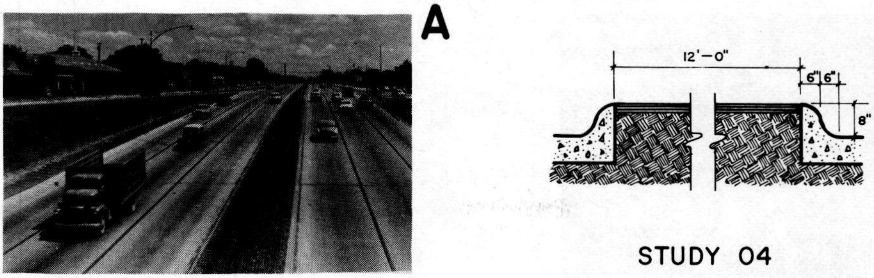
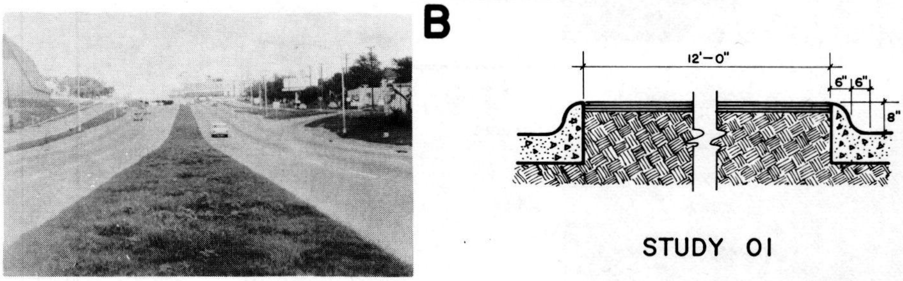


Figure 2. Mobile traffic analyzer (top). Interior of mobile traffic analyzer (bottom).



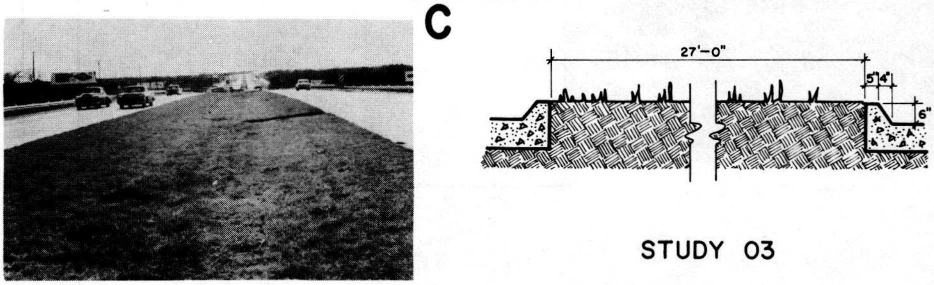
STUDY 04

DALLAS - CENTRAL EXPRESSWAY



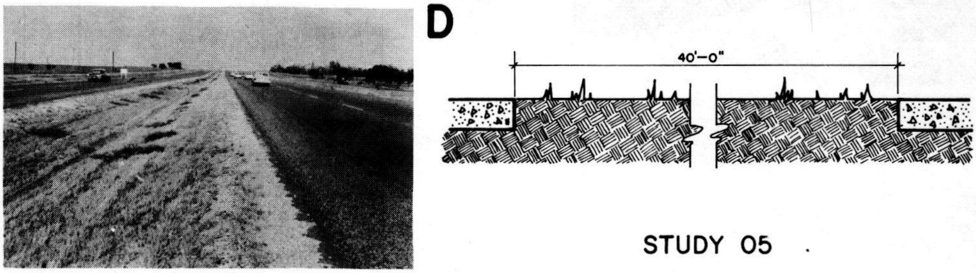
STUDY 01

FORT WORTH - EAST WEST FREEWAY



STUDY 03

DALLAS - CENTRAL EXPRESSWAY



STUDY 05

DALLAS - U.S. 80

Figure 3. Median sections and typical study sites.

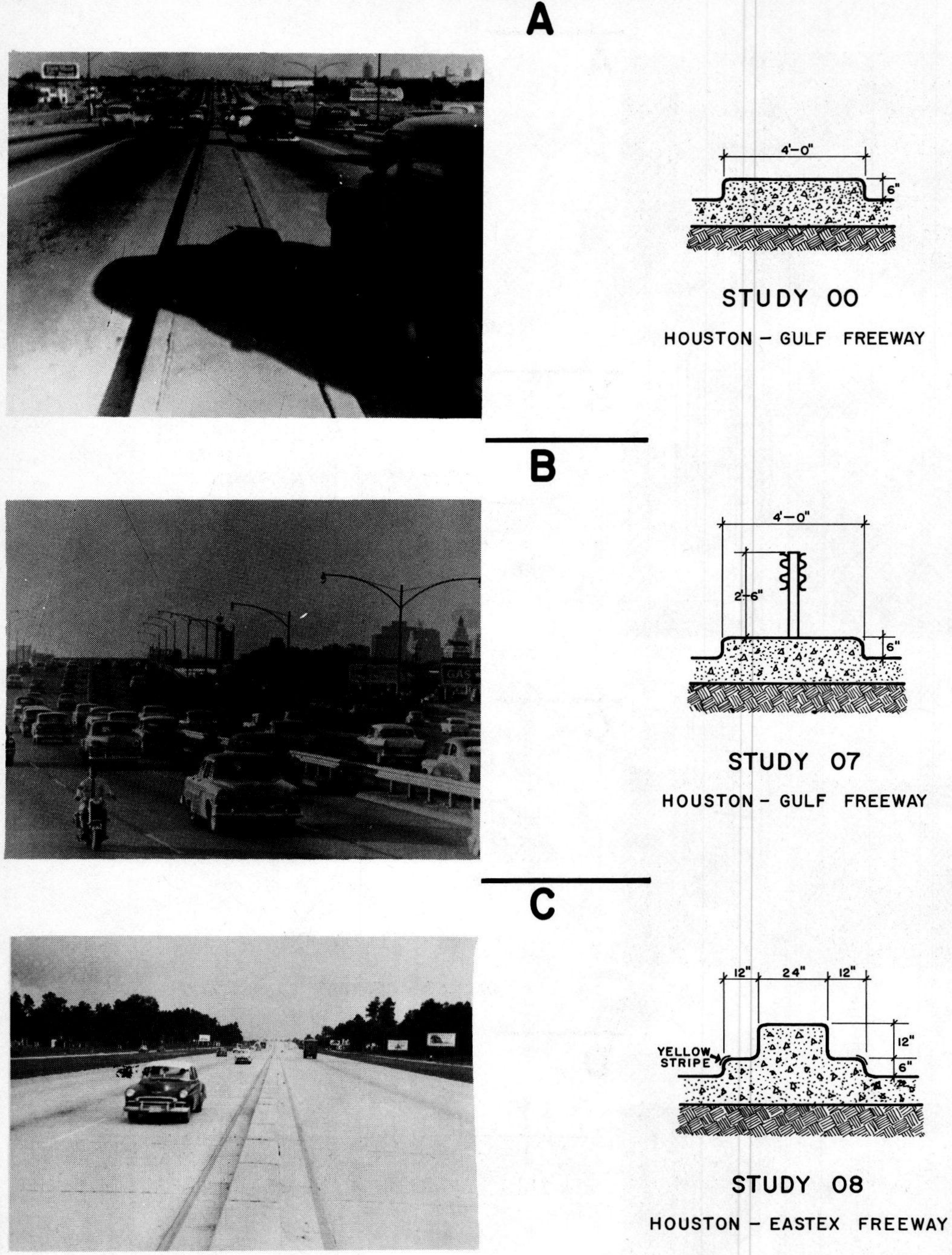


Figure 4. Median sections and typical study sites.

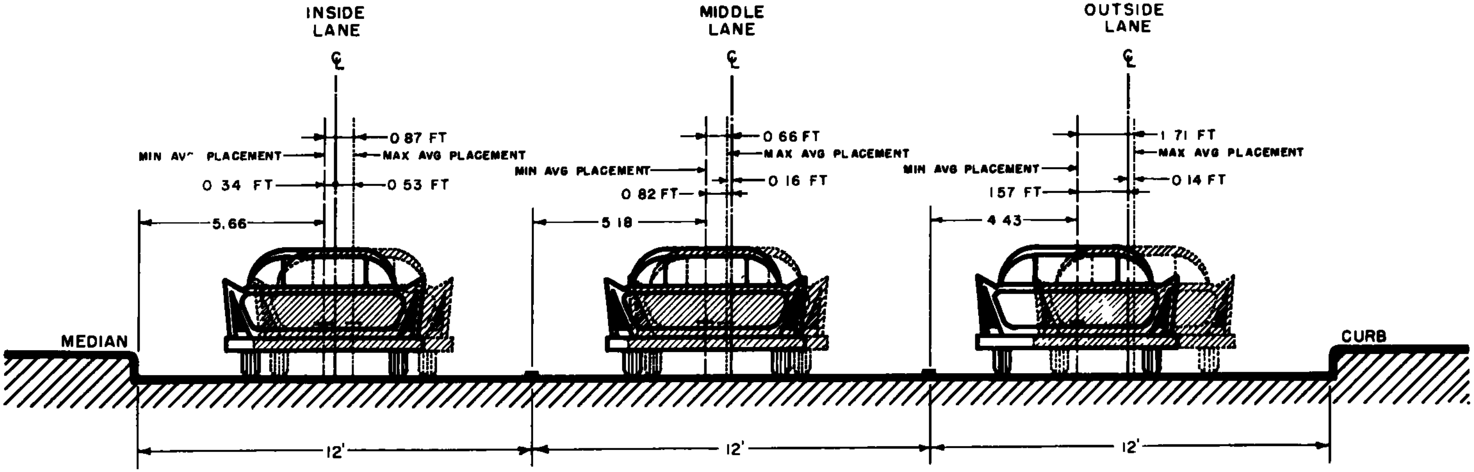


Figure 5. Variation in average placement—all daytime studies.

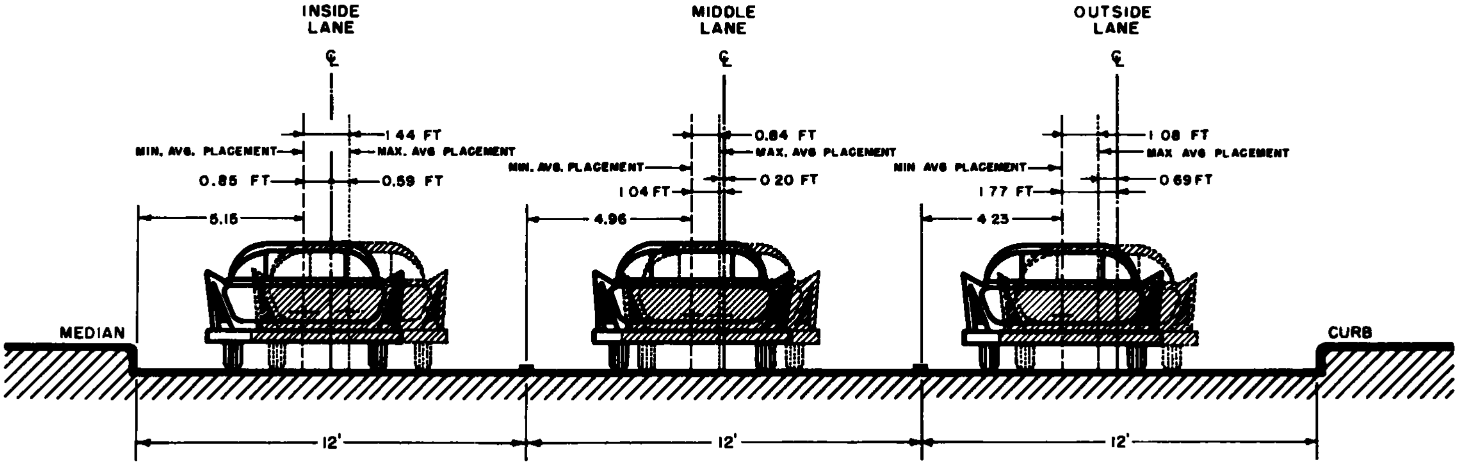


Figure 6. Variation in average placement—all night studies.

TABLE I
AVERAGE VEHICLE PLACEMENTS
ALL B.P.R. STUDIES

	DAY			NIGHT			STUDY NUMBER
	INSIDE LANE	MIDDLE LANE	OUTSIDE LANE	INSIDE LANE	MIDDLE LANE	OUTSIDE LANE	
AVG. PLACEMENT	5.86	5.18	4.87	5.85	4.96	4.23	STUDY 00 4' MEDIAN
NUMBER VEHICLES	5145	6323	3769	1163	2094	1196	
AVG. PLACEMENT	6.26	5.66	4.43	6.52	5.80	4.50	STUDY 01 12' MEDIAN
NUMBER VEHICLES	1924	2438	2576	94	688	120	
AVG. PLACEMENT	6.00	—	5.23	6.19	—	5.06	STUDY 03 27' MEDIAN
NUMBER VEHICLES	1287	—	1368	152	—	264	
AVG. PLACEMENT	5.66	5.38	5.10	5.15	5.35	4.83	STUDY 04 12' MEDIAN
NUMBER VEHICLES	4184	4859	1242	290	793	485	
AVG. PLACEMENT	6.19	—	6.14	6.59	—	5.31	STUDY 05 40' MEDIAN
NUMBER VEHICLES	433	—	1142	36	—	221	
AVG. PLACEMENT	6.53	5.84	5.38	6.23	5.51	5.05	STUDY 08 4' MEDIAN
NUMBER VEHICLES	676	616	528	98	661	103	

PLACEMENT MEASURED FROM LEFT LANE LINE

TABLE 2

AVERAGE SPEEDS, INSIDE LANES—DAYTIME
B.P.R. SURVEYS

	Equivalent Vol. Levels	Equivalent Vol. Levels	
	0 - 600	600 - 1200	
Avg. Speed	48.8	48.8	Study 00
No. Vehicles	1017	2573	
Avg. Speed	54.4	49.5	Study 01
No. Vehicles	1761	202	
Avg. Speed	56.5	57.1	Study 03
No. Vehicles	1073	121	
Avg. Speed	48.7	47.7	Study 04
No. Vehicles	762	1132	
Avg. Speed	59.2	-----	Study 05
No. Vehicles	509	-----	
Avg. Speed	48.9	-----	Study 08
No. Vehicles	718	-----	

EFFECT OF BARRIER FENCE

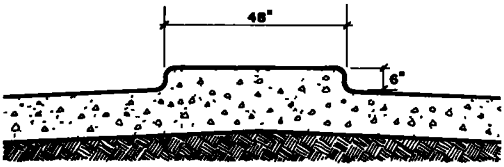
During the median studies, a barrier fence (as shown in Fig. 7) was erected on the 4-ft median of the Gulf Freeway in Houston, Texas. Data taken before (study 00) and after (study 07) erection of this fence were analyzed to determine the effect of the barrier fence on traffic behavior and accidents.

Accident Study

The principal purpose of the barrier fence was to reduce the number of serious accidents resulting from vehicles crossing the median and colliding head-on with traffic in the opposing lanes.

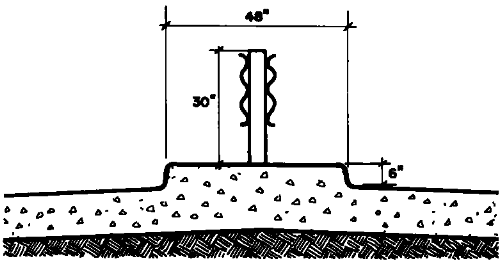
In order to investigate accident experience on the freeway as related to the barrier fence, accident data were collected for periods of 2 yr before and 2 yr after the erection of the barrier fence.

The data were tabluated by total freeway accidents (accidents which occurred on the main freeway lanes and not including ramp and



SECTION BEFORE CONSTRUCTION OF BARRIER FENCE

STUDY 00



SECTION AFTER CONSTRUCTION OF BARRIER FENCE

STUDY 07

Figure 7. Median sections—Gulf Freeway, Houston.

frontage road accidents) and by median accidents (accidents which involved the median) (Table 3).

TABLE 3

ACCIDENT DATA, GULF FREEWAY, HOUSTON, TEXAS
1954 to 1958

Type of Accident	Property Damage	Personal Injury	Fatal	Total
Main-lane freeway (no./100 mil veh-mi):				
Before	166.98	26.33	2.63	195.94
After	206.58	24.34	2.01	232.93
Median (no.):				
Before	15	28	4	47
After	34	11	0	45
Median (no./100 mil veh-mi):				
Before				13.56
After				11.71

The data indicate that although the total accident rate per 100 million vehicle-miles increased (195.94 before to 232.93 after), the rate of the severe accidents decreased slightly (personal injury 26.33 before to 24.34 after and fatal 2.63 before to 2.01 after).

A study of the median accidents indicates that the median accident rate was only slightly reduced from 13.56 before to 11.71 after. The severity of the median accidents, however, appears to have been materially reduced. There were 4 fatal median accidents before compared with none after and 28 personal injury accidents involving the median before compared with 11 during the after period.

Statistical Analysis

Only the inside or median lane placements were studied in the analysis of the before and after data as these are the most critical with respect to the median and would likely reflect any effect on driver behavior that could be attributed to the median.

Two separate studies were analyzed: the Bureau of Public Roads' study taken at the location shown in Figure 8, and the film study conducted at the location shown in Figure 9. The motion picture study was conducted in the vicinity on an entrance ramp while the Bureau of Public Roads' study was conducted on a section with no ramps in the vicinity.

The variables considered in.the study were before and after median conditions and traffic volume. Traffic volume was considered at three separate levels—V_1(0-600 vph), V_2(600-1200 vph), and V_3(1200-1800 vph). The data were analyzed using an analysis of variance technique with the index F as a test statistic.

For both the Bureau of Public Roads and the motion picture studies, the following tests were made:

TABLE 4

ANALYSIS OF VARIANCE: BEFORE-AFTER STUDY OF BARRIER FENCE B.P.R. SURVEYS

Source	df	Variance	F	df$_1$	df$_2$
Before (T_1) and after (T_2), without considering volume levels	1	0.2620	4.2532	1	94
Error	94	0.0616			
Total	95				
Volume levels V_1 (0-600), V_2 (600-1200) without considering before and after conditions	2	0.3198	5.4948[a]	2	93
Error	93	0.0582			
Total	95				
Before and after considering only one level of traffic V_1 (0-600)	1	0.0406	1.5675	1	29
Error	29	0.0259			
Total	30				
Before and after considering only one level of traffic V_2 (600-1200)	1	1.0745	19.8613[b]		
Error	52	0.0541			
Total	53				

[a] Significance at 95% level of confidence.
[b] Significance at 0.999 level of confidence.

TABLE 5

ANALYSIS OF VARIANCE: BEFORE-AFTER STUDY OF BARRIER FENCE MOTION PICTURE SURVEYS

Source	df	Variance	F	df$_1$	df$_2$
Before and after without considering volume	1	0.1380	1.0144	79	1
Error	79	0.1400			
Total	80				
Volume levels V_1 (0-6), V_2 (6-12), and V_3 (12-18) without considering before and after	2	1.4136	13.1742[a]		
Error	78	0.1073			
Total	80				
After and before considering only one level of traffic V_1 (0-600)	1	0.0994	2.1148	1	15
Error	15	0.0470			
Total	16				
After and before considering only one level of traffic V_2 (600-1200)	1	0.0035	41.5428	33	1
Error	33	0.1454			
Total	34				
Before and after considering V_3	1	0.1450	1.4963	1	27
Error	27	0.0969			
Total	28				

[a] Significance at 0.999 level of confidence.

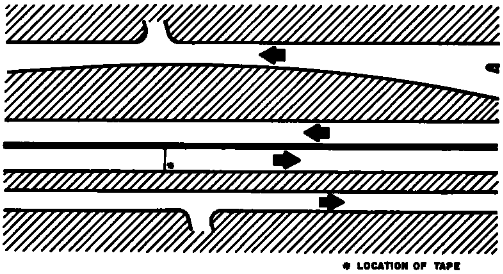


Figure 8. B.P.R. study site—Gulf Freeway, Houston, Texas.

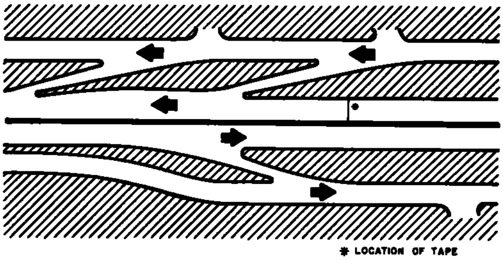


Figure 9. Motion picture study site—Gulf Freeway, Houston, Texas.

1. Test of significance comparing before and after placement data without considering volume levels.
2. Test of significance comparing the three volume levels without considering before and after conditions.
3. Test of significance comparing before and after placement data at each of the three volume levels.

Tabulations of the results from these studies are given in Tables 4 and 5.

The following results were obtained from the analysis of the Bureau of Public Roads' study.

1. There was no significant difference between the before and after placements when volume was not considered.
2. There was no significant difference between the placements grouped according to the three volume levels V_1(0-600), V_2(600-1200), and V_3(1200-1800).
3. There was no significant difference between before and after placements considering only the first level of traffic (0-600 vph).
4. There was a significant difference between before and after placements considering only the second level of traffic (600-1200 vph).
5. The data were not sufficient to compare before and after conditions at the third level of traffic (1200-1800 vph).

The following results were obtained from the analysis of the before and after motion picture studies:

1. There was no significant difference between the before and after placements when volume was not considered.
2. There was a significant difference between the placements grouped according to the three volume levels V_1(0-600), V_2(600-1200) and V_3(1200-1800).
3. There was no significant difference between before and after placements at any of the three volume levels.

Conclusions

The results of the studies indicate the following conclusions:

1. The barrier fence was valuable in reducing the severity of accidents involving the median.
2. The barrier fence had no significant effect upon driver behavior as indicated by vehicle placement.
3. On the section where there were no ramps, a significant differ-

ence between the before and after placements at the second level of traffic (600-1200 vph) indicated that the barrier fence had some effect on driver behavior as the volume increased.

4. The results of the analysis for the motion picture study indicated that volume had a more pronounced effect in this study than in the Bureau of Public Roads' study. This is probably a result of the entrance ramp conditions and the different time periods during which data were recorded. The motion picture study recorded data during three separate periods —7:00-8:30 A.M.; 9:30-10:30 A.M.; 4:00-5:30 P.M.—while the Bureau of Public Roads' study recorded data from 1:00 P.M. to 7:00 P.M. Thus the motion picture study reflected peak morning and afternoon conditions while the Bureau of Public Roads' study reflected only afternoon conditions.

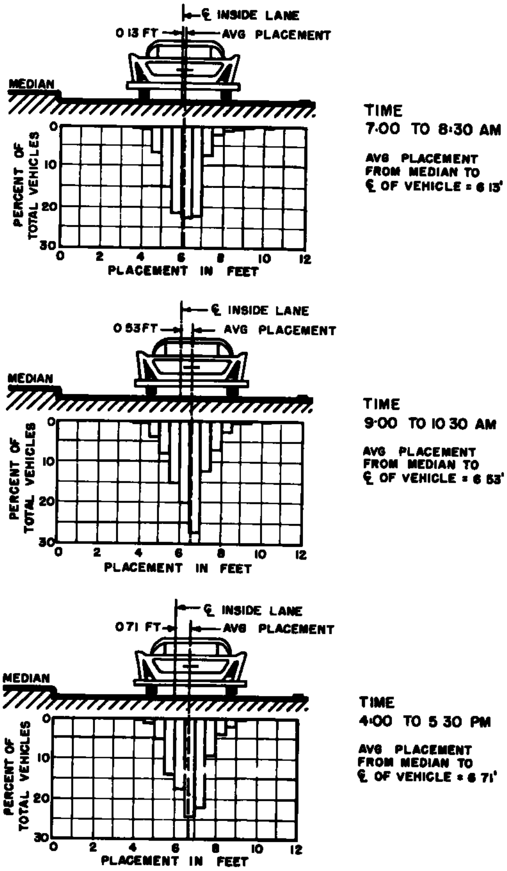


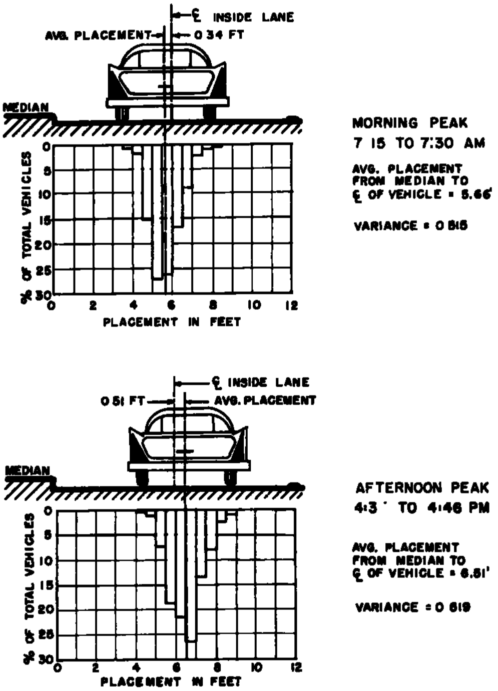
Figure 10. Average placements in median lane—Gulf Freeway.

The motion picture study indicated that volume conditions on both sides of the median affect vehicle placements. The average placements for the morning peak, offpeak and afternoon peak periods are shown in Figure 10 for the inside lane on the Gulf Freeway. A shift in vehicle placements toward the median during the morning peak and away from the median during the afternoon peak is indicated. The total change in average placement, comparing the morning peak (7:00-8:30 A.M.) with the afternoon peak (4:00-5:30 P.M.), is 0.58 ft. This effect is even more pronounced if peak 15-min periods (morning and evening) are compared for study 00 (before barrier fence) as shown in Figure 11. Here the total change is 0.89 ft. This difference was slightly less (0.67 ft) after the barrier fence was erected as shown in Figure 12. Thus it is evident that the opposing flow has a large amount of effect on vehicle placements in this study of a narrow median.

GENERAL MEDIAN STUDY

In order to develop knowledge of the effect of various type and width freeway medians on traffic behavior, a specific study was conducted using placement data recorded on freeways with the following median types:

Study	Location	Median Type
00	Houston - Gulf Freeway	4-ft Concrete with barrier curb
03	Dallas - Central Expressway	12-ft Concrete with barrier curb
04	Dallas - Central Expressway	27-ft Grassed with barrier curb
05	Dallas - US 80	40-ft Grassed, no curb



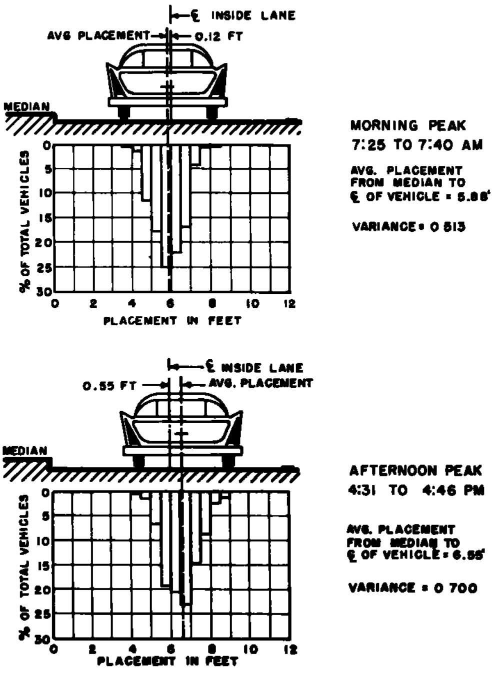


Figure 11. Average placements in median lane before barrier fence—Gulf Freeway.

Figure 12. Average placements in median lane after barrier fence—Gulf Freeway.

Statistical Analysis

In order to study the relationship of various type medians a number of comparisons of placement data were made. Because the difference in the average placements was small for the various type medians, the variance of the data was studied to determine any significant differences that occurred.

The data were grouped according to volume levels V_1(0-600 vph), V_2 (600-1200 vph) and V_3(1200-1800 vph) and by day-night periods. The tests that were made and the results of these tests are given in Table 6.

Comparisons of vehicle placements were made for the following medians:

1. Comparison of all medians;
2. Comparison of 4-ft median with 12-ft median;
3. Comparison of 4-ft median with 27-ft median;
4. Comparison of 4-ft median with 40-ft median;
5. Comparison of 12-ft median with 27-ft median; and
6. Comparison of 27-ft median with 40-ft median.

In order to obtain the various size median sections for study, it was necessary to study a number of freeway sections. This placed some limitations on the comparisons that could be made because it was impossible to obtain a full range of volume conditions on all of the sections. For example, only one level of traffic (0-600) could be compared for night and day. For this reason some comparisons were impossible.

TABLE 6

GENERAL MEDIAN STUDY TEST RESULTS

		1	2	3	4	5	6
S	V	V_1 V_2 V_3	V_1	V_1 V_2 V_3	V_1	V_2	V_3
	T	T_1 T_2	T_1 T_2	T_1	T_1	T_1	T_1
STUDY-00 THROUGH STUDY-08	S	+++	+++	+++	+++	+++	++
	V	+++		+++			
	T	NO SIGNIFICANCE	+				
STUDY-00 & STUDY-03	S_1	+++	+++	NO SIGNIFICANCE	NO SIGNIFICANCE	NO SIGNIFICANCE	NO DATA S-03
	V	NO SIGNIFICANCE		++			
	T	NO SIGNIFICANCE	NO SIGNIFICANCE				
STUDY-00 & STUDY-04	S_2	NO SIGNIFICANCE	+++	NO SIGNIFICANCE	++	NO SIGNIFICANCE	++
	V	+++		+++			
	T	NO SIGNIFICANCE	+++				
STUDY-00 & STUDY-05	S_3	++	++	NO SIGNIFICANCE	NO SIGNIFICANCE	NO DATA S-05	NO DATA S-05
	V	NO SIGNIFICANCE		NO SIGNIFICANCE			
	T	NO SIGNIFICANCE	NO SIGNIFICANCE				
STUDY-00 & STUDY-07	S_4	NO SIGNIFICANCE	NO DATA S-07		NO SIGNIFICANCE		NO DATA S-07
	V	+		NO DATA S-07			
	T	NO DATA S-07	NO DATA S-07				
STUDY-03 & STUDY-04	S_5	++	NO SIGNIFICANCE	+	NO SIGNIFICANCE	NO SIGNIFICANCE	NO DATA S-03
	V	+++		+++			
	T	+	NO SIGNIFICANCE				
STUDY-03 & STUDY-05	S_6	+++	NO SIGNIFICANCE	NO SIGNIFICANCE	NO SIGNIFICANCE	NO DATA S-05	NO DATA S-03 & 05
	V	NO SIGNIFICANCE		NO SIGNIFICANCE			
	T	+++	NO SIGNIFICANCE				
STUDY-04 & STUDY-05	S_7	NO SIGNIFICANCE	NO SIGNIFICANCE	NO SIGNIFICANCE	NO SIGNIFICANCE	NO DATA S-05	NO DATA S-05
	V	+		++			
	T	NO SIGNIFICANCE	NO SIGNIFICANCE				

S – STUDY (00, 01, 03, 04 05, 06, 07, 08)
S_1 – STUDY 00, 03
S_2 – STUDY 00, 04
S_3 – STUDY 00, 05
S_4 – STUDY 00, 07
S_5 – STUDY 03, 04
S_6 – STUDY 03 05
S_7 – STUDY 04, 05

V – VOLUME OF TRAFFIC
V_1 – 0-600 VPH
V_2 – 600-1200
V_3 – 1200-1800

T – PERIOD
T_1 – DAY
T_2 – NIGHT

+ – SIGNIFICANT AT 95% LEVEL OF CONFIDENCE

++ – SIGNIFICANT AT 99% LEVEL OF CONFIDENCE

+++ – SIGNIFICANT AT 999% LEVEL OF CONFIDENCE

COLUMN

1	TEST OF SIGNIFICANCE FOR THE VARIATION IN EACH VARIABLE (STUDY, VOLUME PERIOD) WITHOUT CONSIDERING THE INFLUENCE OF THE OTHER VARIABLES
2	TEST OF SIGNIFICANCE FOR THE VARIATION IN STUDY OR PERIOD CONSIDERING ONLY ONE VOLUME LEVEL (V_1) AND WITHOUT CONSIDERING THE INFLUENCE OF THE OTHER VARIABLE
3	TEST OF THE SIGNIFICANCE FOR THE VARIATION IN STUDY AND VOLUME CONSIDERING ONLY DAYTIME DATA AND WITHOUT CONSIDERING THE INFLUENCE OF THE OTHER VARIABLE
4, 5, 6	TEST OF SIGNIFICANCE FOR THE VARIATION IN STUDY CONSIDERING ONLY DAYTIME DATA AND SEPERATE LEVELS OF VOLUME (V_1 V_2 V_3)

The results of the comparisons were as follows:

General Results - Including all studies:

1. There was a significant difference in placements among the studies.
2. There was a significant difference in placements grouped according to the three volume levels for all studies.
3. There was no significant difference between day and night placements at the first level of traffic (0-600 vph).
4. There was a significant difference in placements at each volume level for all studies.

Study 00 with 04 - 4-ft with 12-ft:

1. There was no significant difference in placements between the studies without considering volume.
2. There was a significant difference in placements grouped according to the three volume levels for both studies.
3. There was no significant difference between day and night placements at the first level of traffic (0-600 vph).
4. There was a significant difference in placements at each volume level for these studies.

Study 00 with 03 - 4-ft with 27-ft:

1. There was a significant difference in placements between the studies without considering volume.
2. There was no significant difference in placements grouped according to the three volume levels for both studies.
3. There was no significant difference between day and night placements at the first level of traffic (0-600 vph).
4. There was no significant difference in placements at each volume level for these studies.

Study 00 with 05 - 4-ft with 40-ft:

1. There was a significant difference in placements between the studies without considering volume.
2. There was no significant difference in placements grouped according to the three volume levels for both studies.
3. There was no significant difference between day and night placements at the first level of traffic (0-600).
4. There was not sufficient data to compare all volume levels for these studies.

Study 04 with 03 - 12-ft with 27-ft:

1. There was a significant difference in placement between the studies without considering volume.
2. There was a significant difference in placements grouped according to the three volume levels for both studies.
3. There was no significant difference between day and night placements at the first level of traffic (0-600 vph).
4. There was not sufficient data to compare all volume levels for these studies.

Study 03 with 05 - 27-ft with 40-ft:

1. There was a significant difference in placements between the studies without considering volume.

2. There was no significant difference in placements grouped according to the three volume levels for both studies.
3. There was no significant difference between day and night placements at the first level of traffic (0-600 vph).
4. There was not sufficient data to compare all volume levels for these studies.

Conclusions

The following conclusions were drawn from the results of the various comparisons made in the general study:

1. Although the change in average placements was relatively small for all studies, a study of the variation in the data indicates that median width does significantly affect traffic behavior.

2. The following comparisons were made:
   a. 4-ft median with 12-ft median;
   b. 4-ft median with 27-ft median;
   c. 4-ft median with 40-ft median; and
   d. 12-ft median with 27-ft median.

The results of the tests indicate no significant difference in placements for comparison (a) but a significant difference in placements for comparisons (b), (c), and (d). Thus the wide medians (27 ft and 40 ft) compared with the narrow medians (4 ft and 12 ft) reflect a significant change in traffic behavior that is not apparent when comparing the narrow medians with each other. This indicates, though all variations in average placement are slight, the narrow medians have a different effect on driver behavior from the wider medians.

3. A study of vehicle placements with regard to volume was made for the following comparisons:
   a. 4-ft with 12-ft;
   b. 12-ft with 27-ft;
   c. 4-ft with 27-ft; and
   d. 4-ft with 40-ft.

The results of these tests indicate that volume had a significant effect on placements for comparisons (a) and (b) but no significant effect for comparisons (c) and (d). This indicates a reduction in the effect of volume on vehicle placement for the wider medians (27 ft, 40 ft) as compared to the narrow medians (4 ft, 12 ft). Thus, the wider medians appear desirable to reduce or eliminate the effect of heavy volumes on the driver's behavior.

SUMMARY

The data analyzed indicated that variations in vehicle placements on freeways are relatively small. Data on vehicle placements and observations of over-all freeway operation indicate that median widths as small as 4 ft are satisfactory. However, numerous median accidents were observed and the accident data indicated that a barrier fence on the 4-ft median was very effective in reducing the severity of median accidents. Also, the results of placement data analyses indicated that the barrier fence had no significant effect on driver behavior.

In the general median studies which compared various width medians, it was found that median widths did affect traffic behavior as indicated by vehicle placements. A difference in driver behavior was noted when comparing wide medians with narrow medians and the data indicated that wide medians are valuable in reducing or eliminating the effect of opposing flow and heavy volumes on traffic behavior.

Comparisons of day and night placement data in the volume range of 0-600 vph indicate no significant difference between day and night vehicle placement.

ACKNOWLEDGMENT

This research project was conducted by the Texas Transportation Institute for and in cooperation with the Texas Highway Department. Grateful acknowledgment is made to representatives of the Texas Highway Department and the Cities of Houston, Dallas, and Fort Worth, who served on the Project Advisory Committee, for their valuable advice and assistance.

Gratitude is also expressed to the Bureau of Public Roads for their participation in these studies.

Traffic Behavior on an Urban Expressway

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●IN A COMPANION paper, "Accident Analysis of an Urban Expressway" (1), two of the authors present a study of the interaction between influencing factors such as weather and light conditions on type of accident. This paper is an effort to study in detail driver behavior in an urban expressway traffic pattern in terms of velocity, spacing, volume and character.

Although the intent was to relate rear-end collisions and traffic patterns somewhat after the fashion of Belmont (2), the largest portion of the paper deals with typical capacity information (3).

The data collection and reduction was similar to that used by Greenshields, et al. (4). A camera was used to record traffic patterns on all six lanes of the Detroit John C. Lodge Expressway for eight consecutive days around the clock.

Functional relationships were obtained for mean velocity, median and modal spacing, lane distribution, and commercial vehicle distribution as a function of volume. A "trend" relationship between annual rear-end collision rate and volume at time of accident was also established. Quantitative information on the effect of rain and night driving conditions on vehicle velocity was determined.

EXPRESSWAY GEOMETRY

This study was performed in June 1957. The expressway system consisted of the John C. Lodge running approximately north and south and intersected near its midpoint by the Edsel B. Ford running approximately east and west. The system is shown in Figure 1. The location of the camera on the John C. Lodge is also shown. The immediate geometry near the camera location is shown in Figure 2. It was approximately midway between the Grand River and Forest ramps, a distance of 0.63 mi. This location was particularly chosen to be as remote as possible from ramp effects.

The cross-section of the Lodge Expressway includes three 12-ft lanes in each direction with a 10-ft medial strip and two 10-ft shoulders.

DATA COLLECTION

A Cine Special camera modified to a speed of 88 frames per minute was mounted on the roof of a 14-story building overlooking the expressway. Figure 3 shows the camera in position while the details of the mechanism are shown in Figure 4. A typical frame is shown in Figure 5. Reference space markers can be seen alongside each curb lane. These were made of reflecting tape and spaced exactly 30 ft apart. These markers were then used to construct a grid which permitted reading off car positions to approximately $\frac{1}{2}$ ft. The film reader developed by the Ford Motor Company is shown in Figure 6. The film viewer's ground-glass cover is

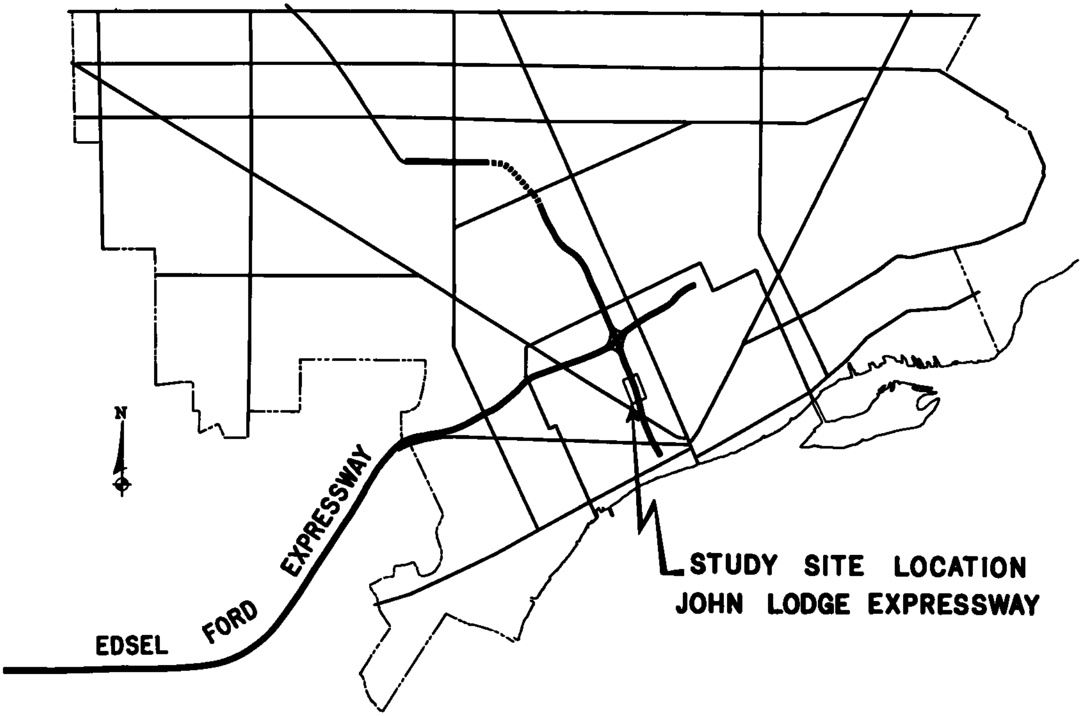

Figure 1.

marked with grid lines by which distance between cars and the velocity of each vehicle may be determined readily. The type of vehicle—passenger, truck, bus—was also recorded. All this information was placed on IBM cards for processing on the IBM 650 computer.

Film records were taken each hour for 5 min, 24 hr per day and for eight consecutive days which included one Saturday and Sunday. Fortunately, some rain fell during this time so that this effect could be evaluated. In all, about 64,000 vehicles were recorded on IBM cards.

RESULTS

The first graph, Figure 7, shows the percentage distribution by lane. Each plotted point represents an average of approximately four 5-min samples, i.e., volumes based on 5-min photographic records were grouped into approximately equal volumes and the average of this group determined the value of the abscissa. Similarly, percent of volume is also the mean of the several samples. It can be seen that the middle lanes carry over 40 percent of the three-lane volume while curb lanes carry slightly more than 31 percent and median lanes carry almost 29 percent.

These same samples were further analyzed for the character of the traffic. In Figure 8 the distribution of commercial vehicles per lane as a function of volume is shown. The commercial traffic reaches a high value of 13 percent during low volumes and is reduced to about 2 percent at rush hours. As would be expected the other two lanes carry much less commercial traffic, about 3 percent at the most.

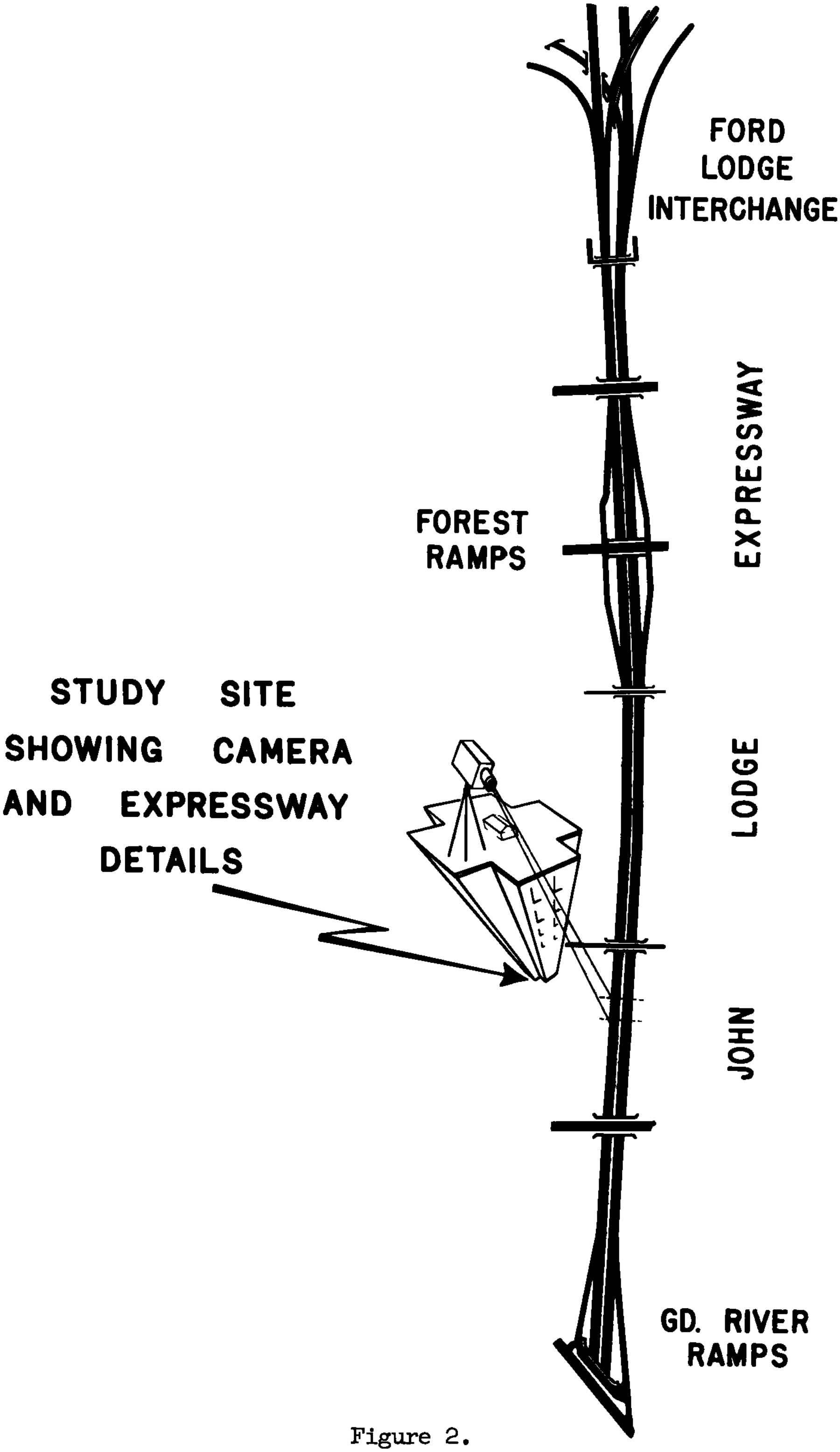
FORD LODGE INTERCHANGE
EXPRESSWAY
FOREST RAMPS
STUDY SITE SHOWING CAMERA AND EXPRESSWAY DETAILS
LODGE
JOHN
GD. RIVER RAMPS

Figure 2.

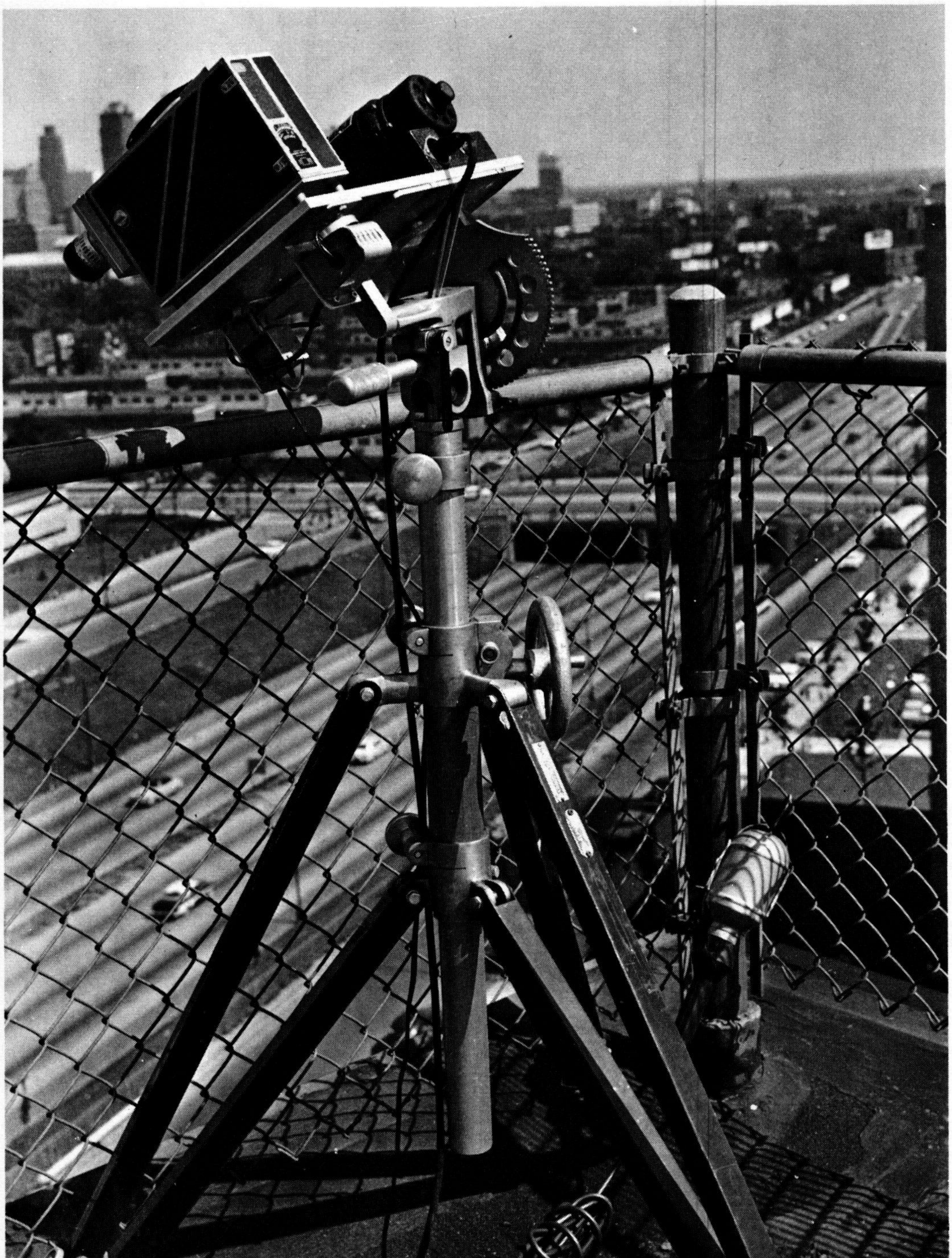

Figure 3.

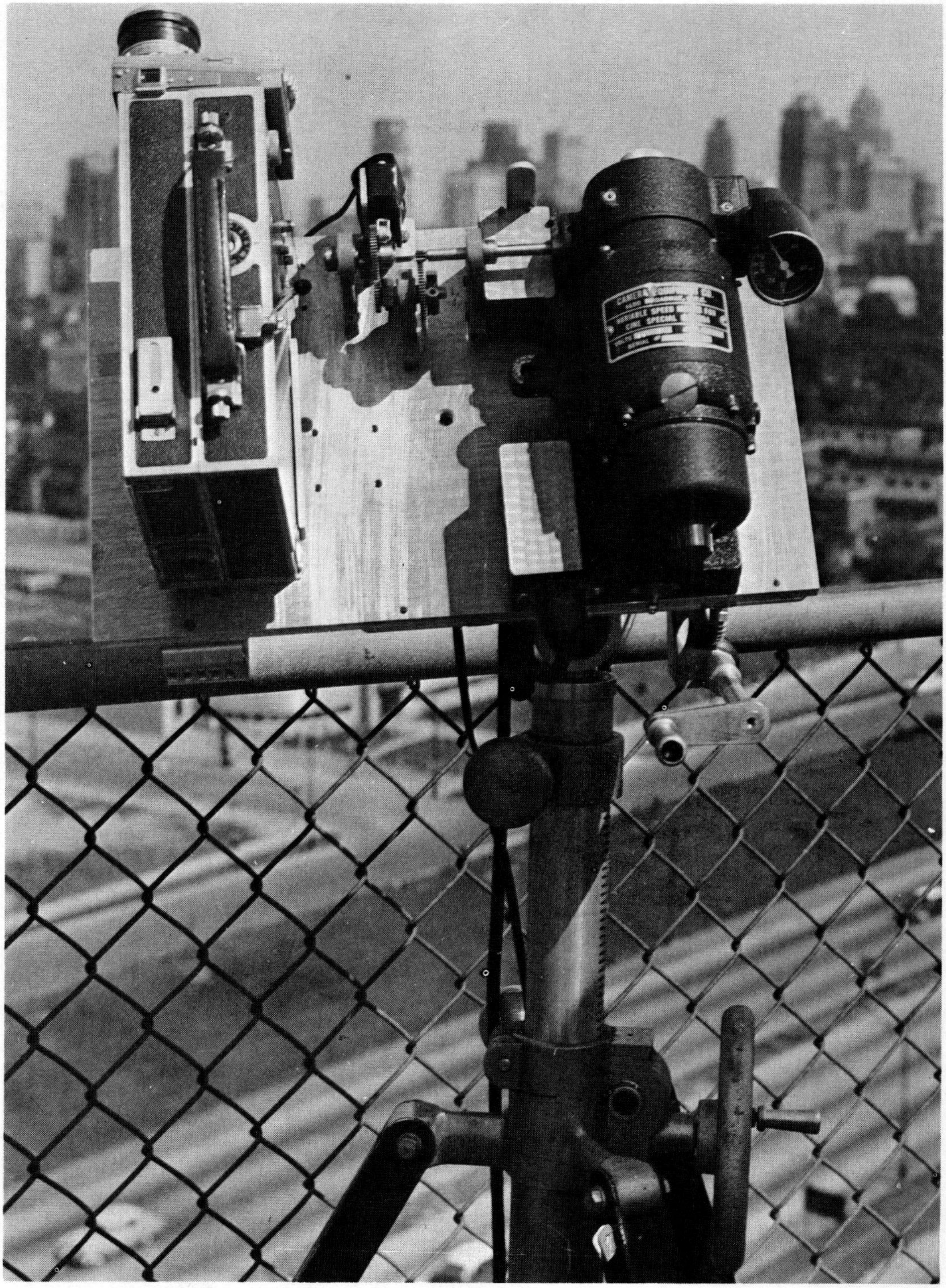

Figure 4.

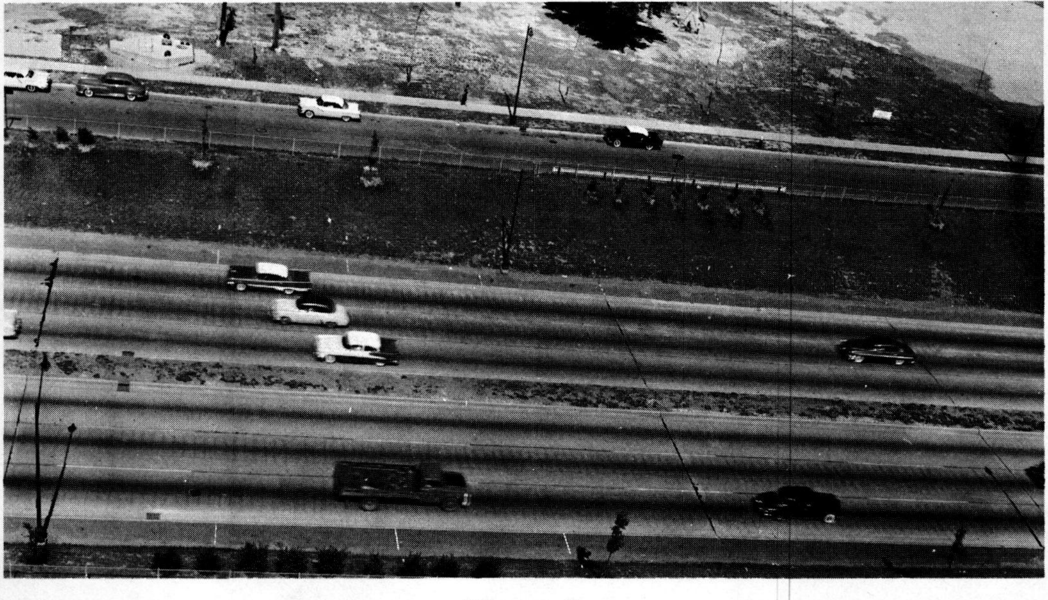

Figure 5.

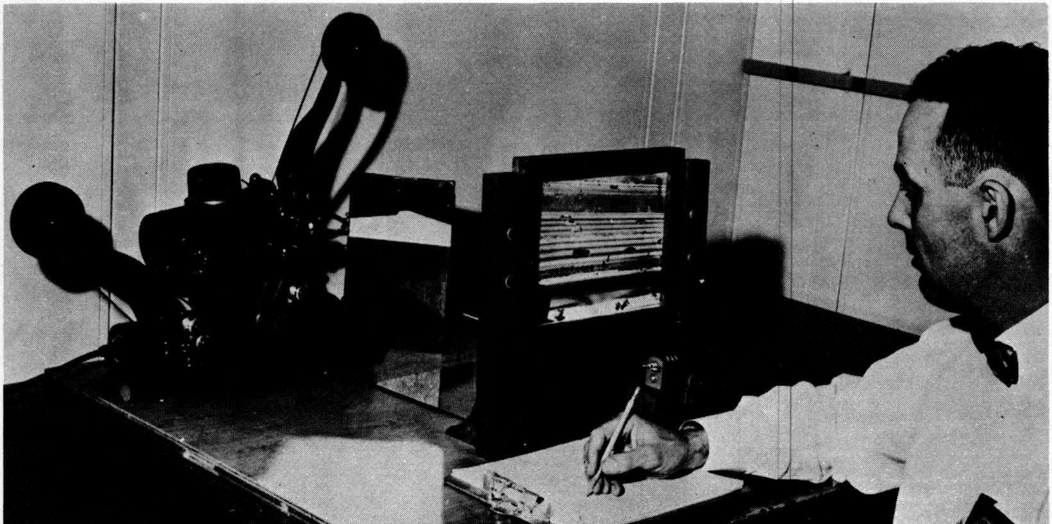

Figure 6.

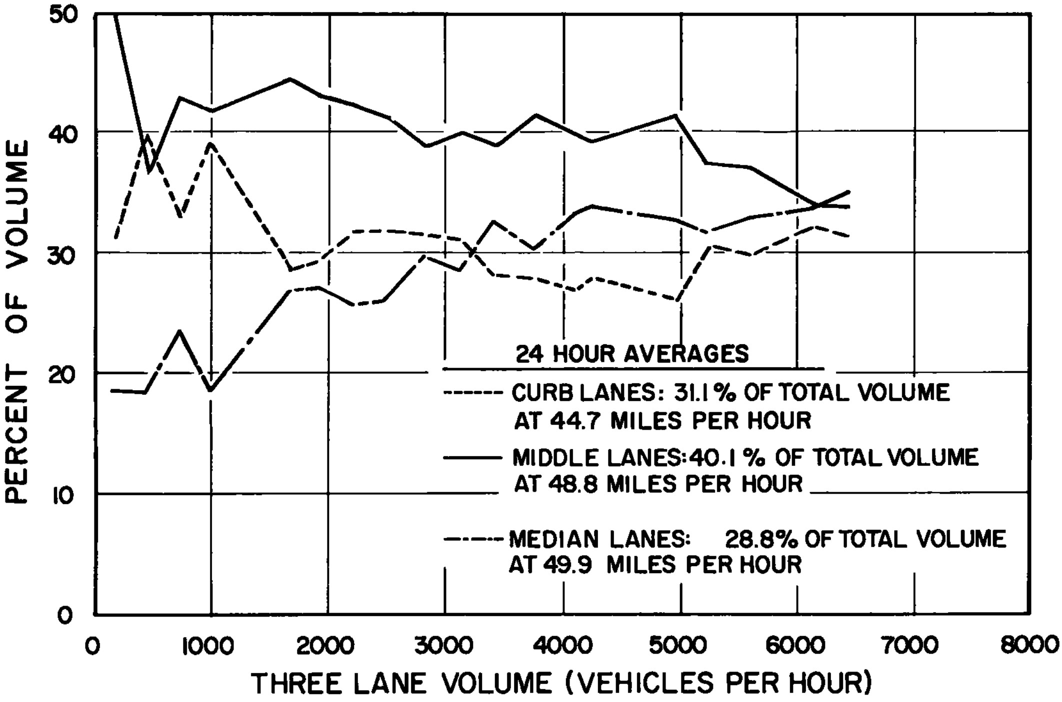

Figure 7. Volume distribution of all vehicles by lane, northbound and southbound—John C. Lodge Expressway (normal weekday traffic, 6 A.M. through 7 P.M., dry pavement, June 1957).

Velocity distribution was obtained for all lanes and volumes. A typical result is shown in Figures 9 and 10 for medium and heavy traffic on the middle lanes. It can be seen that the distribution is close to normal. The curves drawn represent the optimum normal distribution that could be fitted to the experimental information. The Detroit expressway system has a posted speed limit of 55 mph and a minimum limit of 40 mph.

Throughout this study, emphasis was placed on describing traffic behavior by mathematical relationships. The advantages are obvious. For one thing, a systems approach may then be used in further analysis. In Figure 11, the mean velocity of passenger vehicles as a function of three-lane volume is plotted. The data represent samples including almost 34,000 vehicles. In this, as in all the curves shown in this paper, each plotted point represents an average of four to eleven 5-min samplings. Further, each point represents the average of a volume class interval of 300 vph. The justification for a parabolic relationship has been suggested by other authors (5). Basically, it depends on a linear relationship between density and mean velocity. A check of this relationship was made and although it is not quite linear, it is very closely so. The data show the largest deviation from a straight line above about 52 mph. Assuming this approximate linearity, and because the curve must go through the origin, a least square fit was made to the data. The relationship on the curve shows how mean velocity may be predicted from volume. The single-sample point is interesting. It was obtained during a particularly congested situation on the expressway caused by rush-hour traffic combin-

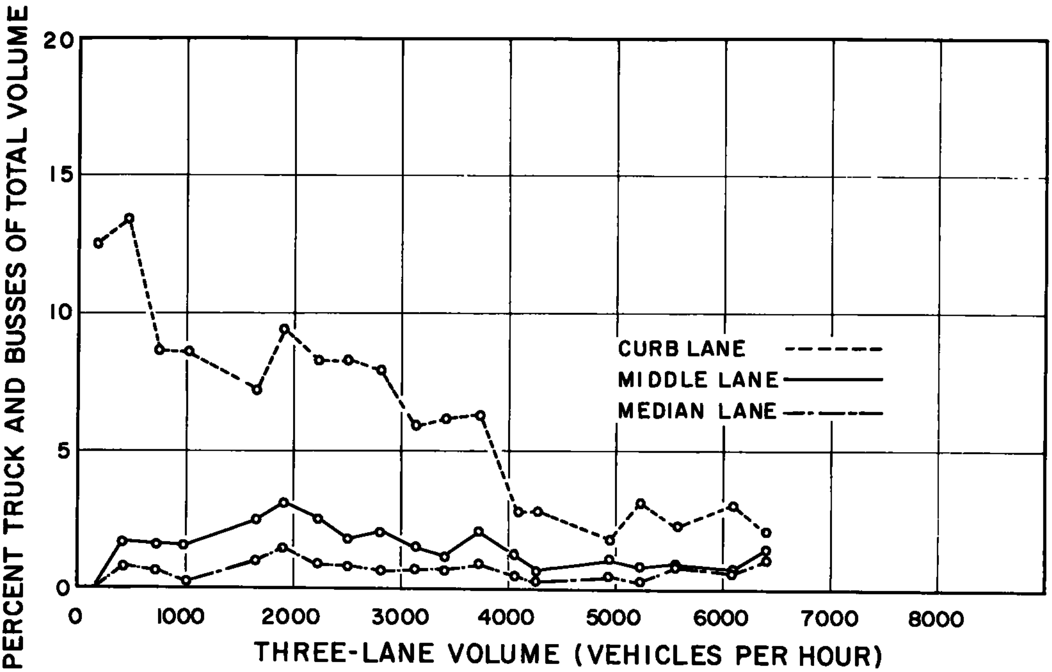

Figure 8. Truck and bus volume distribution by lane, northbound and southbound—John C. Lodge Expressway (normal weekday traffic, 6 A.M. through 7 P.M., dry pavement, June 1957).

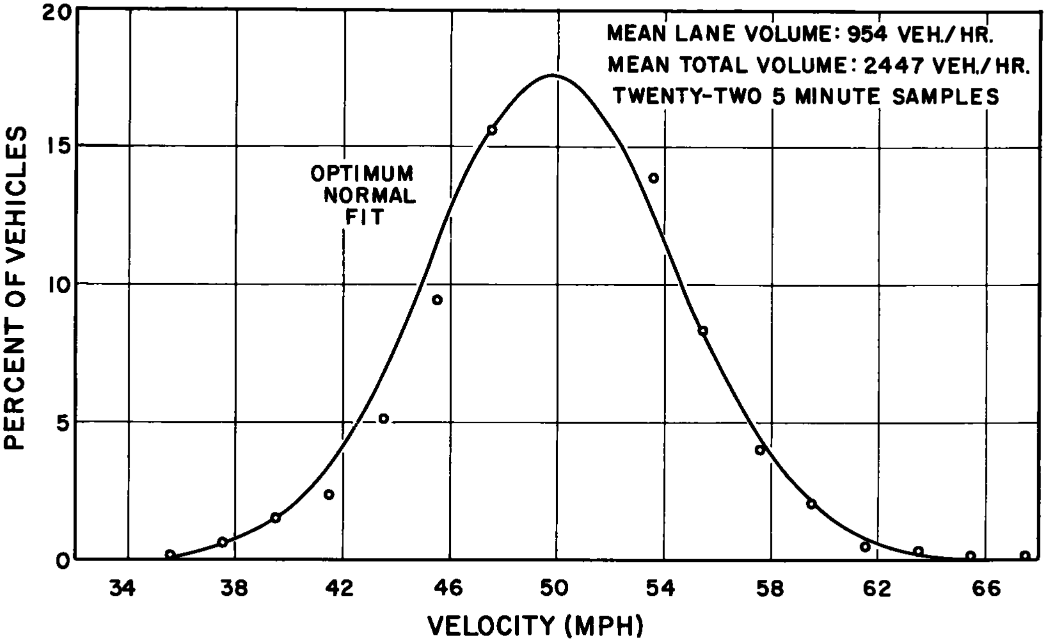

Figure 9. Passenger vehicle velocity distribution, northbound and southbound middle lanes—John C. Lodge Expressway (normal weekday traffic, 6 A.M. through 7 P.M., dry pavement, June 1957).

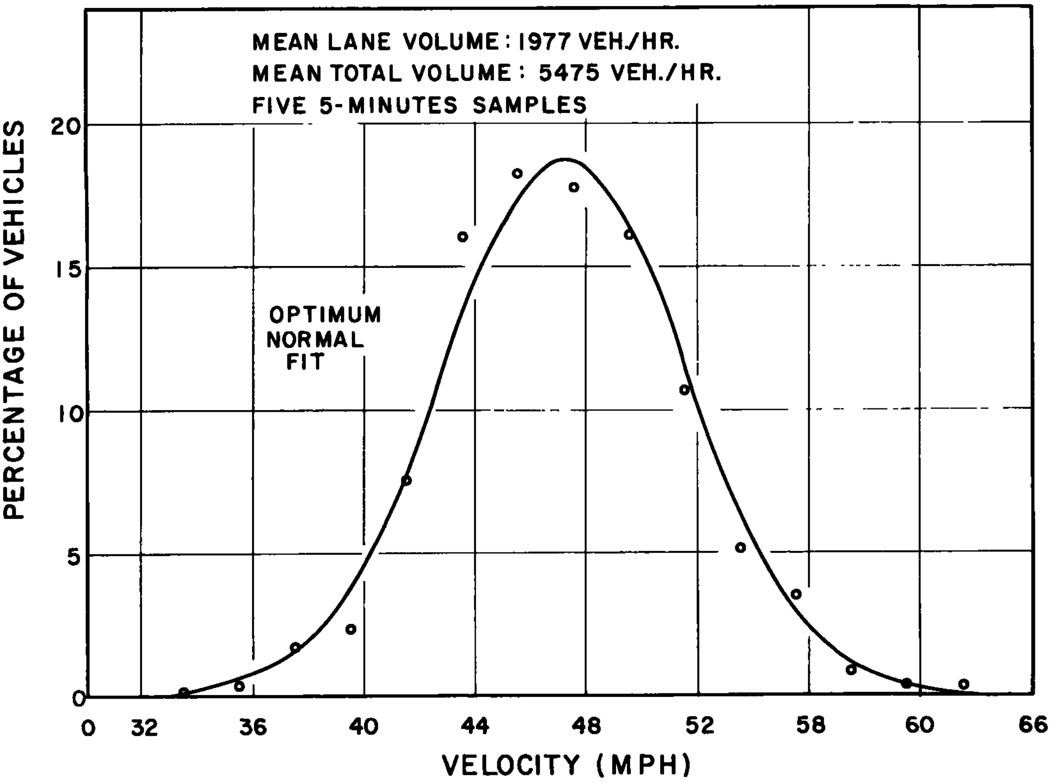

Figure 10. Passenger vehicle velocity distribution, northbound and southbound middle lanes—John C. Lodge Expressway (normal weekday traffic, 6 A.M. through 7 P.M., dry pavement, June 1957).

ing with traffic leaving after the end of a Detroit "Tiger" baseball game. Although a single 5-min sample would be statistically of low reliability, it nevertheless shows that a maximum capacity exists. This maximum capacity is at the vertex of the parabola and indicates a value of 8,250 vph traveling at a mean velocity of about 27 mph.

The same type of relationships were found for the individual lanes, i.e., curb, middle and median.

Using the same volume class intervals, the median spacing (50 percentile) was computed as shown in Figure 12. The relationship is hyperbolic and is represented by the mathematical function shown in the figure. It is to be noted that the least square fit is poor at the very low volumes. However, this region is of very little practical value and, furthermore, the data in this region represent only about two or three samples and a mean has little statistical significance. In other words, it was deemed unnecessary to fit a higher order curve just to obtain a better fit in a relatively unimportant region where the data are also less reliable. Again, similar relationships were found for the individual lanes.

Probably of more importance is the modal (most frequent) spacing between vehicles. It was decided in studying the data that probably the best fit to the data would be obtained by two linear relationships inter-

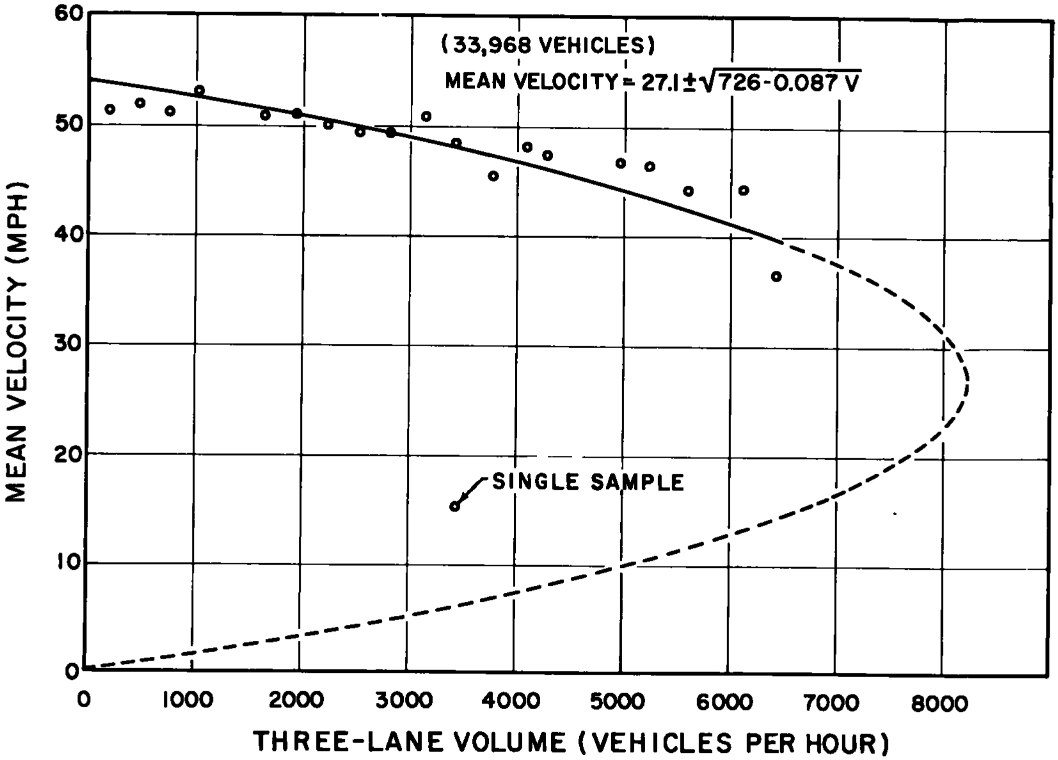

Figure 11. Passenger vehicle mean velocity, northbound and southbound, all lanes combined—John C. Lodge Expressway (normal weekday traffic, 6 A.M. through 7 P.M., dry pavement, June 1957).

secting somewhere between a volume of 1,000 and 2,000 vph. The justification for this belief arises from the fact that a Poisson (6,7) spacing distribution fit in the low volume region was probable, whereas beyond approximately a volume of 1,000 vph the distribution was no longer of this type. The relationship between modal spacing and volume is shown in Figure 13. The break point appears to occur at a volume of 1,250 vph. As in the preceding data, the modal spacing was also broken down by lane with similar results. The "break" volumes were 1,000, 1,750 and 1,700 vph for the curb, middle and median lanes, respectively. Much greater variability in the individual lane data was apparent below the "break" volumes. All the above volumes are referred to the total three-lane volume.

Of practical interest is the relationship between modal spacing and mean velocity. In any automatic spacing control system this relationship would be useful in establishing design criteria and still be acceptable to the largest number of drivers. This relationship is shown in Figure 14. It is constructed directly from the empirical mean velocity (volume curve in Figure 11) and the empirical modal spacing (volume curve in Figure 13). There is a discontinuity in the curve of Figure 14 because of the discontinuity in the modal spacing—volume curve near 1,250 vph. Mathematical functions are also shown in the figure that permit prediction of the most frequent spacing if the mean velocity is known.

The vehicle spacing was also analyzed in terms of time, i.e., the

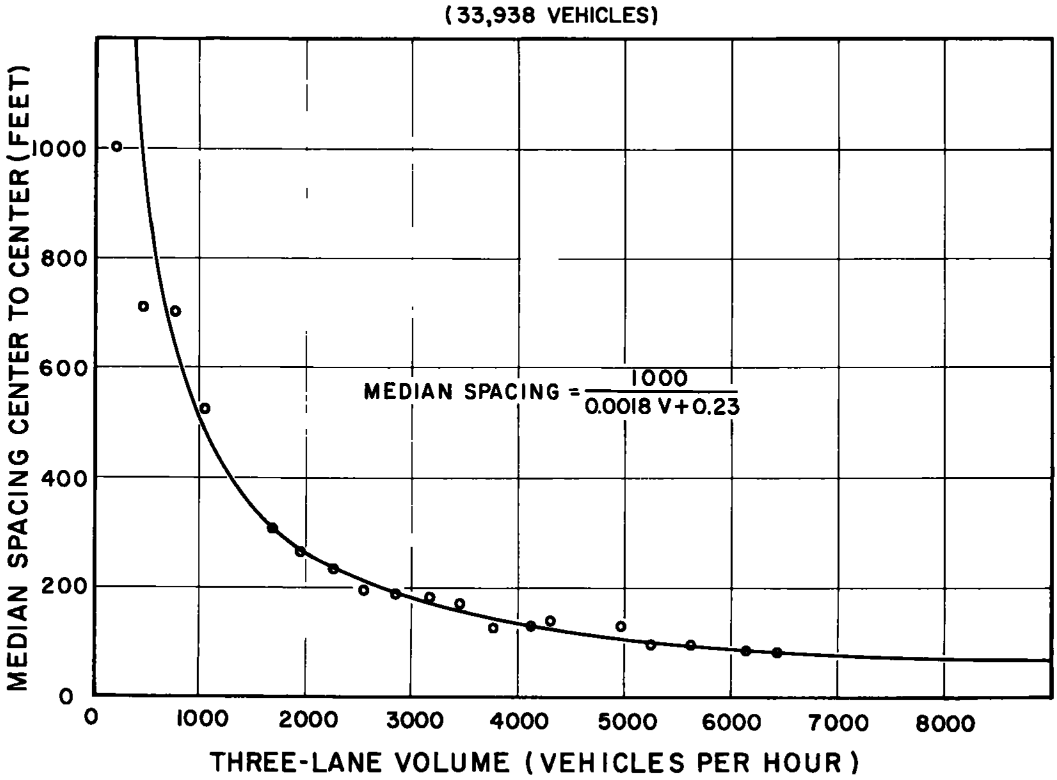

Figure 12. Passenger vehicle median spacing, northbound and southbound, all lanes combined—John C. Lodge Expressway (normal weekday traffic, 6 A.M. through 7 P.M., dry pavement, June 1957).

distance to the vehicle in front divided by the velocity of the following vehicle. The result is a linear relationship between time spacing and three-lane volume as shown in Figure 15. At volumes below 1,000 vph the large variability of distance spacing and velocity produced no meaningful information. In general, time spacing decreases linearly with increase in volume.

It is a generally accepted fact that the mean reaction time of a driver in application of brakes is about 0.7 sec (8). The time spacing data were analyzed to determine the number of drivers that space themselves at 0.9, 0.7 and 0.5 or less seconds. The data, as a function of three-lane volume, were fitted to curves as shown in Figure 16. The 0.9- and 0.7-sec curves are parabolic; but the 0.5-sec curve is linear and indicates that about 1 percent of drivers use a spacing $\frac{1}{2}$ sec or less irrespective of the volume.

Another interesting facet developed from the time spacing data. It was found that traffic behavior is somewhat analogous to the charging of an electrical capacitor. Thus, in Figure 17 a family of curves showing cumulative percentage of volume as a function of time spacing with volume as a parameter were fitted to the data. The largest deviation of data from the curve was found at the highest volume and was not larger

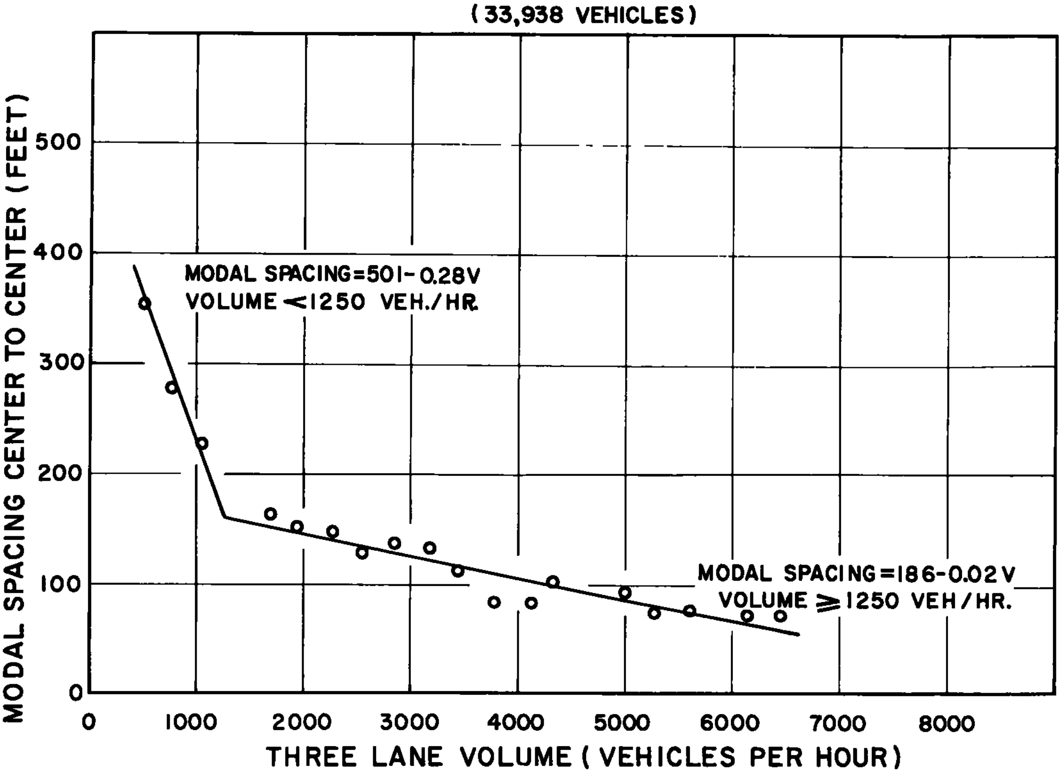

Figure 13. Passenger vehicle modal spacing, northbound and southbound, all lanes combined—John C. Lodge Expressway (normal weekday traffic, 6 A.M. through 7 P.M., dry pavement, June 1957).

than 10 percent. The deviation between empirical data and the least square fit diminished as the volume decreased.

For example, at a volume of 3,000 vph it is expected that 74 percent of all vehicles will be spaced at 4 sec or less. The mathematical function that describes the data is of the form

$$\text{Cumulative Percentage} = \left(1 - \Sigma^{-Vt/A}\right).$$

It is, of course, dangerous to interpret this equation literally as exactly the same as that describing the charging of a capacitor in a series capacitance-resistance circuit because the "t" in Figure 17 is not an independent variable, i.e., the cumulative percentage is not changing continuously as a function of time. However, it is interesting to draw the analogy that the constant "A" corresponds to the capacitance "C" of a capacitor and volume (V) corresponds to the conductivity—reciprocal of resistance—of the resistor.

The data discussed thus far were specifically for traffic behavior on dry pavement primarily because rain data during the period of observation were limited. However, a reasonable number (seven) of 5-min samples were taken to establish the effect of rain on the mean velocity for the

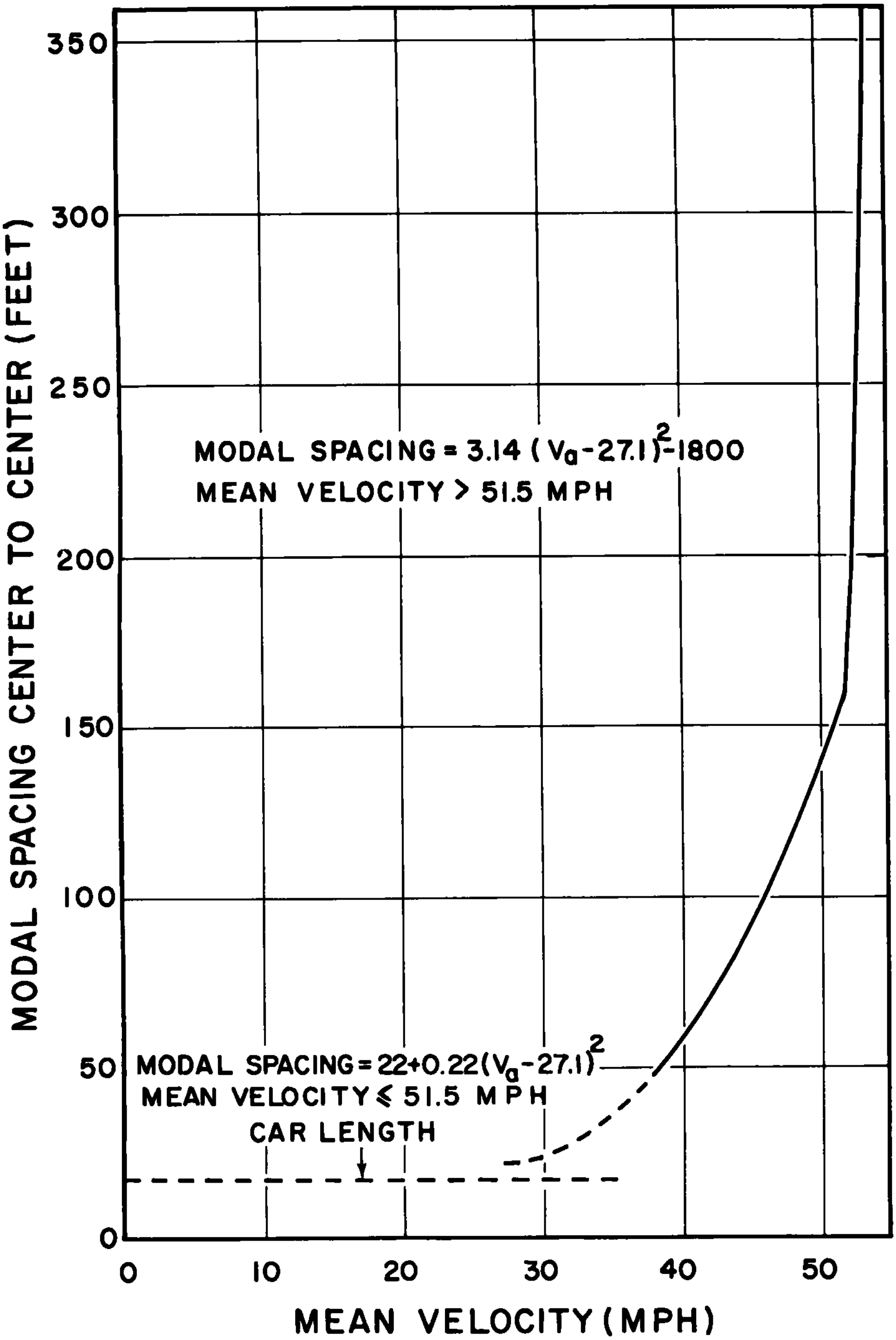

Figure 14. Modal spacing as function of mean velocity, passenger vehicles, northbound and southbound, all lanes combined—John C. Lodge Expressway (normal weekday traffic, 6 A.M. through 7 P.M., dry pavement, June 1957).

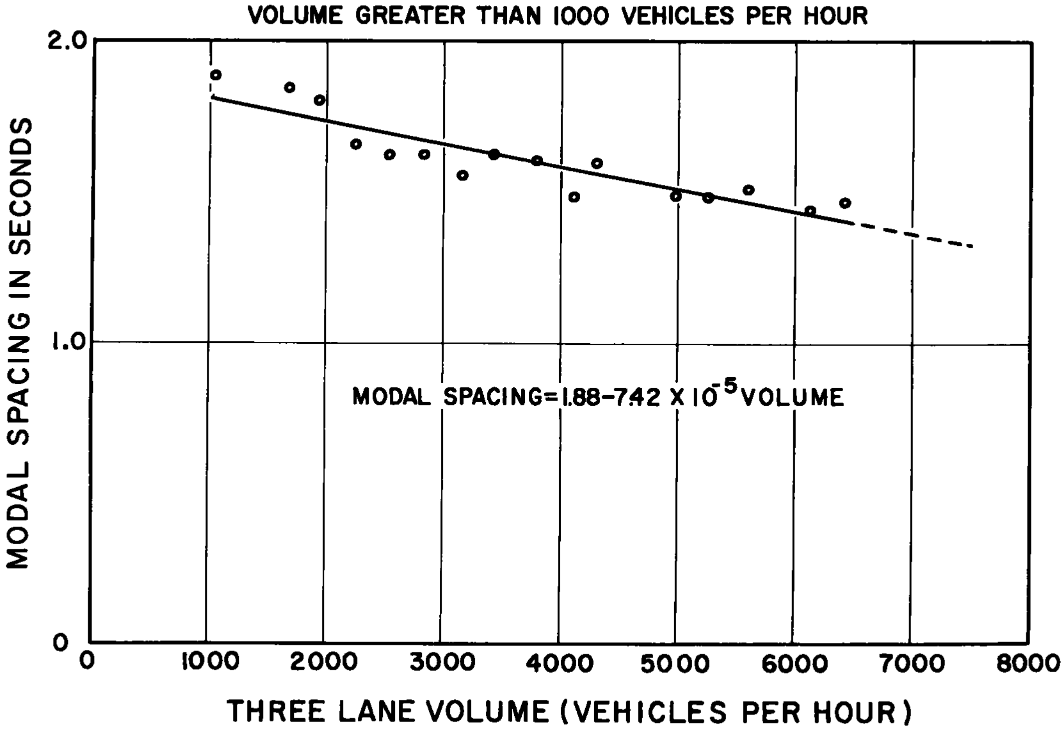

Figure 15. Time spacing, modal vs volume—John C. Lodge Expressway (normal weekday traffic, dry pavement, 6 A.M. to 7 P.M., June 1957).

same volumes that were measured during dry conditions. Table 1 summarizes this information according to lane.

TABLE 1

Lane	Change in Mean Velocity Due to Rain
Curb	-8.7
Middle	-8.6
Median	-12.4

Similar comparison was made between day and night driving during similar volumes. This information is given in Table 2.

TABLE 2

Lane	Change in Mean Velocity at Night
Curb	-4.3
Middle	-4.4
Median	-6.6

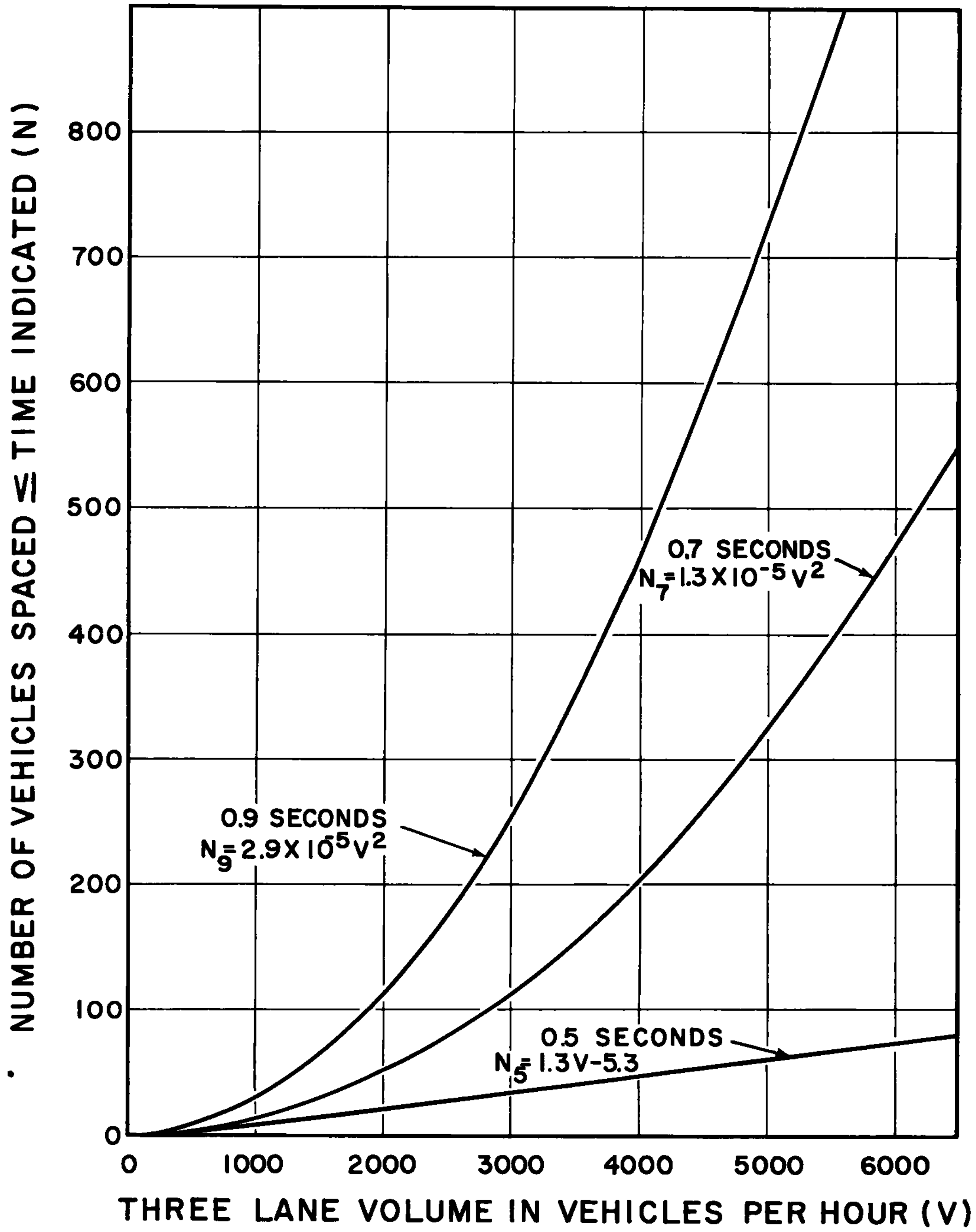

Figure 16. Vehicle time spacing vs volume—John C. Lodge Expressway (normal weekday traffic, dry pavement, June 1957).

No difference existed in mean velocity at similar volumes between weekday and weekend drivers.

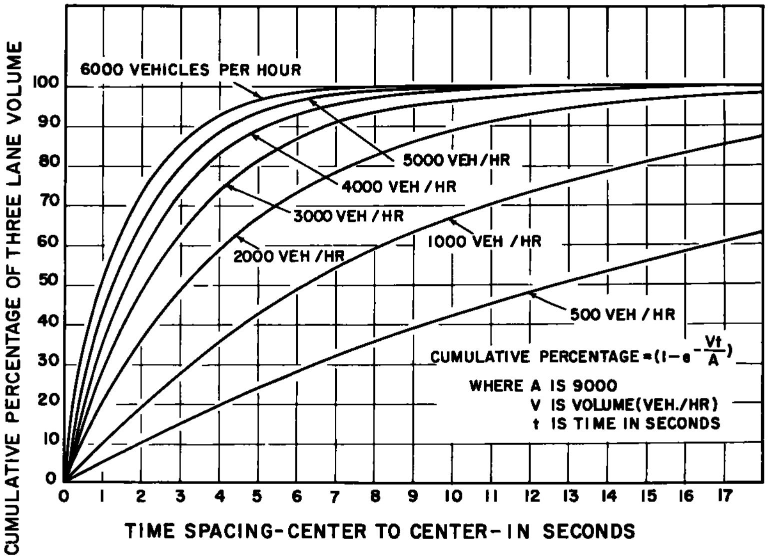

Figure 17. Cumulative percentage vs time spacing—John C. Lodge Expressway (normal weekday traffic, dry pavement, 6 A.M. to 7 P.M., June 1957).

REAR-END COLLISIONS

This paper reports in detail primarily the results of daytime, weekday main roadway traffic behavior. Because of this, only the rear-end collisions during 1956 that occurred under these conditions were used in studying correlation between these accidents and driver behavior. A total of 223 rear-end collisions were reported on the Lodge Expressway during 1956, but only 109 as Table 3 shows, matched the conditions of this study.

TABLE 3

Time	Northbound	Southbound	Total
6 A.M. - 12 Noon	6	34	40
12 Noon - 7 P.M.	11	58	69
	17	92	109

However, all dry pavement, weekday rear-end collisions were used to show the percentage of these rear-end collisions as a function of hour of day (Figs. 18 and 19).

An attempt was also made to establish a "trend" curve between rear-end collisions and volume. A sample of 109 accidents appears too small to establish statistical significance of the relationship. Nevertheless, a regression line was established for the data representing number of rear-end collisions annually during daylight and the volume at time of accident. This is shown in Figure 20. Three points representing night rear-end collisions under otherwise similar conditions are plotted for comparison. The relationship shown is of necessity dependent on the volume distribution, i.e., the percentage of time a given volume would be

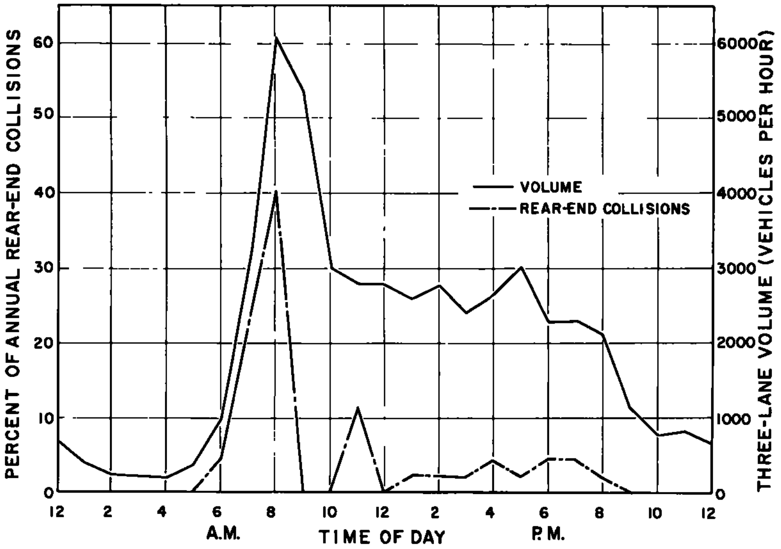

Figure 18. Volume and rear-end collision distribution—John C. Lodge Expressway, southbound (normal weekday traffic, dry pavement, June 1957).

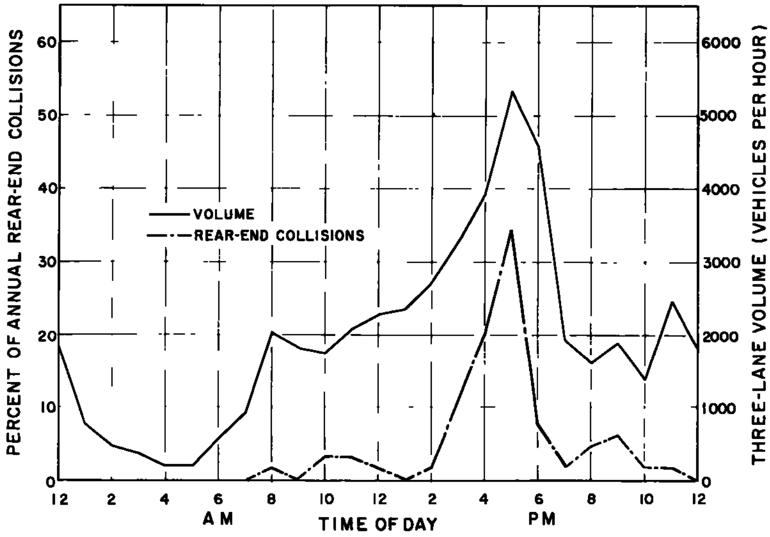

Figure 19. Volume and rear-end collision distribution—John C. Lodge Expressway, northbound (normal weekday traffic, dry pavement, June 1957).

expected. This distribution is also plotted on the same figure. Using previously established relationships between volume and mean velocity, rear-end collisions could be readily plotted as a function of mean velocity.

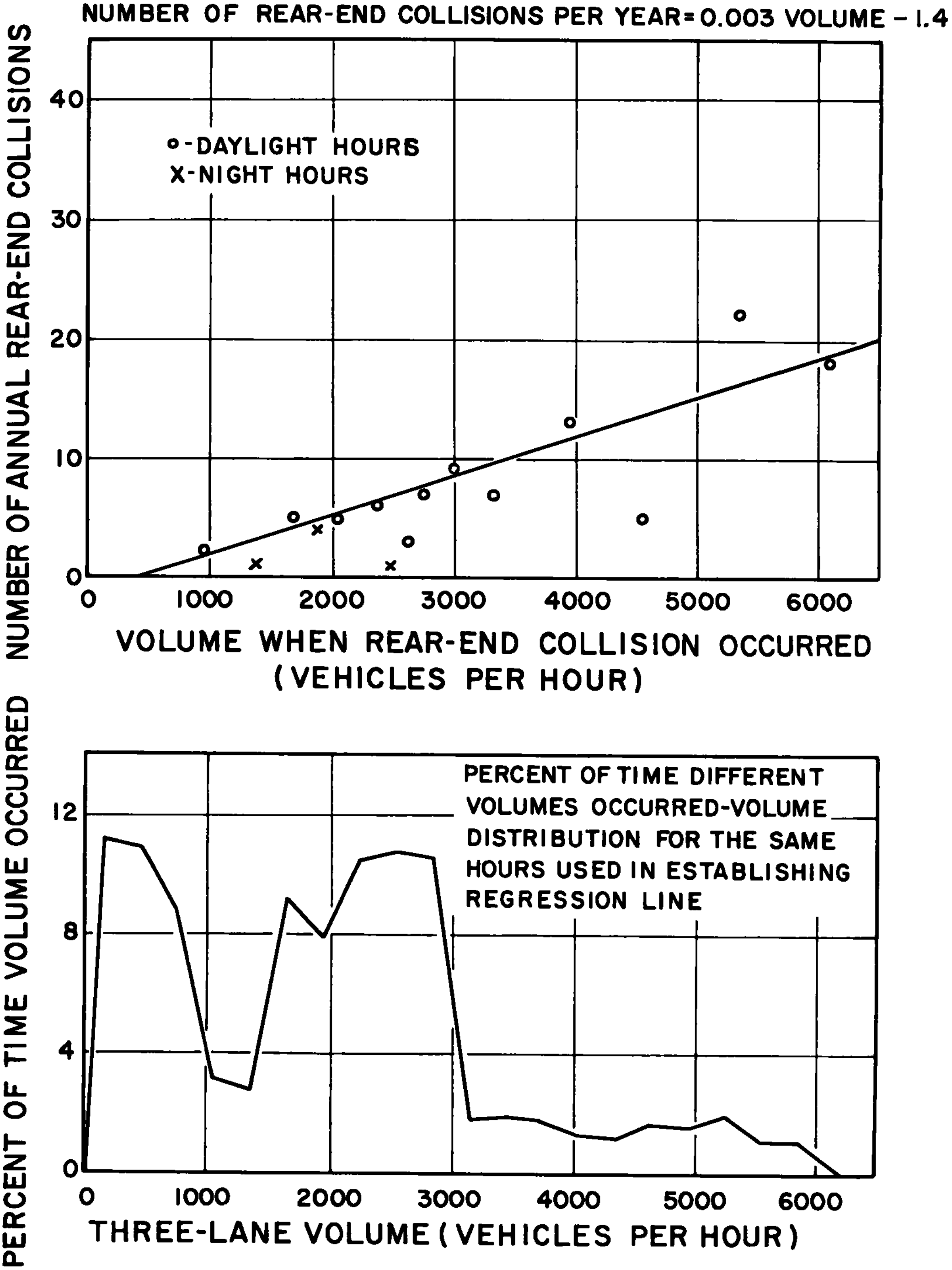

Figure 20. Rear-end collisions vs volume when collision occurred—John C. Lodge Expressway (normal weekday traffic, dry pavement, June 1957).

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Traffic Behavior and On-Ramp Design

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Three ramp terminal designs were painted successively at one on-ramp location. The first sequence of observations was made with the ramp curb encroaching on the shoulder (2 ft from edge of freeway pavement) and a second sequence was observed with the ramp curb offset shoulder width from the freeway pavement (in this case 8 ft), resulting in six separate studies. Speed and placement of vehicles were recorded and movies were taken during each phase. Freeway volume varied from 2,400 to 6,000 vph, while ramp volume varied from 240 to 1,200 vph. Findings include the following:

1. All three designs resulted in similar vehicle paths, because essentially they were all liberal designs and traffic was able to drive a natural path. When the nose was offset, a long gradual taper (50:1) appeared to cause vehicles to use a greater portion of the ramp than a parallel ramp of the same length.
2. Somewhat more length was used at low volumes than at high volumes, except during the 8-ft offset 50:1 taper phase, where the length used was approximately constant for all volumes.
3. Merging distance required at high turning speed is as great as that required at low speed.
4. The natural path of nearly all vehicles is contained within a 50:1 taper, and this design provides sufficient acceleration distance for all turning speeds.

It is concluded that ramp terminal design should be standardized and a tentative standard is offered together with supporting data and reasoning.

●IN CALIFORNIA, where more than 600 traffic interchanges have been constructed, the shape of on-ramp terminals has gone through an evolutionary process through the years. In general, this process has been in the direction of more liberal design to provide greater smoothness in merging operations. There is still discussion, however, as to how liberal the design should be. On one hand is the requirement of liberality as determined through experience to date, and on the other are the limitations of cost and space.

The objective of the present study was to provide a factual background regarding traffic behavior as affected by ramp geometry.

SITE

At the Ashby Avenue Interchange on the Eastshore Freeway (US 40) just across the Bay from San Francisco (Fig. 1), there was an entrance ramp

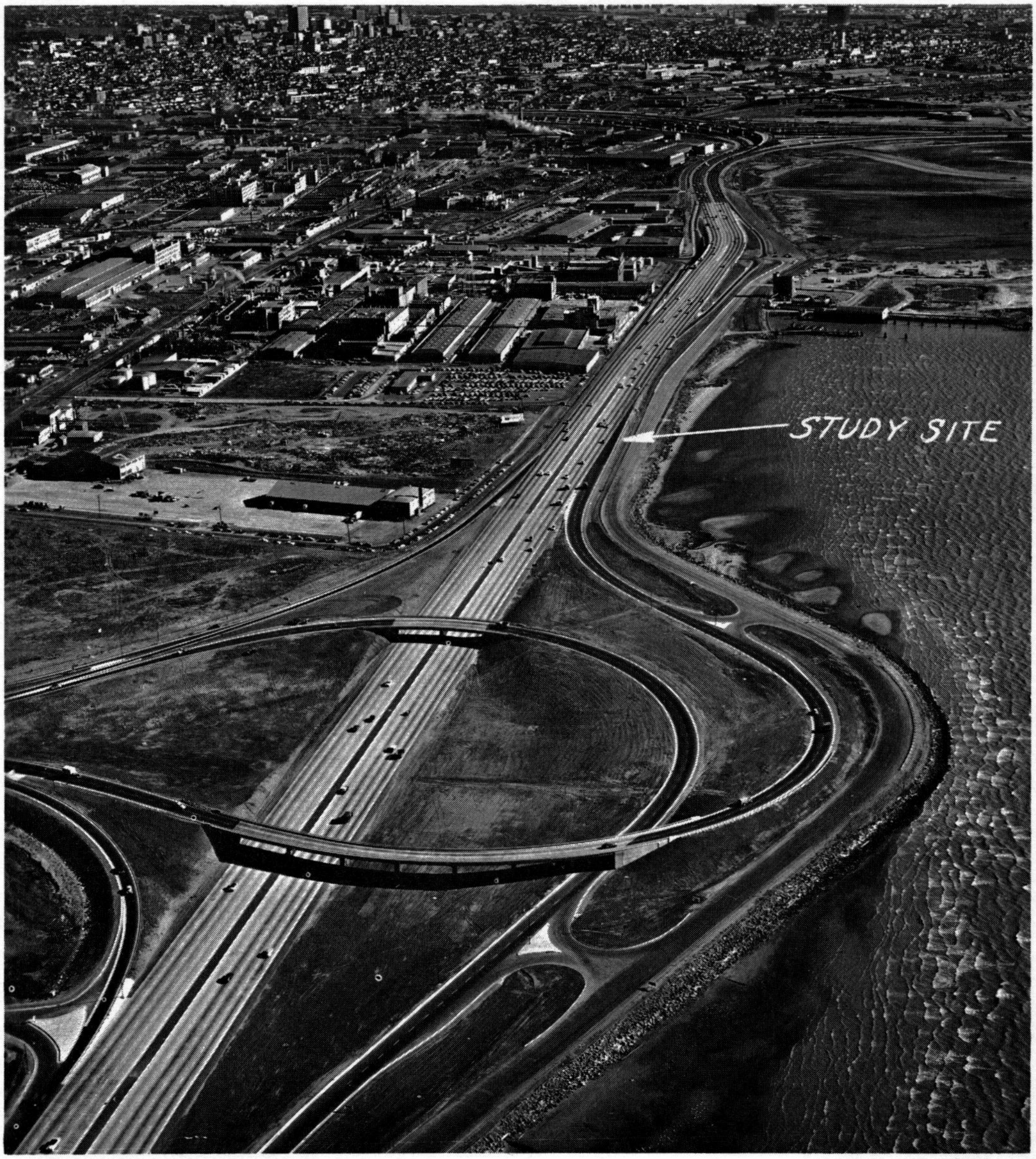

Figure 1. Looking south on Eastshore Freeway. Ashby Avenue Interchange in foreground with study site noted. This picture was taken before studies began and shows a two-lane entrance ramp terminal.

originally designed as a two-lane ramp. This design resulted in a triangular area beyond the ramp nose 840 ft long and 28 ft wide at the nose (Figs. 2, 3 and 4). This unusual paved area provided an opportunity for testing several different shapes of ramp terminal while other variables remained constant. The freeway is level tangent and has 4 lanes in each direction.

It would have been desirable, for study purposes, to select a loca-

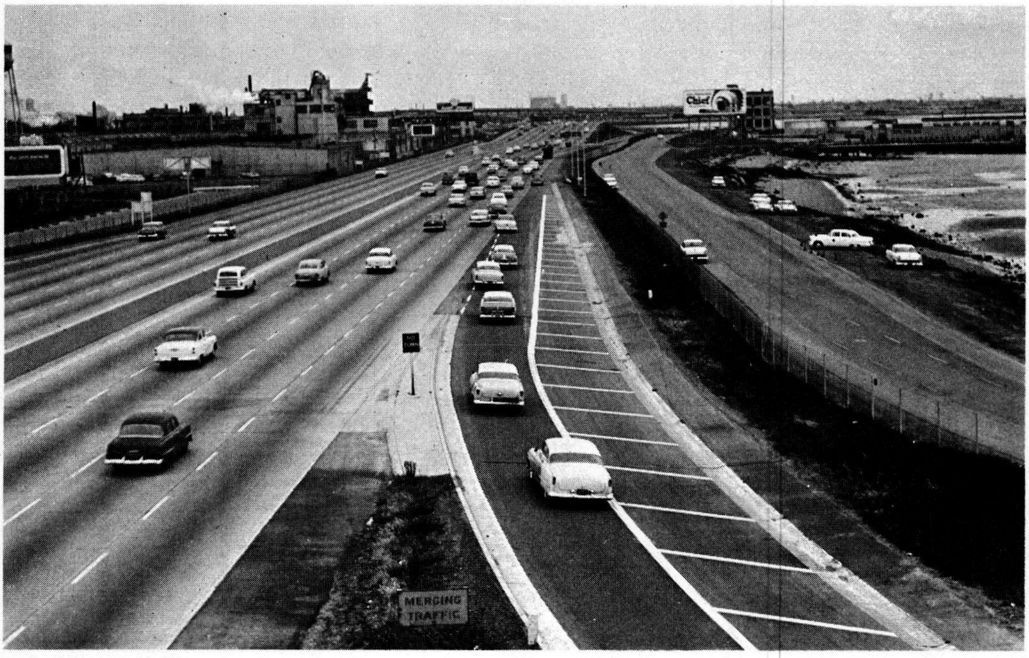

Figure 2. Test site with ramp curb encroaching on shoulder (2 ft from edge of freeway pavement).

Figure 3. Test site with ramp curb offset shoulder width (in this case 8 ft from freeway pavement).

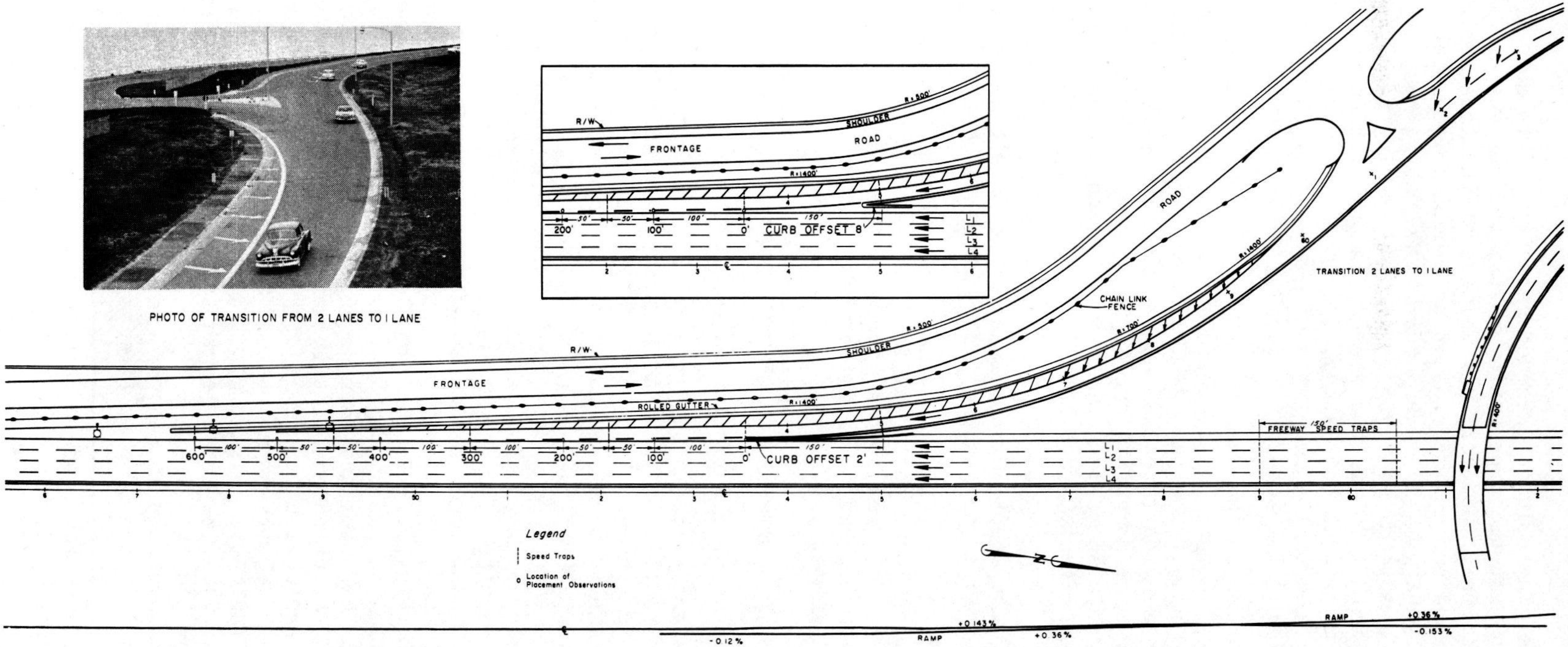

Figure 4. Diagram of test site—southbound Ashby Avenue on-ramp on Eastshore Freeway.

tion where merging volumes exceeded capacity. Some such locations exist in California, but the opportunity to try various shapes does not occur at these locations. However, the volumes at the location selected are substantial, and the maximums observed exceed commonly accepted values for "practical capacity." The peak hour volume on the ramp is 900, merging with 4,800 for a total of 5,700 vph in the morning peak, and 800 on the ramp merging with 3,000 on the freeway in the evening peak. During the peak hours observed in this study, the hourly rate on the four lanes going away from the end of the merging area exceeded 5,800 vph for about 30 min out of the hour. The total includes 7.7 percent trucks.

The vehicles on the ramp do not come at random intervals (as they do on the freeway) because of signal controls on the street system about 4,000 ft before the nose. The ramp vehicles, which come in platoons, make the instantaneous merging rate much higher than the 5-min volumes indicated and result in some momentary congestion. However, these momentary accordions last such a short length of time that no backup occurs and the average speed is affected very little.

The speed of on-ramp vehicles is controlled by a 700-ft radius curve, which is good for about 50 mph; in other words, it can be assumed that the distance required after passing the nose is needed for merging and not for acceleration.

Observations were spaced at least one week apart to permit the traffic to become accustomed to the geometric changes. The location and method of study were chosen to minimize the effect of variables other than ramp terminal geometry.

DESCRIPTION OF RAMP SHAPES STUDIED

The sequence of observation was as follows:

1. One-lane 50:1 (in this report, a ramp terminal described by a ratio such as "50:1" is a constantly tapering area, with the ratio representing the cotangent of the angle of convergence between the outer edge of the ramp terminal and the pavement edge of the freeway) on-ramp with lane stripe on left and a painted hatched area on right (Fig. 5). The right-hand edge tapers from 18 ft at the curb nose of the on-ramp to 8 ft in a distance of 500 ft. An imaginary projection of this right-hand edge would go another 400 ft, making a total of 900, to an intersection with the right-hand edge of the through lane.
2. One-lane parallel on-ramp with lane stripe on left and hatched area on right (Fig. 6). In the parallel ramp, the right-hand edge was carried parallel to the through pavement, and 12 ft wide, up to a point 500 ft beyond the nose, and then squeezed off on a 30:1 (rolled gutter) taper for 120 ft, at which point it was 8 ft from the through pavement. An imaginary projection of the right-hand edge would intersect the pavement in another 240 ft, or a total of 860 ft from the nose.
3. One-lane 30:1 on-ramp with lane stripe on left and hatched area on right (Fig. 7). The total length to the imaginary intersection of the right edge was 540 ft.
4. The above ramp shapes were repeated with the ramp curb reconstructed at a distance of 8 ft (freeway shoulder width) from the edge of the through traffic lanes, resulting in six separate studies. Reconstructing the curb moved the curb nose back 130 ft as shown in the inserts in Figures 4, 5, 6 and 7.

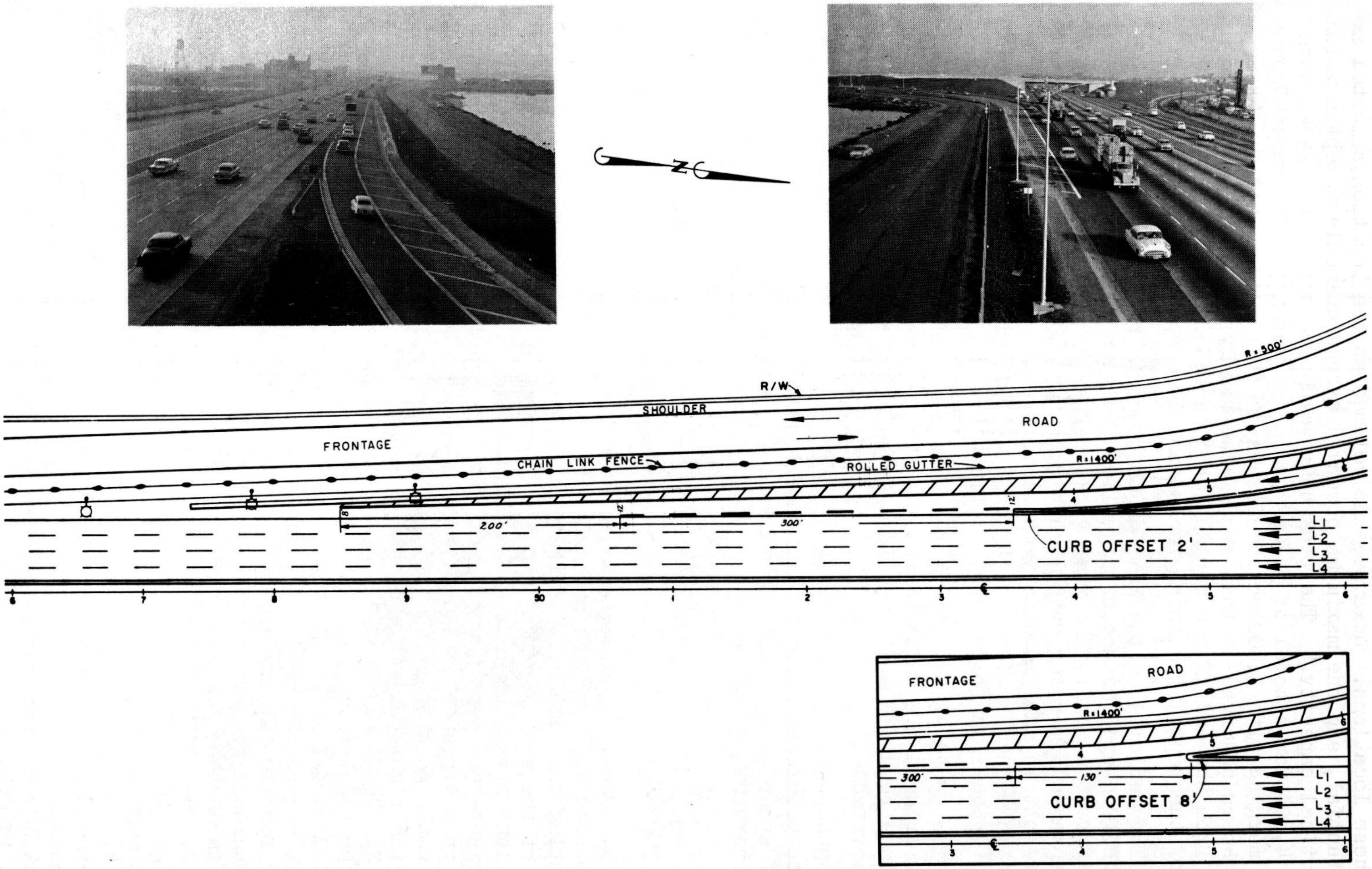

Figure 5. Plan—50:1 tapered on-ramp.

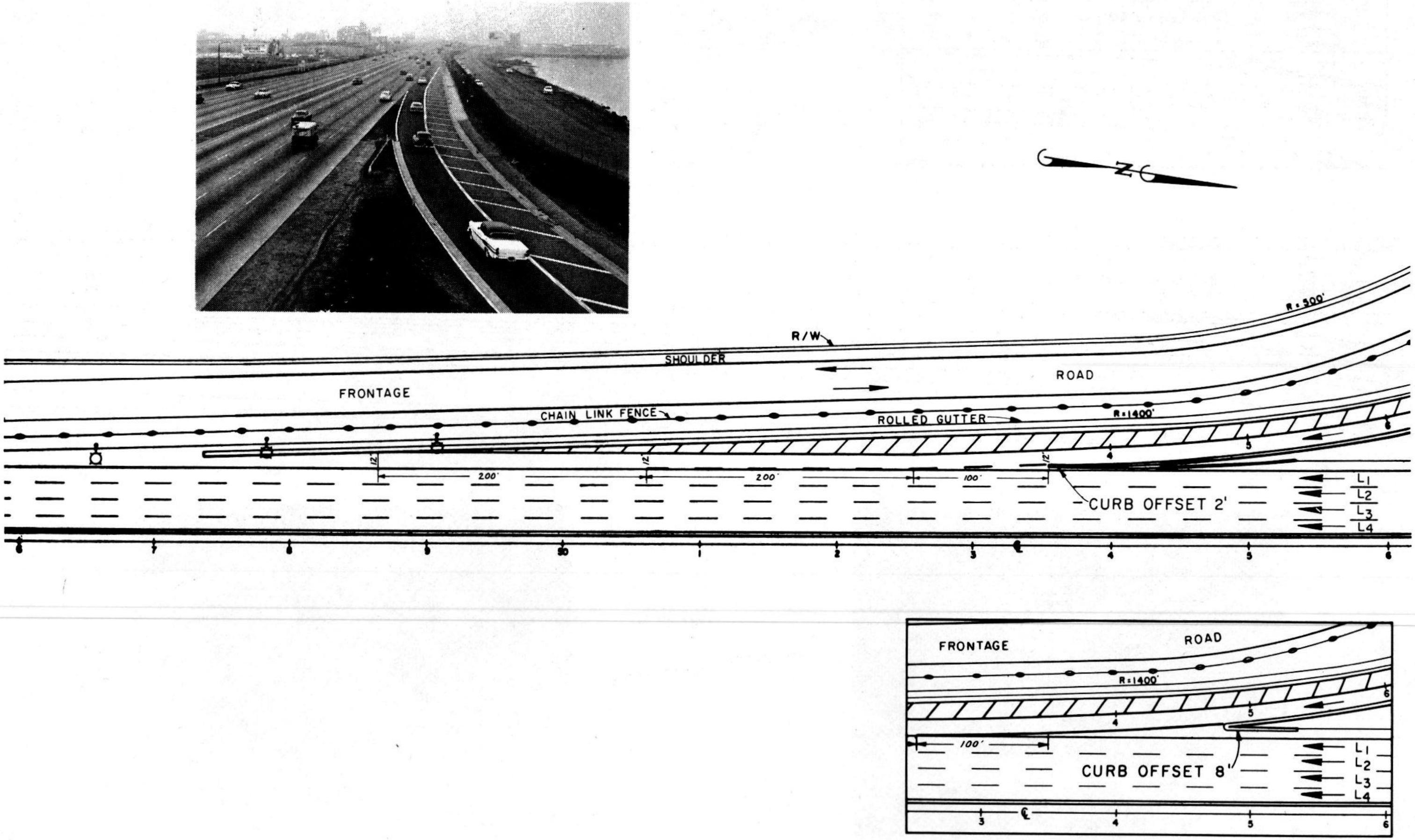

Figure 6. Plan—parallel on-ramp.

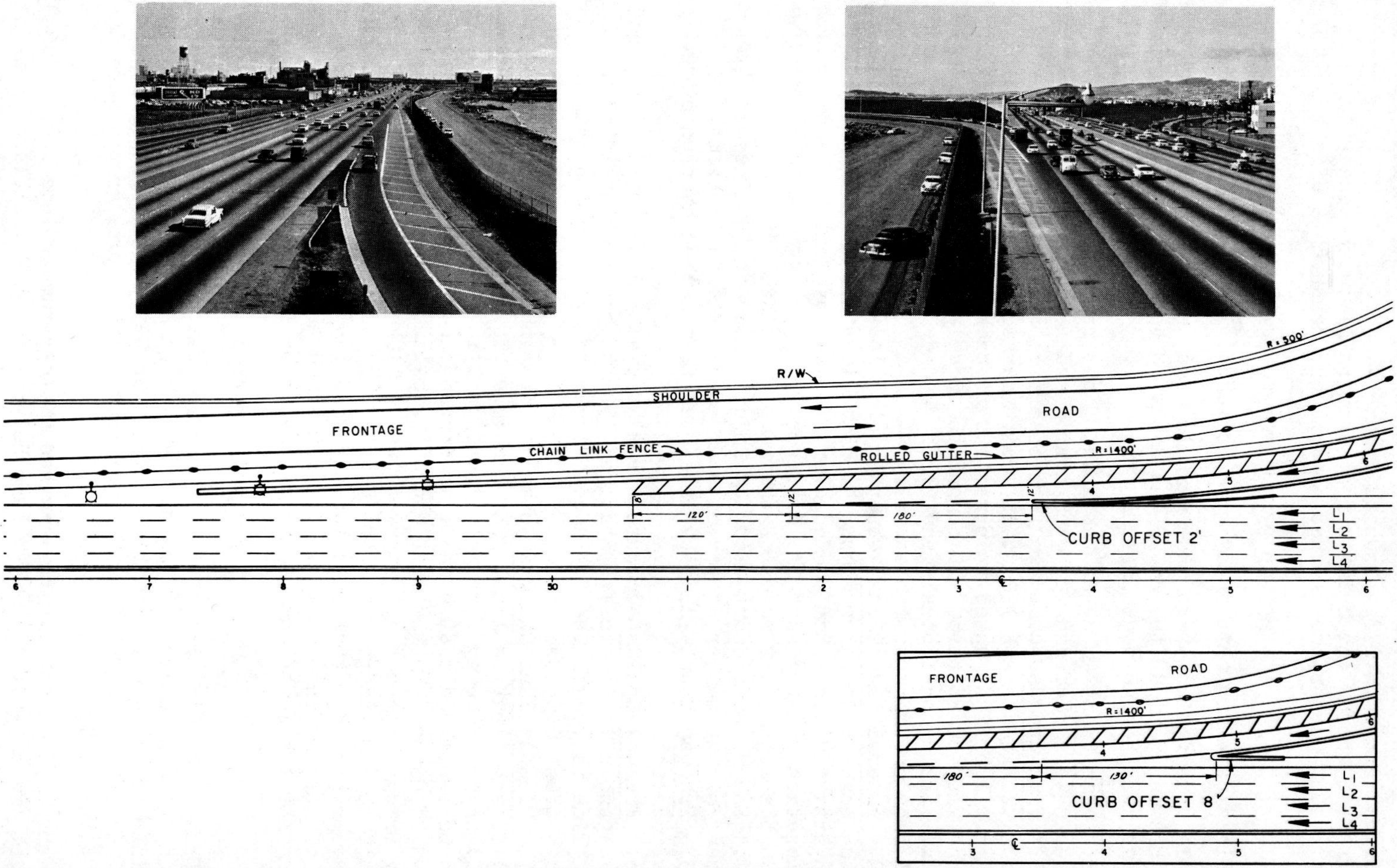

Figure 7. Plan—30:1 tapered on-ramp.

The transition from 2 lanes to 1 and the delineation of the various sequences in the study were by means of white traffic paint. The transition from 2 lanes to 1 is shown in Figure 4.

Traffic obeyed the paint almost universally. The exceptional car that traveled across the hatched area had no measurable effect on the data.

METHOD OF COLLECTING DATA

Field data for this study were collected in the following manner:

All observations were made manually and based on 5-min counts with 2 min between periods to record the data. Observers were located on the frontage road behind a chain link fence.

1. Ramp Count—made at the nose of the ramp. The number of autos and trucks were recorded for each period and each break between periods.
2. Ramp Speeds—computed from observations with stop watches and 5 consecutive speed traps 150 ft in length marked with road tubes across the ramp. The first speed trap was 150 ft back of the ramp nose and the last one was 450 ft to 600 ft beyond the nose as shown on Figure 4. Samples were taken continuously and times recorded for sample vehicles to travel from one mark to the other.
3. Lateral Placements—observed at 5 locations at 100-ft intervals from the nose as shown on Figure 4. Each location was marked by 5 lines 1 ft apart, starting from the edge of freeway pavement. One man observed each location and recorded the distance from the edge of the freeway pavement to the right rear wheel of the ramp vehicles.
4. End of Ramp Count—made at location 600 ft from nose. Counts were made of the number of vehicles in Lane 1 and on the ramp.
5. Freeway Count—made by lanes before the merging area of the acceleration lane.
6. Freeway Speeds—computed from stopwatch observations of speed traps as shown in Figure 4. Stations 150 ft apart were painted in each lane. Time to travel the distance between the two stations was estimated to the nearest 0.05 sec.
7. Freeway Lane Changes—observed from the location of freeway count to end of acceleration lane. The lane changes made by traffic that was already on the freeway were not significant in the study. However, it should be mentioned that a major interchange having a 3-lane branch connection to Oakland on the left and a three-lane branch to the San Francisco Bay Bridge on the right was located 1¼ mi beyond the observation site. For this reason, there was a noticeable tendency for many of the ramp cars to weave right on across into Lanes 2 or 3 (and occasionally Lane 4) instead of merging into Lane 1. It is assumed that most of these cars were heading for the left-hand branch of the major interchange.

ANALYSIS OF DATA

Due to the wide range of ramp and freeway volumes during the study of each on-ramp design, it was necessary to classify placement and speed data into volume groups so that comparisons between the three designs could be made for equal volume conditions. The volume groups were divided as given in Table 1.

Thus a group labeled R1 - F2 has a 5-min ramp volume between 20-39 vehicles and a 5-min freeway volume between 200-299 vehicles. Freeway volume distribution by lane is given for all volume groups in Table 2.

TABLE 1

VOLUME GROUP CLASSIFICATION

Ramp Group	5-Min Volume	Hourly Rate	Freeway Group	5-Min Volume	Hourly Rate	Hourly Rate in Lane 1[a]
R 1	20-39	240-479	F 1	100-199	1,200-2,400	190-380
R 2	40-59	480-719	F 2	200-299	2,400-3,600	380-580
R 3	60-79	720-959	F 3	300-399	3,600-4,800	580-770
R 4	80-100	960+	F 4	400-500	4,800-6,000	770-960

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[a] Hourly rate in Lane 1 based on 16 percent of freeway volume (see Table 2). This volume does not include ramp vehicles.

TABLE 2

DISTRIBUTION BY LANE AT APPROACH TO ON-RAMP MERGING AREA

Volume Group	Ramp Design	Lane 1		Lane 2		Lane 3		Lane 4	
		2-ft Curb Offset (%)	8-ft Curb Offset (%)	2-ft Curb Offset (%)	8-ft Curb Offset (%)	2-ft Curb Offset (%)	8-ft Curb Offset (%)	2-ft Curb Offset (%)	8-ft Curb Offset (%)
R1-F1	50:1	19.1	17.0	26.0	26.7	31.8	31.4	23.1	24.9
	Parallel	19.1	17.9	27.4	25.6	30.7	30.4	22.8	26.1
	30:1	16.0	14.8	29.7	27.9	32.5	32.1	21.8	25.2
R1-F2	50:1	16.5	16.0	24.2	23.9	31.9	31.6	27.4	28.5
	Parallel	17.1	x	23.1	x	31.1	x	28.7	x
	30:1	12.6	17.0	25.2	23.5	29.7	31.3	32.5	28.2
R2-F1	50:1	17.6	15.6	25.6	25.8	31.9	32.4	24.9	26.2
	Parallel	16.1	16.0	25.0	25.8	31.8	30.7	27.1	27.5
	30:1	16.2	14.6	28.8	24.9	30.8	33.2	24.2	27.3
R2-F2	50:1	15.8	14.8	25.3	25.4	29.9	30.2	29.0	29.6
	Parallel	16.6	14.9	25.4	24.2	30.5	31.0	27.6	29.9
	30:1	15.1	15.2	25.1	24.2	31.6	31.2	28.0	29.4
R2-F3	50:1	15.7	15.4	26.6	22.2	29.1	28.7	29.6	33.7
	Parallel	15.0	15.2	24.0	26.5	30.4	30.2	30.6	28.1
	30:1	15.5	x	23.9	x	30.0	x	30.6	x
R3-F2	50:1	15.1	15.5	24.4	23.9	30.6	29.9	29.9	30.7
	Parallel	14.5	14.1	26.1	24.1	30.2	31.0	29.2	30.8
	30:1	16.7	16.4	24.8	21.8	30.1	28.7	28.4	33.1
R3-F3	50:1	15.8	15.7	24.8	23.3	29.3	29.7	30.1	31.3
	Parallel	16.0	14.8	22.1	24.0	29.4	28.2	32.5	33.0
	30:1	16.7	15.0	24.1	24.2	28.4	28.9	30.8	31.9
R3-F4	50:1	15.6	14.6	24.7	23.0	29.0	27.9	30.7	34.5
	Parallel	14.8	13.2	24.5	22.2	28.4	30.7	32.3	33.9
	30:1	15.7	14.7	24.1	22.6	28.4	27.8	31.8	34.9
R4-F2	50:1	15.1	13.6	24.4	29.1	30.6	30.1	29.9	27.2
	Parallel	13.1	13.8	25.3	22.2	33.2	30.0	28.4	34.0
	30:1	16.7	14.1	24.8	25.9	30.1	28.7	28.4	31.3
R4-F3	50:1	15.7	14.8	25.1	24.0	28.9	28.6	30.3	32.6
	Parallel	16.4	16.7	24.4	23.3	29.1	28.4	30.1	31.6
	30:1	16.3	13.8	24.3	22.8	24.7	29.7	32.0	33.7
R4-F4	50:1	15.6	16.4	24.0	22.3	28.3	29.0	32.1	32.3
	Parallel	15.9	14.6	21.5	22.9	30.8	29.1	31.8	33.4
	30:1	16.0	13.4	22.8	22.9	29.0	29.6	32.2	34.1

NOTE: x indicates insufficient data.

TABLE 3

NUMBER OF RAMP VEHICLES OBSERVED IN EACH VOLUME GROUP

		One-Way Freeway Volume Rate Prior to Ramp (vph)							
		F1 1,200-2,400		F2 2,400-3,600		F3 3,600-4,800		F4 4,800-6,000	
Ramp Volume Rate (vph)	Ramp Design	2-ft Curb Offset	8-ft Curb Offset	2-ft Curb Offset	8-ft Curb Offset	2-ft Curb Offset	8-ft Curb Offset	2-ft Curb Offset	8-ft Curb Offset
R1	50:1	210	335	39	206	x	x	x	x
240-480	Parallel	172	315	71	x	x	x	x	x
	30:1	132	333	39	108	x	x	x	x
R2	50:1	360	227	450	768	210	105	x	59
480-720	Parallel	279	460	321	769	160	57	56	114
	30:1	497	223	551	869	158	x	99	57
R3	50:1	x	x	341	345	767	330	405	432
720-960	Parallel	x	x	265	384	280	423	206	70
	30:1	x	x	340	263	492	608	294	212
R4	50:1	x	x	x	101	259	437	184	84
960-1,200	Parallel	x	x	186	92	82	90	264	806
	30:1	x	x	199	172	254	348	514	520

NOTE: x indicates insufficient data.

It is to be noted that the distribution for the various ramp designs is very similar and can be minimized as a variable affecting the study.

In this study, some combinations of volume groups were eliminated due to insufficient data. The groups used in the analysis and the number of observations in each group are given in Table 3.

RESULTS

Placement

Paths of the right rear wheels of observed vehicles are shown in Figures 8, 9 and 10 for the 2-ft curb offset studies and Figures 12, 13 and 14 for the 8-ft curb offset studies. The diagrams on these figures are drawn on a scale that exaggerates the lateral distance in a ratio of 5 to 1 as compared with the longitudinal distance. Each figure represents one ramp terminal shape, and the four diagrams on each figure represent the four ramp-volume groups, with the lowest ramp-volume at the top.

1. It will be noted that the variation in wheel paths for changing freeway volumes with any given ramp volume is small. This fact does not necessarily show that freeway volume is unimportant in determining ramp length, but it does suggest that when adequate length is available, it will be used during light volumes as much as during heavy volumes.

Because the paths for varying freeway volumes were similar, two additional drawings were made (Figs. 11 and 15) in which freeway volumes were combined for any given ramp volume. On these diagrams it is easier to see the relationship between the paths as affected by geometry.

2. An unexpected result was to find that as the ramp volume increased, the length of ramp used decreased.

With the 2-ft curb offset, the 85th percentile did not change much but the 50th percentile decreased from about 390 ft to about 300 ft as the ramp volume increased from less than 480 vph to more than 960 vph. With the 8-ft curb offset and the 50:1 design, the 50th percentile decreased from about 480 ft to about 420 ft through this volume range and with the parallel and 30:1 designs, the 50th percentile decreased from about 430 ft to 300 ft. During the high ramp volumes, the freeway volumes were also higher.

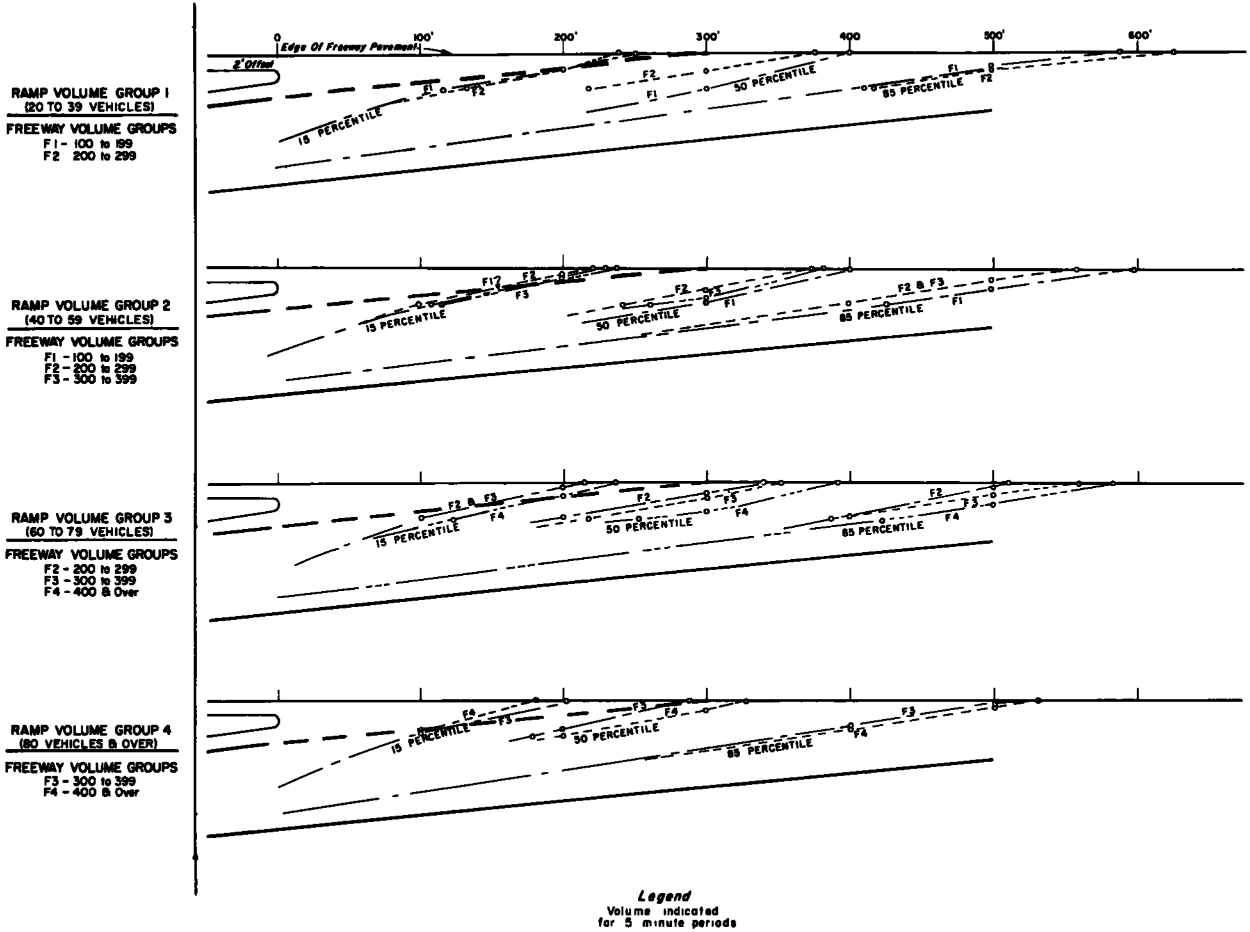


Figure 8. Right rear wheel path of 15, 50 & 85 percentile vehicles—50:1 tapered on-ramp (curb offset 2 ft).

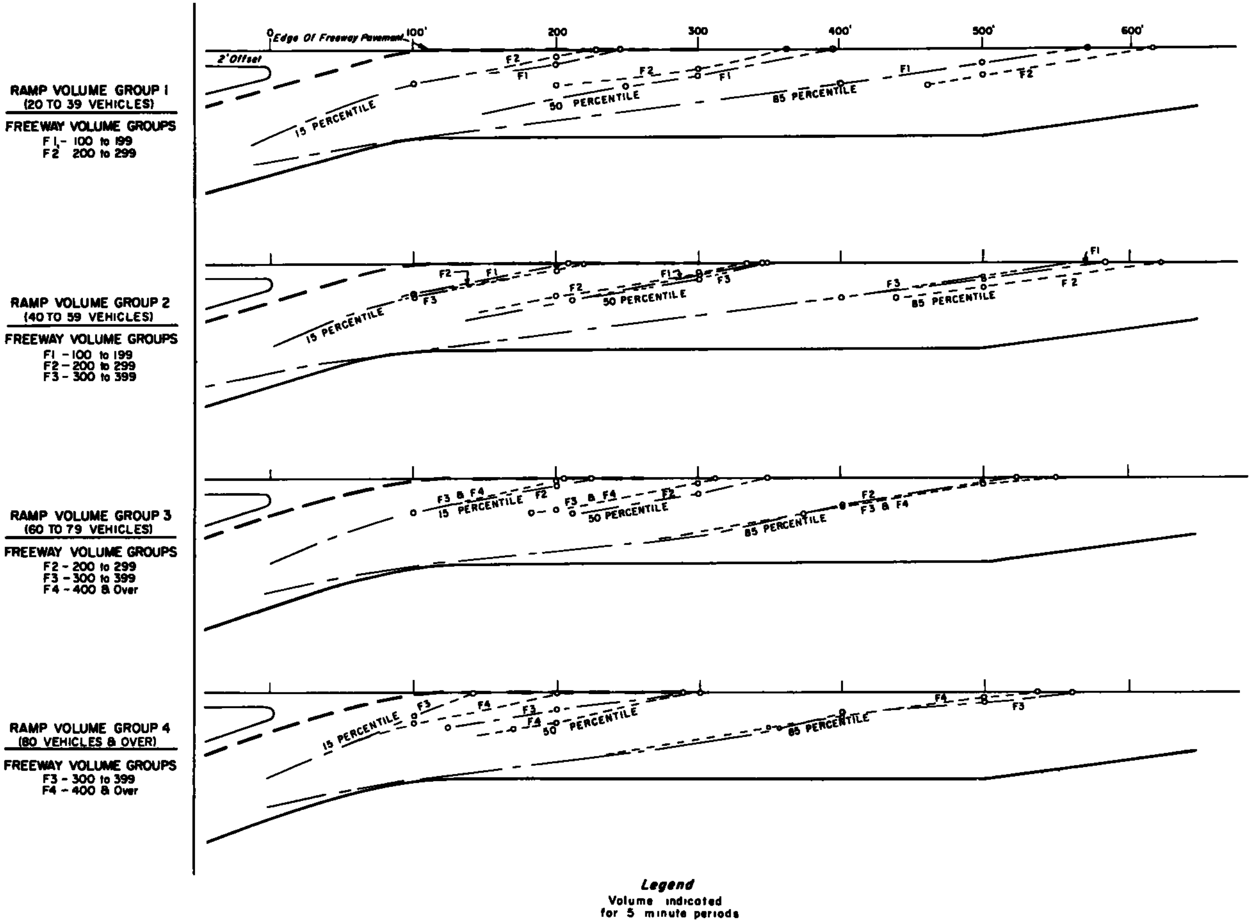


Figure 9. Right rear wheel path of 15, 50 & 85 percentile vehicles—parallel on-ramp (curb offset 2 ft).

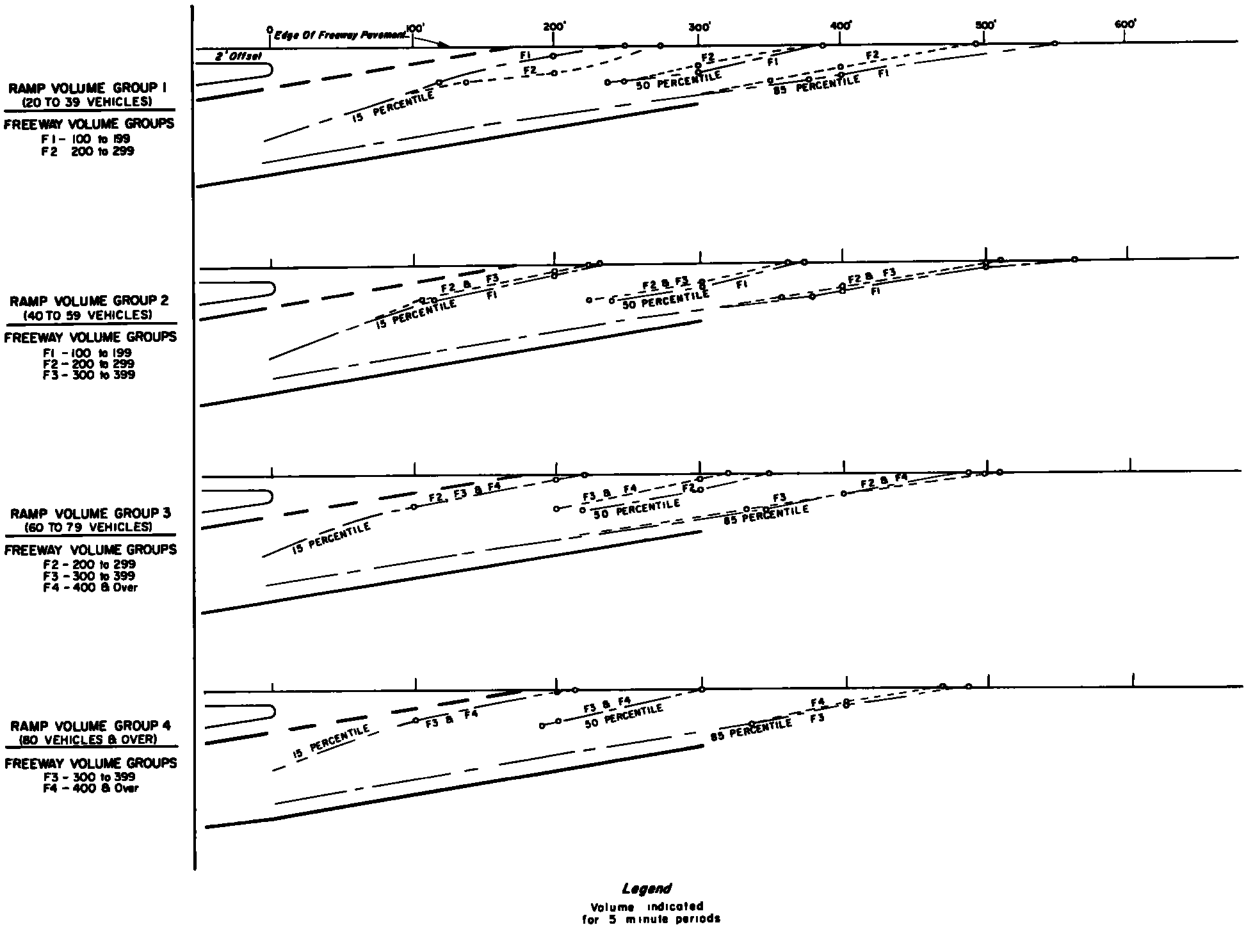


Figure 10. Right rear wheel path of 15, 50 & 85 percentile vehicles—30:1 tapered on-ramp (curb offset 2 ft).

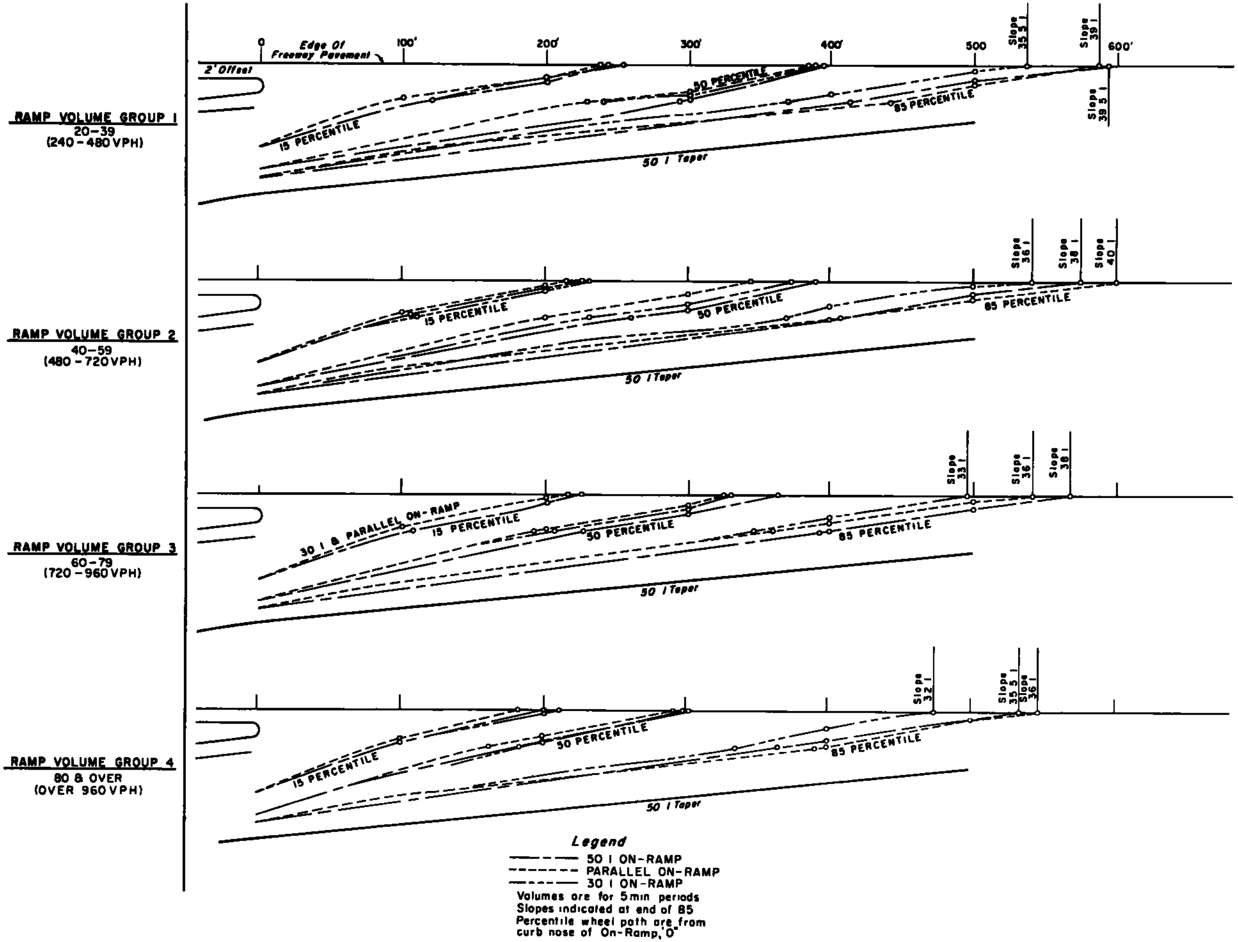


Figure 11. Right rear wheel path of 15, 50 & 85 percentile vehicles—various on-ramps (curb offset 2 ft).

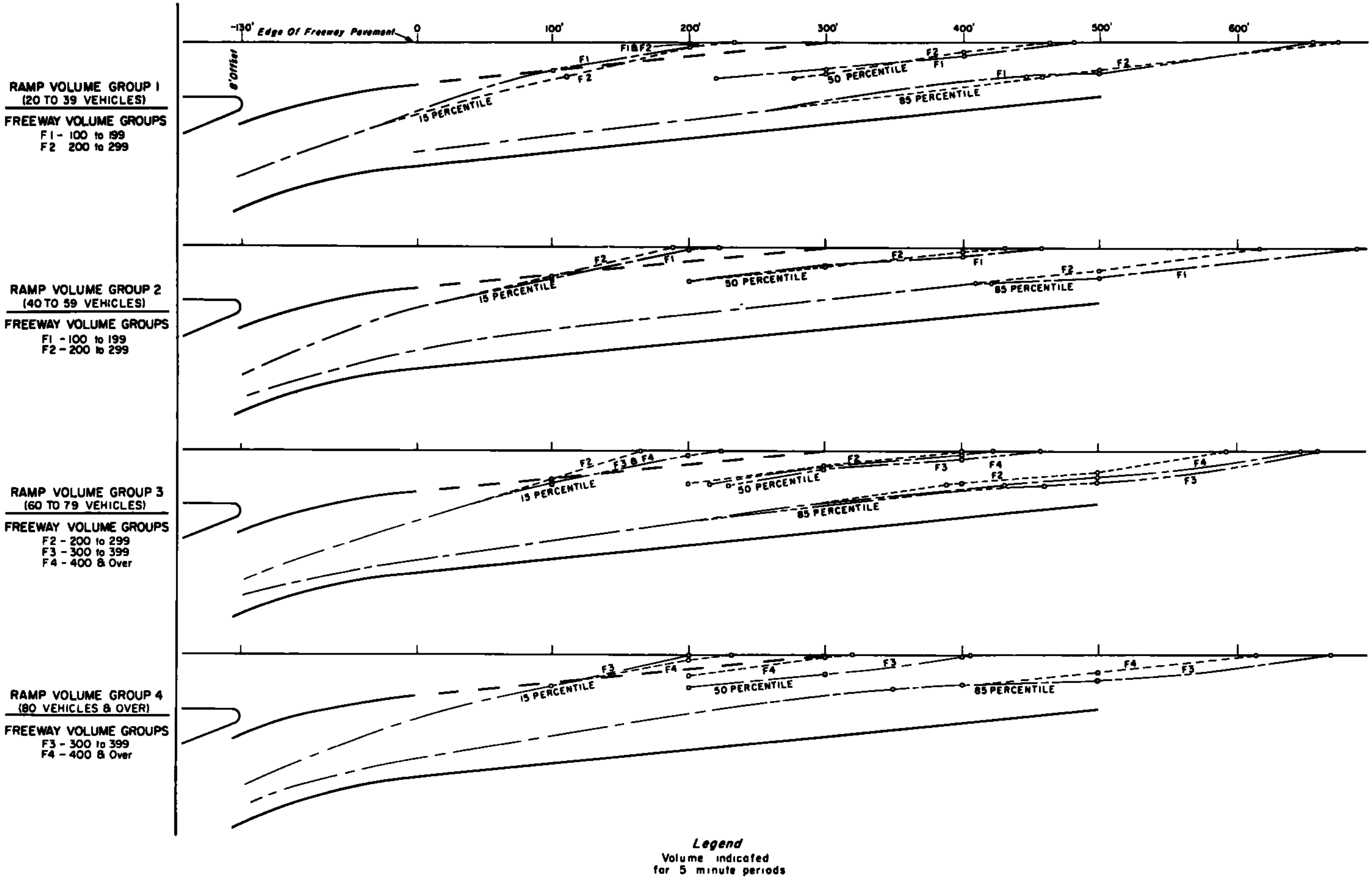


Figure 12. Right rear wheel path of 15, 50 & 85 percentile vehicles—50:1 tapered on-ramp (curb offset 8 ft).

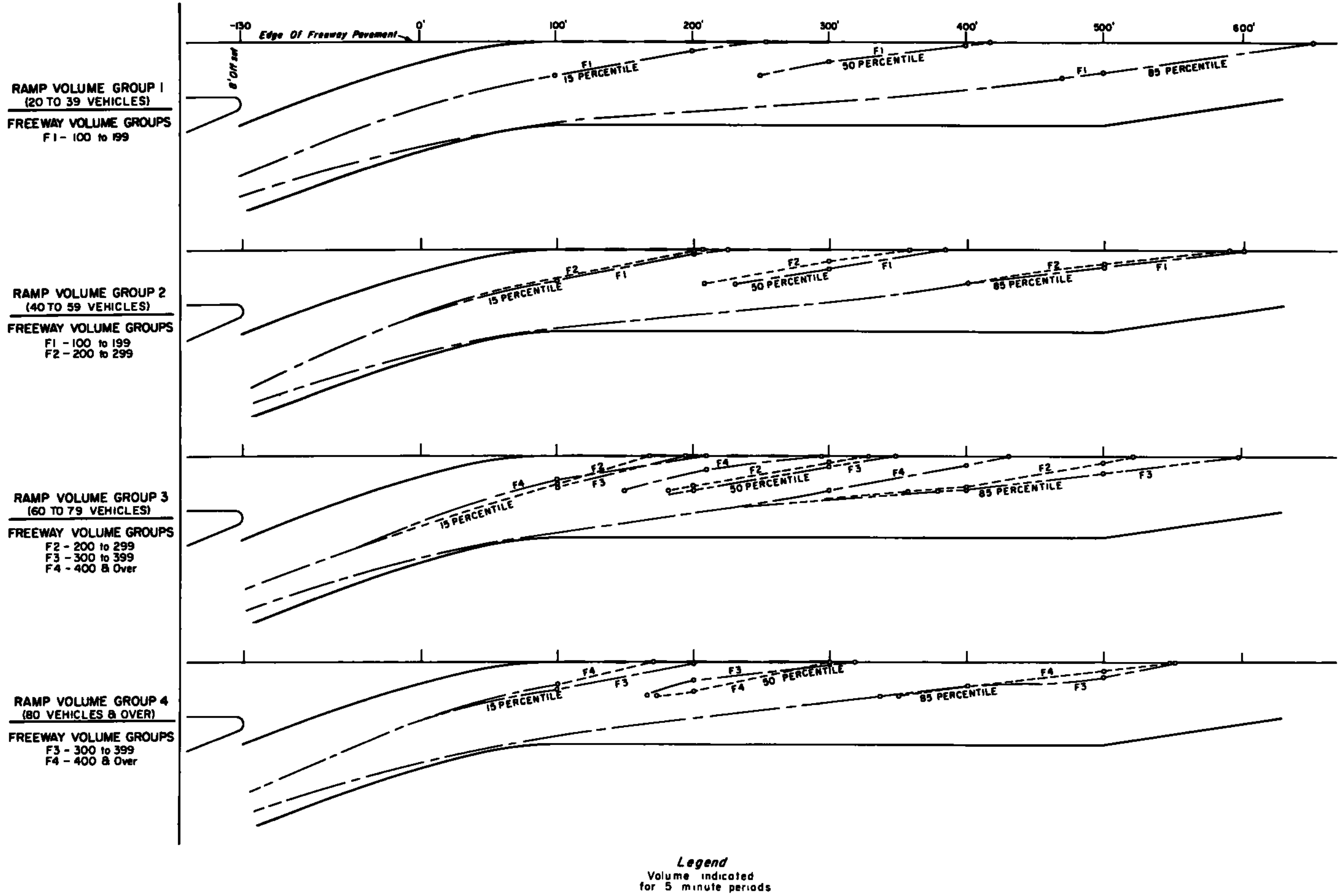


Figure 13. Right rear wheel path of 15, 50 & 85 percentile vehicles—parallel on-ramp (curb offset 8 ft).

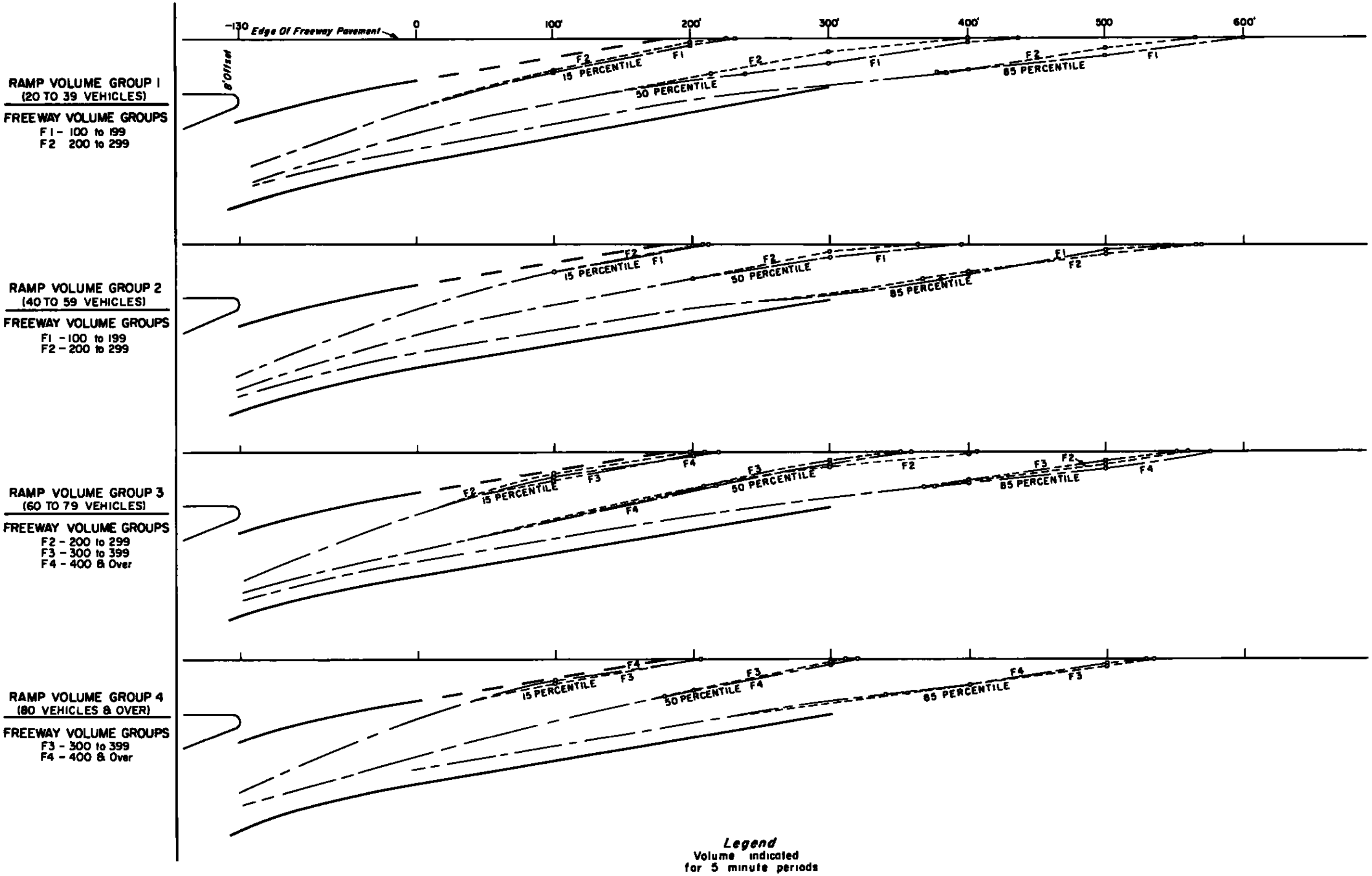


Figure 14. Right rear wheel path of 15, 50 & 85 percentile vehicles—30:1 tapered on-ramp (curb offset 8 ft).

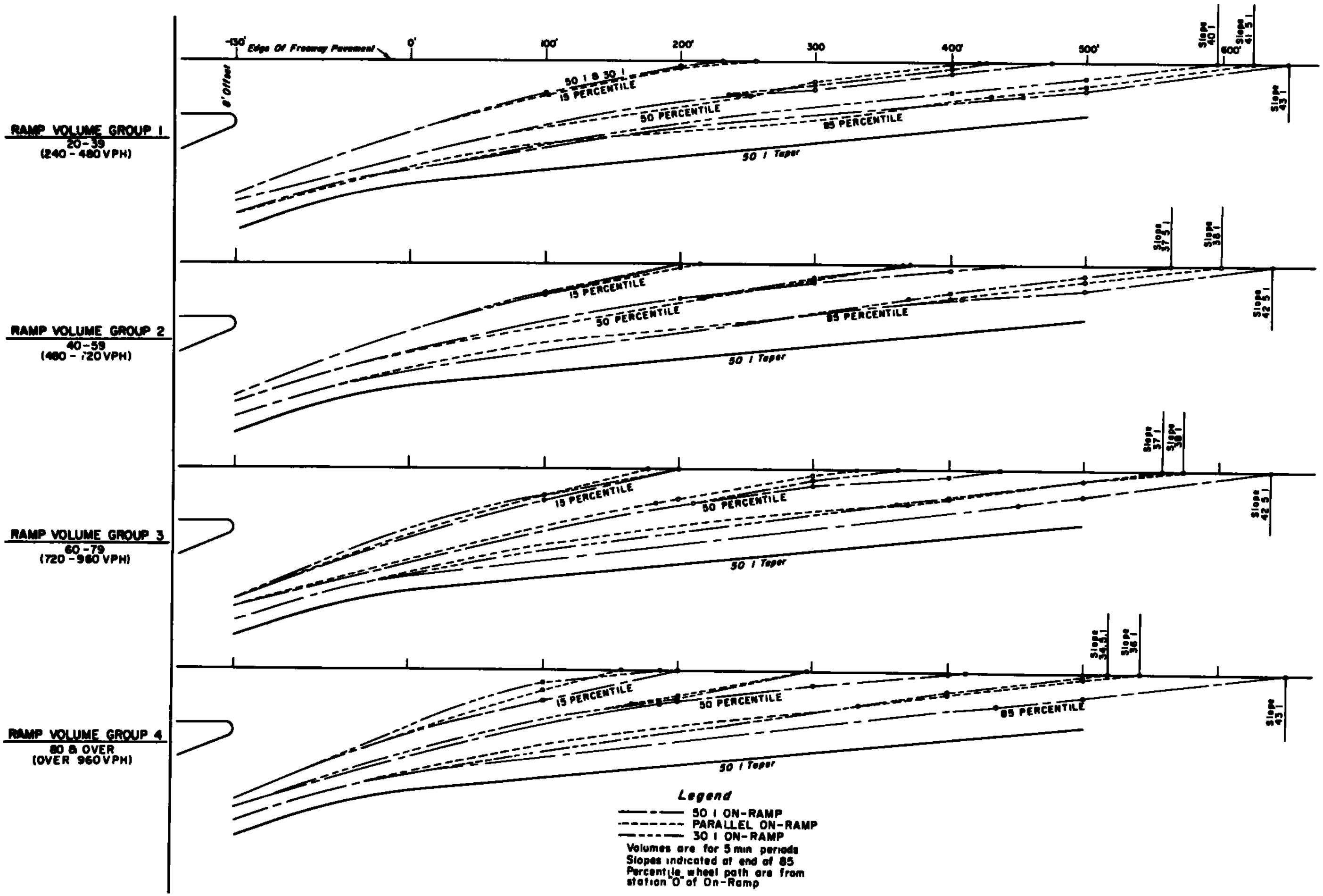


Figure 15. Right rear wheel path of 15, 50 & 85 percentile vehicles—various on-ramps (curb offset 8 ft).

This result (decreased distance with increased volume) was not expected. However, it is easy to explain and should have been expected. It is simply because more cars come on simultaneously when volume is high, and while the car (or truck) at the head of the platoon behaves very much like the ones at the head of the line during the low-volume periods, there are more "following" cars that are anxious to get into the main stream in the same gap as the lead car than there are during low-volume periods.

3. Wheel paths were similar for all designs except the 50:1 design with an 8-ft curb offset, which resulted in a more gradual path at high ramp volumes than the other designs.

In retrospect, it is not hard to see why this result was observed. It is because all designs studied actually provided ample room, especially if the 8-ft paved shoulder continuing beyond the end of the taper was used, as it was used by more than 15 percent of the vehicles in the 30:1 study. The 50:1 and "parallel" shapes, as pointed out in the introduction, actually were within 40 ft of being the same length. When the study was being planned, however, the lack of variability was not foreseen. It was thought, instead, that drivers would be influenced by the shape. This thought was based on the common knowledge that ramps of many shapes are working fairly well, and it was assumed that drivers comform to what is provided. The important finding here is that they tend to drive one way regardless of ramp shape, within the limits, of course, of what is available to drive on.

It would, of course, be possible to think of endless combinations of geometry and try them with many combinations of ramp and freeway volumes and also with several different turning speeds. It would not be prudent, however, to experiment with public traffic on a design more restrictive than the 30:1 study. Despite the lack of variation between the three designs, some principles have been evolved which will be discussed later.

4. For the low ramp volumes, the 85th percentile calls for a merging distance of about 600 ft from the point where the left edge of the ramp is 6 ft from the edge of the freeway to the point where the right wheels enter the through lane. Because the right-hand edge of the ramp is 18 ft away at the beginning and can be assumed to be 3 ft away from the right wheel at the point where the right wheel enters the freeway, this represents a taper of 15 ft in 600, or 40:1. At higher ramp volumes, the distance for the 85th percentile was slightly reduced, but this is mainly because at the higher volumes, the vehicles using more than 600 ft comprised a smaller percentage of the total.

Unfortunately, the free-running vehicles (as opposed to those caught in platoons) were not identified during the study so it is not possible to make a quantitative statement about free-choice paths. However, observation in the field, confirmed by study of the movies, showed that the vehicles caught in a platoon felt obliged to sidle on over into the freeway at an earlier location than did the vehicles at the head of a platoon or those running by themselves.

5. The percentile paths, as plotted, indicate that vehicles drive nearly a straight line instead of zigzagging. It was observed in the field and is demonstrated in the movies that this is the case, although it must be pointed out that it would have been possible for them to zigzag and still the lines connecting equal percentiles could have come out straight. With five observation stations, however, it would be extremely unlikely that a straight line for a given percentile could be drawn through more than two stations if many of the individual cars comprising that percentile zigzagged.

AVERAGE VEHICLE SPEED ALONG RAMP (Miles Per Hour)

E

Ramp Vol Group	Fwy Vol Group F1	F2	F3	F4
R1	44			
R2	37	42		
R3		39	35	28
R4			34	

D

Ramp Vol Group	Fwy Vol Group F1	F2	F3	F4
R1	41	42		
R2	38	40	34	
R3		36	36	32
R4			33	34

C

Ramp Vol Group	Fwy Vol Group F1	F2	F3	F4
R1	43	42		
R2	41	42	39	
R3		40	38	38
R4			38	39

B

Ramp Vol Group	Fwy Vol Group F1	F2	F3	F4
R1	44	43		
R2	43	43	43	
R3		42	40	40
R4			38	39

A

Ramp Vol Group	Fwy. Vol Group F1	F2	F3	F4
R1	45	41		
R2	45	46	44	
R3		45	42	42
R4			38	39

AVERAGE VEHICLE SPEED ENTERING FREEWAY AT VARIOUS LOCATIONS (Miles Per Hour)

Ramp Vol Group				
R1	41			
R2	38	39	33	
R3		35	36	33
R4			33	38

Ramp Vol Group				
R1	44			
R2	41	43	39	
R3		40	36	39
R4			38	39

Ramp Vol Group				
R1	45	43		
R2	43	44	46	
R3		41	41	40
R4			37	38

Ramp Vol Group				
R1	44			
R2	43	46	41	
R3		46	42	40
R4			37	36

AVERAGE VEHICLE SPEED APPROACHING IN OUTSIDE FREEWAY LANE (L_1)

Ramp Vol Group	Fwy Vol Group F1	F2	F3	F4
R1	45	50		
R2	46	46	44	
R3		45	46	46
R4			47	50

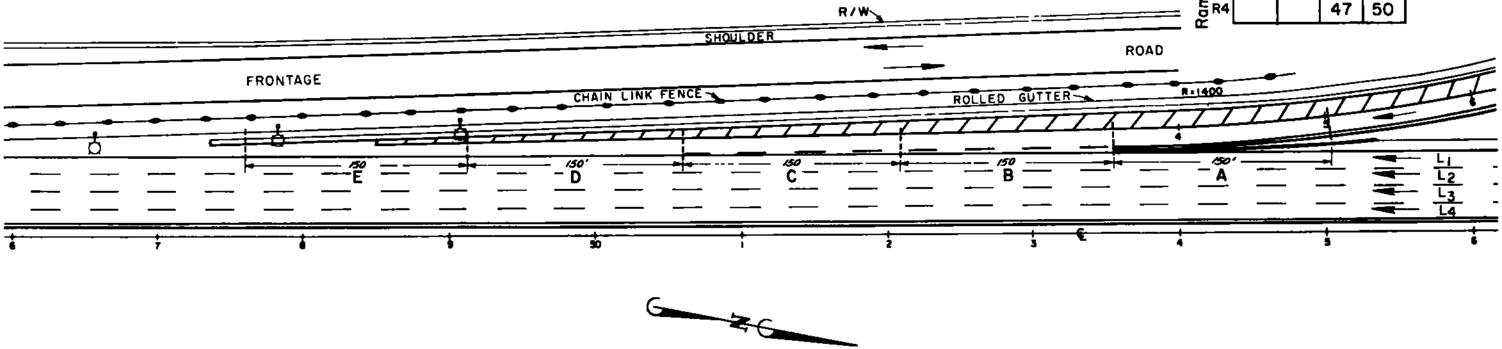


Figure 16. Ramp speeds—50:1 tapered on-ramp (curb offset 2 ft).

AVERAGE VEHICLE SPEED ALONG RAMP (Miles Per Hour)

E

Ramp Vol Group	F1	F2	F3	F4
R1				
R2	39		28	
R3		30		
R4				

D

Ramp Vol Group	F1	F2	F3	F4
R1	36	41		
R2	38	44	36	
R3		32	41	34
R4			44	34

C

Ramp Vol Group	F1	F2	F3	F4
R1	40	40		
R2	42	42	40	38
R3		38	41	40
R4		46	39	39

B

Ramp Vol Group	F1	F2	F3	F4
R1	43	42		
R2	42	44	43	42
R3		42	42	43
R4		42	39	39

A

Ramp Vol Group	F1	F2	F3	F4
R1	46	43		
R2	45	44	45	42
R3		44	44	45
R4		43	42	43

AVERAGE VEHICLE SPEED ENTERING FREEWAY AT VARIOUS LOCATIONS (Miles Per Hour)

Ramp Vol Group				
R1	36			
R2	39	43	36	
R3				33
R4		47	44	33

41	39		
42	41	41	43
	39	41	39
	45	32	40

45	43		
42	44	44	45
	43	42	44
	41	35	38

42			
46	44	44	
	44	44	43
	39	41	41

AVERAGE VEHICLE SPEED APPROACHING IN OUTSIDE FREEWAY LANE (L_1)

Ramp Vol Group	F1	F2	F3	F4
R1	46	45		
R2	46	46	45	
R3		45	48	48
R4			46	49

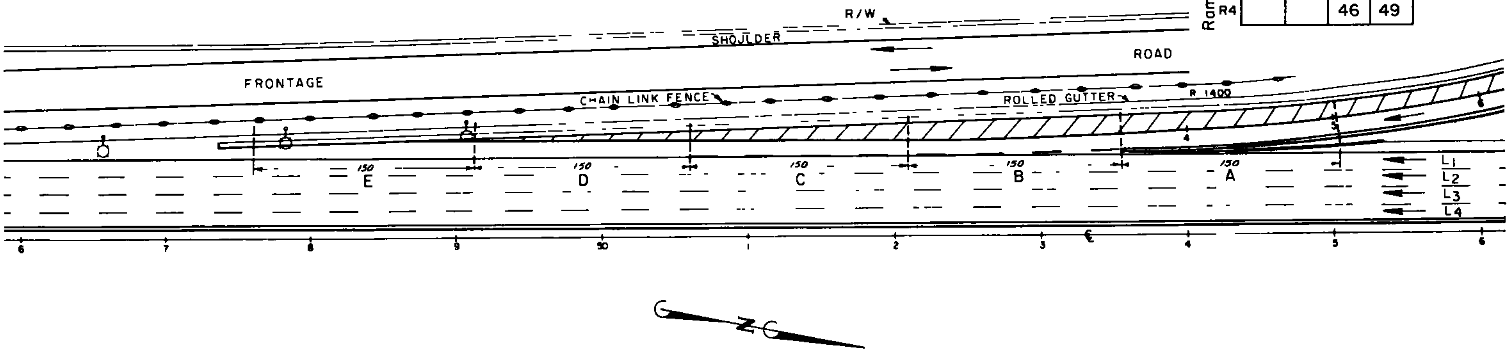


Figure 17. Ramp speeds—parallel on-ramp (curb offset 2 ft).

AVERAGE VEHICLE SPEED ALONG RAMP (Miles Per Hour)

E

Ramp Vol. Group	Fwy Vol Group F1	F2	F3	F4
R1				
R2	45			
R3			36	
R4				36

D

Ramp Vol. Group	Fwy Vol Group F1	F2	F3	F4
R1	36			
R2	37	36	39	
R3		38	36	37
R4			32	33

C

Ramp Vol. Group	Fwy Vol Group F1	F2	F3	F4
R1	39	44		
R2	40	41	42	40
R3		41	38	38
R4		39	37	37

B

Ramp Vol. Group	Fwy Vol Group F1	F2	F3	F4
R1	41	41		
R2	41	41	41	41
R3		40	37	39
R4		40	38	38

A

Ramp Vol. Group	Fwy Vol Group F1	F2	F3	F4
R1	39	39		
R2	40	40	39	41
R3		40	38	38
R4		39	37	38

AVERAGE VEHICLE SPEED ENTERING FREEWAY AT VARIOUS LOCATIONS (Miles Per Hour)

Ramp Vol Group				
R1	37			
R2	36	35	38	
R3		37	35	37
R4			31	33

40	44		
40	41	42	41
	41	38	37
	39	37	37

43	37		
40	40	39	41
	38	36	38
	41	39	38

40			
39	40		
	41	37	35
	39	36	34

AVERAGE VEHICLE SPEED APPROACHING IN OUTSIDE FREEWAY LANE (L_1)

Ramp Vol Group	Fwy Vol Group F1	F2	F3	F4
R1	46	46		
R2	45	46	48	
R3		45	48	46
R4			48	47

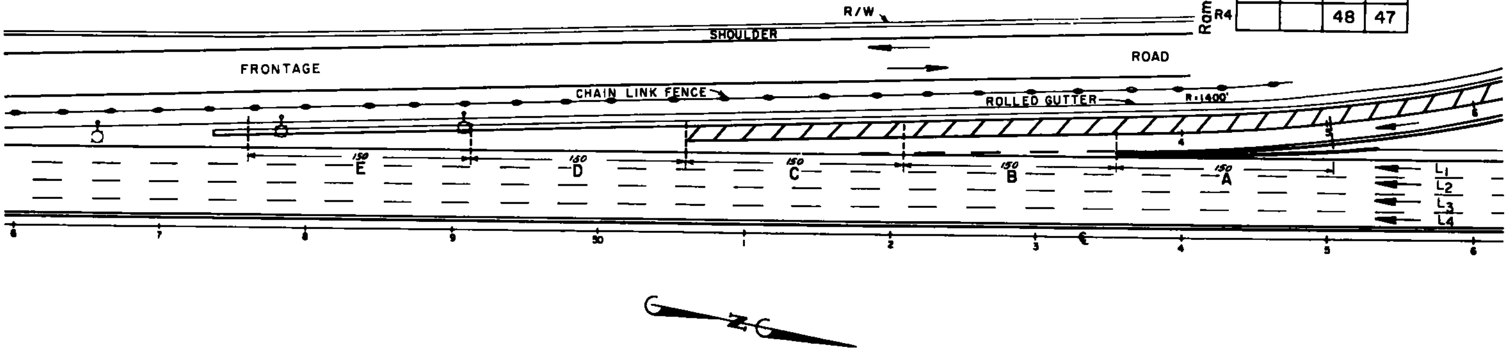


Figure 18. Ramp speeds—30:1 tapered on-ramp (curb offset 2 ft).

AVERAGE VEHICLE SPEED ALONG RAMP (Miles Per Hour)

E

Fwy Vol Group

Ramp Vol Group	F1	F2	F3	F4
R1	39	38		
R2	38	38	40	
R3		40	37	38
R4		38		

D

Fwy Vol Group

Ramp Vol Group	F1	F2	F3	F4
R1	41	42		
R2	40	41	40	
R3		41	40	42
R4		41	42	

C

Fwy Vol Group

Ramp Vol Group	F1	F2	F3	F4
R1	42	42		
R2	41	42	41	40
R3		40	40	40
R4		41	40	38

B

Fwy Vol Group

Ramp Vol Group	F1	F2	F3	F4
R1	44	43		
R2	42	42	42	44
R3		43	42	41
R4		41	42	42

A

Fwy Vol Group

Ramp Vol Group	F1	F2	F3	F4
R1	42	42		
R2	41	42	43	44
R3		43	40	40
R4		42	43	45

AVERAGE VEHICLE SPEED ENTERING FREEWAY AT VARIOUS LOCATIONS (Miles Per Hour)

Ramp Vol Group				
R1	39	43		
R2	40	41		
R3		41	39	41
R4			42	

42	41		
39	44		39
	43	40	38
		40	37

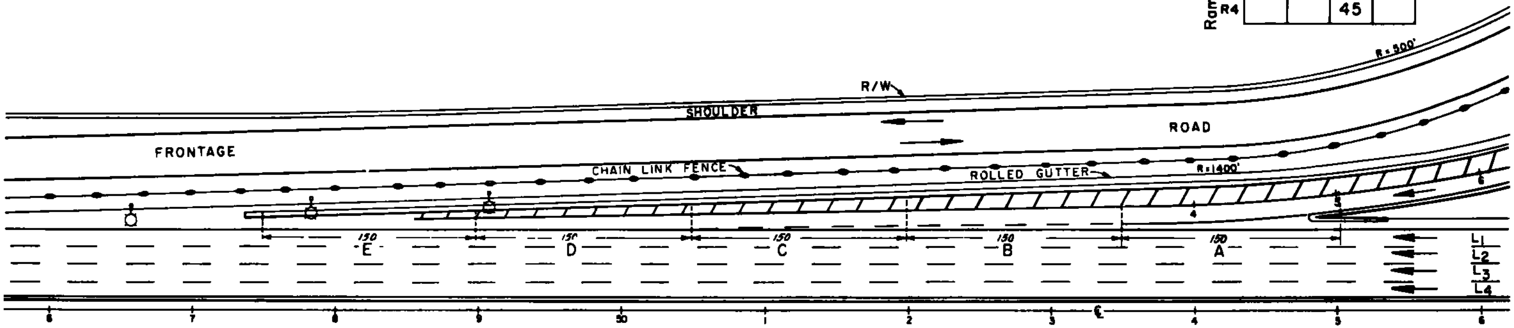
44	42		
42	42	40	
	40	45	40
		41	

44	52		
	43		
	47	42	39
		46	

AVERAGE VEHICLE SPEED 500' AHEAD OF CURB NOSE

Fwy Vol Group

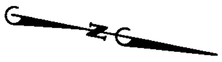
Ramp Vol Group	F1	F2	F3	F4
R1	43	44		
R2	41	44	46	
R3		43	47	47
R4			45	



AVERAGE VEHICLE SPEED IN FREEWAY LANE L_1, SECTION E

Fwy Vol Group

Ramp Vol Group	F1	F2	F3	F4
R1	43	44		
R2	42	43	44	44
R3	43	43	42	42
R4		42	42	45



AVERAGE VEHICLE SPEED IN FREEWAY LANE L_1, SECTION A

Fwy Vol Group

Ramp Vol Group	F1	F2	F3	F4
R1	45	45		
R2	43	45	43	46
R3		46	45	45
R4			43	42

Figure 19. Ramp speeds—50:1 tapered on-ramp (curb offset 8 ft).

AVERAGE VEHICLE SPEED ALONG RAMP (Miles Per Hour)

E

Fwy Vol Group

Ramp Vol Group	F1	F2	F3	F4
R1	39			
R2	39	38		
R3		36	39	
R4				38

D

Fwy Vol Group

	F1	F2	F3	F4
R1	41			
R2	41	41		43
R3		41	39	
R4		41	37	40

C

Fwy Vol Group

	F1	F2	F3	F4
R1	43			
R2	42	42	43	37
R3		41	40	40
R4		44	37	40

B

Fwy Vol Group

	F1	F2	F3	F4
R1	44			
R2	43	43	41	40
R3		42	42	42
R4		43	38	40

A

Fwy Vol Group

	F1	F2	F3	F4
R1	41			
R2	40	41	39	41
R3		40	40	40
R4		42	36	39

AVERAGE VEHICLE SPEED ENTERING FREEWAY AT VARIOUS LOCATIONS (Miles Per Hour)

Ramp Vol Group				
R1	41			
R2	41	41		44
R3		41	36	
R4				38

44			
42	43	44	30
	41	40	
	47		40

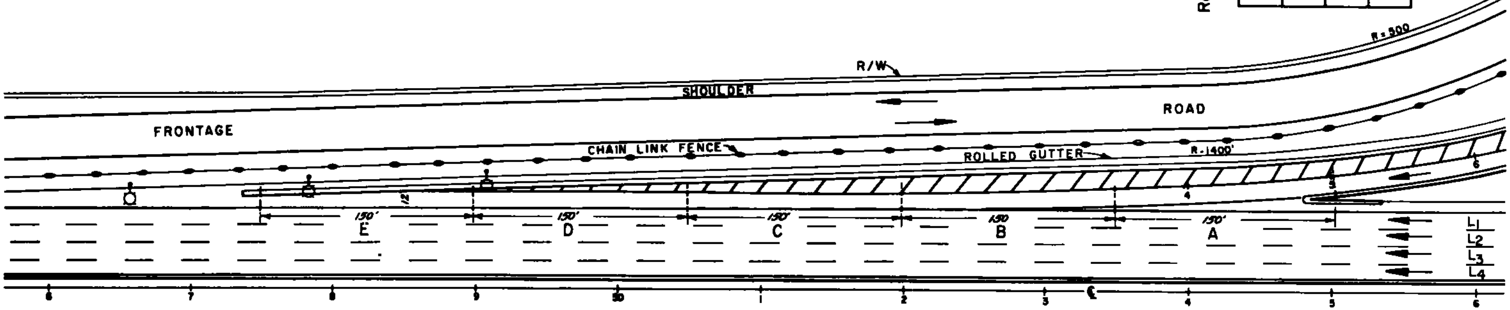
43			
43	45		41
	42	43	43
	42	38	39

47			
41	42		
	40	46	
			39

AVERAGE VEHICLE SPEED 500' AHEAD OF CURB NOSE

Fwy Vol Group

Ramp Vol Group	F1	F2	F3	F4
R1	46			
R2	45	45	45	
R3		44	46	45
R4			44	46



AVERAGE VEHICLE SPEED IN FREEWAY LANE L1, SECTION E

Fwy Vol Group

Ramp Vol Group	F1	F2	F3	F4
R1	44			
R2	43	43	43	
R3	44	43	43	42
R4		41	43	43

AVERAGE VEHICLE SPEED IN FREEWAY LANE L1, SECTION A

Fwy Vol Group

Ramp Vol Group	F1	F2	F3	F4
R1	42			
R2	43	45	49	
R3	42	45	48	44
R4			46	46

Figure 20. Ramp speeds—parallel on-ramp (curb offset 8 ft).

AVERAGE VEHICLE SPEED ALONG RAMP (Miles Per Hour)

E

Fwy Vol Group

Ramp Vol Group	F1	F2	F3	F4
R1	39			
R2	40	40		
R3			39	36
R4			38	39

D

Fwy Vol Group

	F1	F2	F3	F4
R1	40	38		
R2	41	42		
R3		41	42	38
R4		40	40	36

C

Fwy Vol Group

	F1	F2	F3	F4
R1	42	42		
R2	43	43		42
R3		44	41	39
R4		42	40	39

B

Fwy Vol Group

	F1	F2	F3	F4
R1	43	43		
R2	44	43		42
R3		44	42	39
R4		46	40	39

A

Fwy Vol Group

	F1	F2	F3	F4
R1	40	42		
R2	42	42		40
R3		44	38	38
R4		47	37	35

AVERAGE VEHICLE SPEED ENTERING FREEWAY AT VARIOUS LOCATIONS (Miles Per Hour)

Ramp Vol Group				
R1	40	40		
R2	41	42		
R3		42	42	39
R4			38	36

R1	42	45		
R2	39	43		
R3		45	40	39
R4		42	39	39

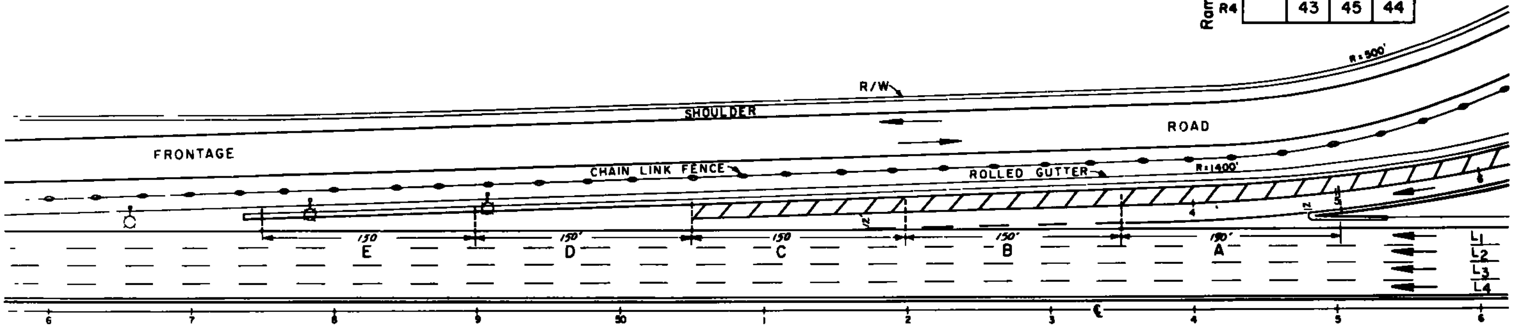
R1	44	40		
R2	43	41		41
R3		43	41	37
R4		48	37	39

R1	43			
R2	46	43		
R3		42	38	
R4		51	36	34

AVERAGE VEHICLE SPEED 500' AHEAD OF CURB NOSE

Fwy Vol Group

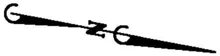
Ramp Vol Group	F1	F2	F3	F4
R1	43	43		
R2	42	44		45
R3		45	45	46
R4		43	45	44



AVERAGE VEHICLE SPEED IN FREEWAY LANE L_1, SECTION E

Fwy Vol Group

Ramp Vol Group	F1	F2	F3	F4
R1	43	41		
R2	44	43		44
R3		43	43	40
R4		43	41	40



AVERAGE VEHICLE SPEED IN FREEWAY LANE L_1, SECTION A

Fwy Vol Group

Ramp Vol Group	F1	F2	F3	F4
R1	44	45		
R2	45	43		44
R3		45	45	43
R4		42	43	41

Figure 21. Ramp speeds—30:1 tapered on-ramp (curb offset 8 ft).

This point is made because the "parallel" design calls for the vehicles to drive a zigzag path if they are to follow the outlines of the ramp.

6. A comparison of Figure 11 with Figure 15 shows that the distance from the physical nose is increased just about the same amount as the nose was moved back. This shows that the nose should not be used as a control in computing length required, but that a distance of about 6 ft from the edge of the through lanes to the left edge of the ramp marks the real beginning of the merging area. It may also be implied that angle of convergence is a more significant control than distance from the physical nose.

Speed

Figures 16 to 21 show the speeds observed for each ramp shape and volume group. The upper row of boxes on each figure shows the speed of ramp vehicles for each speed trap labeled on the plan, but does not include vehicles which have already entered the freeway. The lower row of boxes shows the average speed of entering vehicles at the point of entry indicated. Blank squares in the boxes indicate a lack of sufficient measurements to establish a reliable estimate for the particular volume combination. The lower right-hand box shows the average speed approaching from Lane 1 of the freeway. For studies made with the curb offset 8 ft, additional average speeds for Lane 1 of the freeway at the beginning and end of the on-ramp are shown in the two boxes at the bottom of Figures 19, 20 and 21.

1. With a 700-ft radius approach lane (turning lane), the turning speed (box A in upper row) was in most cases higher than the merging speed. This does not necessarily mean that the ramp area was not used for accelerating. But it does indicate that when drivers attained the speed they thought necessary, they drove on in to the freeway without accelerating.
2. With ramp curb offset 8 ft, the ramp and freeway speeds were similar for all ramp designs.
3. The difference between entering speed and speed of the approaching traffic in Lane 1 was from 2 to 8 mph, and speeds of both the ramp vehicles and freeway vehicles in the right-hand lane are in the 40-50 mph range.
4. The freeway speeds, 45 to 50 mph, were higher than expected for Lane 1 which included 35 percent trucks during the off-peak hours and 10 percent trucks during the peak hours.

CONCLUSIONS

As a result of the present study and previous experience of the authors in the design of interchanges and in making freeway capacity studies, it is concluded that entrance ramp terminal design should take into consideration the following requirements:

1. A direct alinement should be provided. This study reaffirmed findings reported elsewhere (1) that drivers tend to follow a straight line from the point where ramp curvature ends until they have entered the freeway traffic lane.

Merging vehicles can be broadly classified as: (a) individual unobstructed vehicles, and (b) vehicles in platoons. The individual vehicles almost invariably drive a direct line, and if the outline of the ramp terminal is a series of curve, then diagonal, then parallel, then squeeze-off, these drivers cut across the convex corners which appear alternately on the left and right. Vehicles in platoons frequently execute a "left-oblique" maneuver in which each vehicle can execute either a zigzag motion or a direct line. If the left-oblique is performed zigzag, the azimuths of each path will be equal, whereas if each vehicle on reaching the nose assumes a different azimuth (with the rear vehicle taking the greatest angle of convergence), the same effect will be achieved. At high volumes, this effect is to be desired, because it results in any long gap in the freeway traffic being filled. At low volumes, a direct but gradual approach will give the freeway traffic more "notice" that the entering car is encroaching, and thus provide an opportunity for cooperative adjustment of speeds.

The direct alinement, or constant taper design, makes it possible to perform any of these desirable maneuvers. Although the zigzag design will, if long enough, usually provide space for the same maneuvers, it is always possible that the designer may leave a nose or a corner in such a place that traffic will have to cut across it, and at best the zigzag design will waste pavement on one side while restricting clearance on the other.

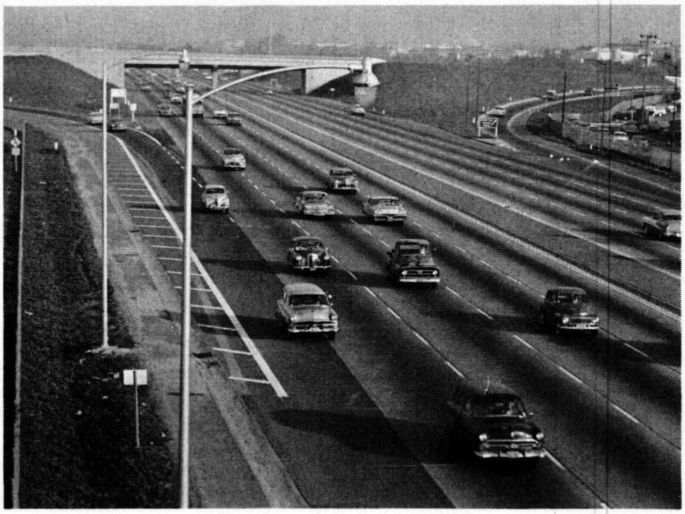
2. The angle of convergence is an important control. Drivers should be encouraged to merge at a small angle of convergence (Figs. 22A, 22B, 22C and 22D).

A ramp terminal is essentially an elongated intersection. If the intersection area is short, as on a conventional highway, freeway operating characteristics are not present and as a result both capacity and safety suffer. The difference between traffic operation at an ordinary intersection and that at a freeway ramp terminal is primarily in the angle at which the entering traffic and the through traffic converge, which in turn controls the lateral speed at which the entering vehicle approaches a vehicle on the through highway.

If the lateral speed of approach is slow enough, it is almost impossible for two cars to collide. One of them will adjust his speed so as to fall in behind the other. If both cars are in the centers of the 12-ft lanes at the point where the left edge of the ramp lane intersects the right edge of the freeway lane, there will be 6 ft between them and the convergence angle should be such that they have about 300 ft in which to adjust.

There is no mathematical formula nor psychological test that can be cited to show that 300 ft is the amount of distance needed for this adjustment; neither is there any to show that 1 sec, 2 sec, or any particular length of time is required. However, a distance such as 300 ft is much easier for the driver and, for that matter, for the engineer to visualize. A distance of 300 ft for a lateral movement of 6 ft results in a 50:1 taper. With this taper, the entering driver can confidently accelerate continuously, secure in the knowledge that he will see any freeway vehicle before he hits it, and soon enough to avoid hitting it. Vice versa, the freeway driver will see the entering vehicle before hitting it and in time to adjust his speed to avoid it.

A parallel ramp with a sudden squeeze-off at the end forces a decision on the driver: Shall I go on down and take a chance when I get there, or shall I cut in short? A constant taper design makes it easy for the driver to do what he is supposed to do, because he has a line to follow. When properly delineated by pavement markings, it also gives notice to the freeway driver that he is in a merging area.



Foreground ramp car is merging into a 166-foot, 2.7-sec. gap in Lane 1. Average headway between merged vehicles is 1.35 sec. Note that third car in Lane 1 is moving to Lane 2, anticipating that traffic in Lane 1 will slow down slightly. The four cars now occupying 275 feet (4.3 sec.) will stretch out to about 5.4 sec. or 400 feet.

Instantaneous rate-of-flow in this picture is:

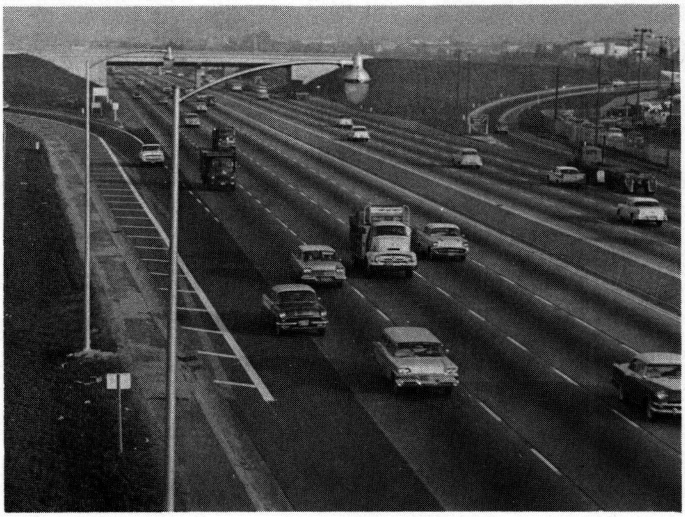
Ramp	960 vph
Freeway Lane 1 (near lane)	860 vph
Lane 2	950 vph
Lane 3	1400 vph
Lane 4	220 vph
TOTAL	4390 vph

Figure 22A. Light Traffic—merging maneuvers with a 50:1 tapered on-ramp (heavy white stripe is 50:1 taper).

Another reason why rate of convergence should be a control is capacity. It has been observed in capacity studies elsewhere (2,3) that "saturated flow" can only be obtained where the squeeze-off distance is about 500 ft or more. The only way saturated flow (usually more than 2,000 vph per lane) can be obtained is to have more lanes coming in to a point than go away from it (as is typical of an entrance ramp), and in order to convert the stop-and-go motion behind the point of convergence into steady flow, the convergence has to be gradual.

3. Adequate merging distance should be provided for low volumes as well as high volumes.

It has been shown in this study that vehicles entering at low ramp and freeway volumes use as much as or more distance than those entering at higher volumes. The R1-F1 group of observations was taken when freeway



Foreground ramp car is merging into a 75-foot gap (1.2 second) in Lane 1. This shows that even with very light traffic, a gradual merge is necessary. After the merge, the average headway of the 3 cars in the foreground will be 0.6 sec., for a short length of time.

Instantaneous rate-of-flow in this picture is:

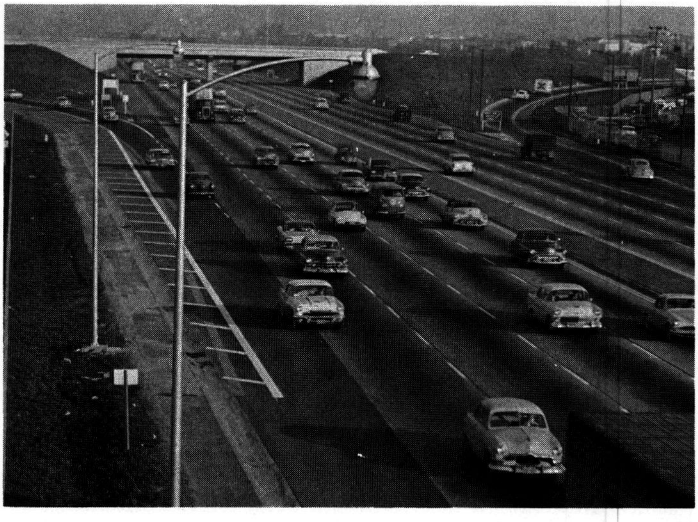
Ramp	600 vph
Freeway Lane 1 (near lane)	690 vph
Lane 2	760 vph
Lane 3	800 vph
Lane 4	680 vph
TOTAL	3530 vph

Figure 22B. Very light traffic—merging maneuvers with a 50:1 tapered on-ramp (heavy white stripe is 50:1 taper).

volume was less than 600 per lane per hour. Conversely, it has been shown that with a taper which is adequate for proper merging of a single pair of vehicles, there is adequate length for any combination of ramp and freeway volumes up to possible capacity. Controls which call for high volumes before providing adequate merging distance are therefore not tenable.

Furthermore, the science of predicting traffic for a 20-yr period is far from exact. Freeways cost so much and ramp terminals so little that it would seem only sensible to design for maximum conditions, especially when considering ramp traffic. One industrial plant, unforeseen at the design stage, not only can change the ramp volume but can radically change the design hourly volume on the freeway itself.

4. Adequate merging distance should be provided for high speeds as well as low speeds.



Foreground ramp car is merging into a 150-foot, 2.5-sec. gap. Judging by the space between 2nd and 3rd cars in Lane 1 (about 0.3 sec.), 2nd car has yielded right-of-way to ramp vehicle. This is the only way that smooth flow can be obtained at saturated rate-of-flow.

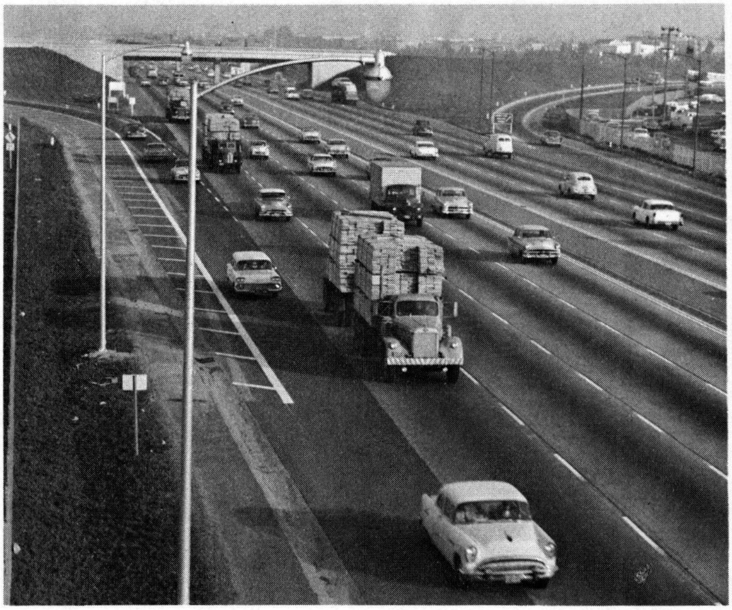
Instantaneous rate-of-flow in this picture is:

Ramp		1440 vph
Freeway	Lane 1	860 vph
	Lane 2	760 vph
	Lane 3	1600 vph
	Lane 4	2250 vph
TOTAL		6910 vph

Figure 22C. Heavy traffic—merging maneuvers with a 50:1 tapered on-ramp (heavy white stripe is 50:1 taper).

As previously intimated, the higher the speed of the converging traffic, the more distance is required for a given length of time in which to adjust speeds, and also the higher the lateral rate of approach will be. This seems self-evident, and yet it must be mentioned because when the length of merging area is controlled by the difference between turning speed and freeway speed, it turns out that very short merging areas are provided for high turning speeds. Another way of stating this principle is that assumed high turning speeds should not result in reduced merging distance.

At the Ashby Avenue site where the observations were made, the design speed of the freeway was 60 mph, and the turning radius was 700 ft. Assuming that this is a "high volume" highway, Table VII-10 of the AASHO policy (1) would provide a total length of 250 ft, including taper. Ex-



Note that by gradual angle of convergence, ramp and freeway traffic will merge like a hand in a glove.

Instantaneous rate-of-flow in this picture is:

Ramp		**1200 vph**
Freeway	**Lane 1**	**700 vph**
	Lane 2	**600 vph**
	Lane 3	**1200 vph**
	Lane 4	**1800 vph**
TOTAL		**5500 vph**

Figure 22D. Heavy commercial traffic, especially in Lane 1—merging maneuvers with a 50:1 tapered on-ramp (heavy white stripe is 50:1 taper).

amination of Figures 11 and 15 shows that less than 15 percent of the cars observed could have stayed within this ramp, and probably less than 5 percent could have driven with 3-ft clearance on the right.

5. In combination with the approach ramp, adequate length should be provided for entering cars to accelerate from any turning speed.

6. It would be highly desirable for every entrance ramp terminal to have the same shape. When the length of the ramp terminal is dependent on assumed design speed of the freeway and safe turning speed of the approach ramp, a driver entering a level tangent freeway can be confronted with ramp terminals varying from 250 ft to 1,200 ft in length, and unless he is a commuter, he never knows quite what to do; i.e., whether to stop and take a look, to feel his way along gingerly, or to boldly step on the gas and go on into the traffic stream as the designer intended him to.

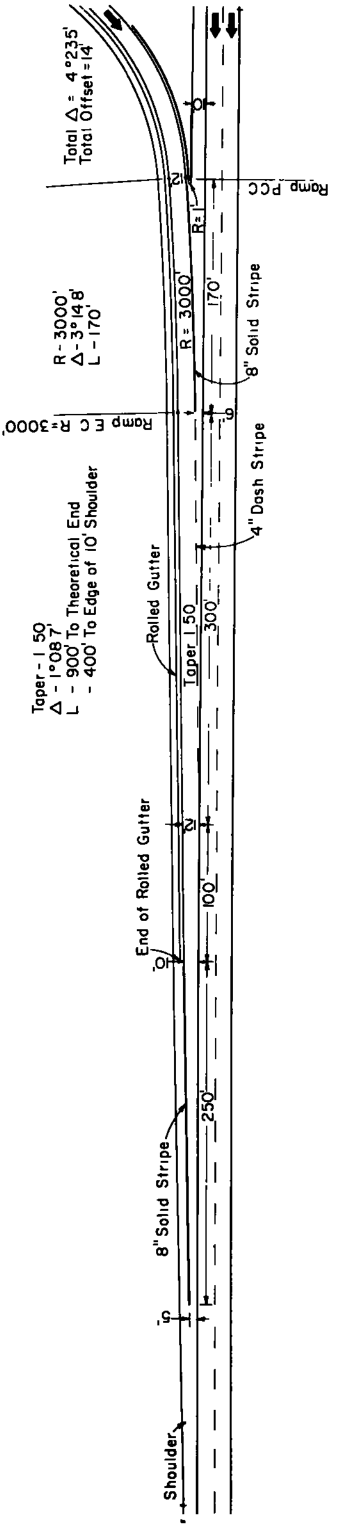


Figure 23. Suggested standard—entrance ramp.

It is obvious that a standard design for all locations would go a long way toward eliminating this confusion. A standard design would also simplify design and stake-out procedure, and would make signing, pavement marking and delineation more foolproof and uniform.

An anomaly which has arisen out of designs that vary with assumed turning speed is that the merging area is long (and adequate) at the unimportant ramps but is frequently inadequate at the important ramps, because the less important ramps are usually designed with a sharper turning radius than the more important ramps.

7. The 10-ft shoulder offset must be accommodated. Current control standards ignore the lateral space between the freeway lane and the ramp lane. Because the total length is controlled by design speeds, designs with shoulder offsets provide a sharper approach angle and a shorter merging distance than those with narrow shoulders or curb noses adjacent to the freeway lane.

8. Pavement area must not be excessive.

9. A "natural" or unforced appearance should be achieved.

A ramp design that meets all of the above requirements is offered in Figure 23. This design can be used for any typical application and has been adequately tested and observed under traffic at the Ashby Avenue site for level tangent freeways with high turning speeds.

Subjective tests have been made showing that a 1952 model 6-cylinder medium-priced car with 60,000 miles since the last overhaul, and a 1958 6-cylinder low-priced car can merge smoothly with heavy freeway traffic from a 10 mph start at the nose (marked "ramp PCC" on the drawing). It may be noted that the length of the proposed standard ramp, using the definition of length given in Fig. VII-20 (p. 494) of the AASHO

Policy (1) is 1,070 ft. Accepting the tabular values of the Policy, this makes it sufficiently long for all turning speeds on "main" highways regardless of design speed of the latter, and for "high volume" highways having design speeds of 60 mph. It is long enough for "high volume" highways with a 70 mph design speed provided that the turning radius is 150 ft or better.

It may be reasoned that the tabular values in the Policy are conservative because of the increase in auto acceleration during the past few years, a trend which is not likely to reverse. It follows that the proposed ramp design is sufficient for low turning speeds as well as the high turning speeds observed.

The data collected in the present study would warrant a 40:1 taper instead of 50:1 if the 85 percentile vehicle path is accepted as being all that should be accommodated, but 50:1 is recommended, first because of the margin of safety, and for two other reasons: it makes the ramp terminal long enough to accommodate all the lengths in the AASHO table, and this in turn makes it possible to use a uniform shape at all locations. The difference between a 40:1 and a 50:1 taper amounts to 35 sq yd of pavement and 107 sq yd of shoulder, outside of the 10-ft shoulder of the through roadway.

The 3,000-ft radius curve shown in Figure 22 was arrived at because it was desired to lose width as rapidly as possible for the sake of economy, and yet not introduce so much delta that a straight ramp from a diamond interchange would require a reverse curve.

Any offset between nose and through pavement can be fitted to this curve without changing the design. The 8-in. solid stripe has proven very effective in guiding traffic into the desired 50:1 taper.

EFFECT OF GRADES

Although no quantitative observations were made of traffic behavior on ramps having grades, the logic of the relation between grade and length may be examined. It is obvious, of course, that for a given increase in speed, more length is required by a car (on the ramp) going uphill than on the level. But it is also true that vehicles in the right-hand lane of a freeway going uphill are on the average moving much less than 50 mph. "Design speed" here becomes meaningless. Passenger cars on the entering ramp can easily overtake the slow vehicles on the freeway with less acceleration distance than they need on the level, and the time rate of convergence is less than it would be on the level with the same taper. Passenger cars in the right-hand lane of the freeway will have less difficulty avoiding entering cars than they will have avoiding slow trucks that are already on the freeway and which they encounter continuously on the main line. It therefore seems that the design shown in Figure 23 will work on any grade.

ACKNOWLEDGMENT

The work reported was done for the California Division of Highways by the Traffic Department. G. M. Webb is Traffic Engineer and was in general charge. D. C. Chenu and several members of the San Francisco District forces did most of the field work. The proposed standard ramp was designed by the senior author; the junior author is responsible for the conclusions drawn from the data.

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A Study of Freeway Traffic Operation

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In 1956 the Texas Transportation Institute initiated a research project for the Texas Highway Department to correlate freeway operational characteristics with design features. A preliminary report of this study has been published in HRB Bulletin 170. The data presented herewith represent additional studies and analyses of this work.

The study was made principally by the motion picture method, which facilitated the simultaneous evaluation of various operational characteristics and provided the distinct advantage of being able to re-create traffic situations for more thorough study. Traffic operations were recorded on approximately 22,000 ft of 16-mm film during the course of nine separate studies made on freeways in Houston, Dallas, and Fort Worth.

Research was conducted on: operation and capacity, freeway volume control, lane use and placement, entrance ramps, and weaving. A study of freeway median design was also made and the results are being presented in a separate report.

The results of these various studies indicate that the factors having the greatest effect on freeway operation are the design and operation of ramps and interchanges. Additional research and development are needed in this area.

The volume control, weaving, and entrance ramp studies produced some significant results which are discussed in the report and will contribute to over-all knowledge of freeway operation.

● NO LONGER mere designers' dreams, freeway-type facilities are rapidly becoming vital parts of the vast highway system of this nation. Because the development of such facilities has been so rapid and the problems of research on such facilities—equipment required, volume of data, magnitude of the project—so complex, relatively little comprehensive evaluation of freeway traffic operation and the various freeway design features has been possible.

Though freeway facilities have served exceedingly well in the capacity for which they were built, some operational difficulties have developed and there is a need for data from which to correlate the effects of design on the operational characteristics of the freeways. Data of this type will aid in an evaluation of present design of the various elements and provide the basis for future design that would eliminate some of the present operational difficulties.

Because of the lack of sufficient information as to the interrelationships of certain design features and their combined effects on certain operational characteristics, a research project was undertaken, beginning in May 1956, by the Texas Transportation Institute of Texas A. and M. College for the Texas Highway Department to explore the operational characteristics of the Texas freeways and determine what features warranted specific study and analysis.

The purpose of this project was to determine the effects of certain geometric features of freeways on traffic operation through a study of the actual operation of vehicles on representative sections of freeways in Texas cities.

Method of Study

Because of two complex factors—traffic maneuvers and the interrelationship between various design features and those maneuvers—it was impossible to gather from on-the-spot observation and manual tabulation sufficient data for analysis. After consideration of various methods of obtaining data on operational characteristics of freeway traffic, the motion picture type of study was selected as the best for providing the simultaneous evaluation of such complex operational characteristics of traffic in a study area. In addition, the motion picture provided the possibility of restudy of specific traffic conditions recorded on film.

Traffic operation on representative sections of the freeways was recorded on film by the use of a 16-mm motion picture camera. The filming was done from a vantage point at a considerable elevation above the traffic stream. Three types of towers were used to obtain the necessary vantage point. For the Dallas studies, a tower truck was parked on an overpass structure overlooking the freeway, and for the Gulf Freeway studies, a 48-ft temporary tower was first used and later replaced by the 60-ft portable tower shown in Figure 1. This portable tower, designed specifically for the photographic studies, was also used for the Fort Worth studies. In the first series of studies, pictures were made by a commercial photographer at a constant camera speed of 8 frames per sec; after a camera was acquired for the research project, pictures were made at a speed of 10 frames per sec. Both camera speeds allowed the accurate determination of vehicle speeds, headways and other desirable traffic characteristics.

A 12-in. electric clock with a sweep second hand was positioned to appear in an unused portion of each frame of the motion picture film. Though time-distance relationships were determined by frame count, the clock provided a check on camera speed and a record of the period of the day. Figure 2 shows a sample of the motion picture film and the location of the clock.

Transverse white lines were painted on the pavement 176 ft apart to provide reference points for speed, headways and other time-distance determinations.

Two projectors were used to analyze the motion pictures. The first, which maintained constant focus and contained a daylight screen in the machine, was used to obtain time-space relationships. This projector (Fig. 3), was especially constructed so that it could be stopped for "still" or single-frame viewing. Because the film was held firmly between two glass plates, warping from lantern heat was eliminated. A microfilm reader was used in obtaining placement data. It projected an image at a fixed magnification which could be scaled. Both projectors provided the advantage of being able to replay or re-create traffic situations as well as stopping the film to permit more comprehensive visual analysis of each frame of the movie.

In order to obtain average weekday conditions on the freeways, the survey motion pictures were taken on either a Tuesday or Wednesday, or both. Test film was usually taken on the previous Monday. The tower from which the film was taken was erected at each site at least one week previous to the film study and personnel were on the tower at peak periods during this time. Observations made before and during the study did not indicate that the tower or the personnel on the tower caused any apparent influence on the driving pattern of the freeway traffic.

Continuous motion pictures were taken of each test section for approximately 1 hr and 30 min during the morning and evening peak periods (7:00-8:30 a.m., 5:00-6:30 p.m.) and for 1 hr (9:30-10:30 a.m.) during off-peak conditions.

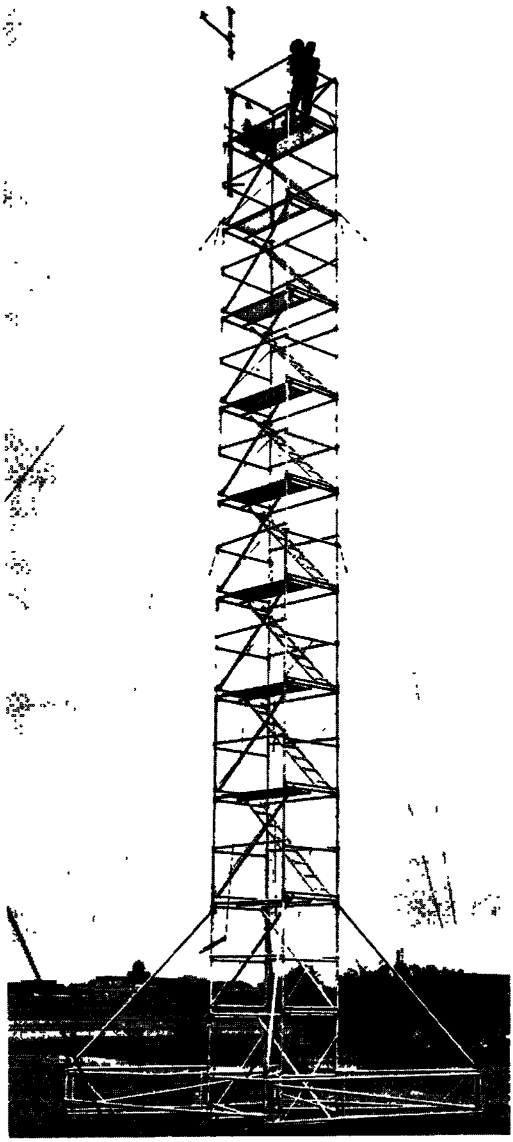


Figure 1. Portable tower used in filming freeway traffic.

Selection of Study Sites

During the early phases of the study, the Project Advisory Committee, composed of representatives of the Texas Highway Department and the cities in which studies were made, selected three sites showing the greatest operational difficulties: one section of the Gulf Freeway (Calhoun to Scott) in Houston, one section of the Central Expressway (Fitzhugh to Haskell) in Dallas, and one section of the East-West Freeway (University to Montgomery) in Fort Worth.

The Gulf Freeway in Houston and Central Expressway in Dallas were similar facilities. Both had three lanes in each direction, diamond-type interchanges, continuous one-way frontage roads through the study area and the same type pavement. Figures 4 and 5 show the general layout of the freeways.

Figure 2. Sample of motion picture film from freeway studies.

Though similar in over-all construction characteristics, the Houston and Dallas freeways had several principal differences in design. The through lanes of the Gulf Freeway overpassed the intersecting roadways; the through lanes of the Central Expressway were under the intersecting roadways. The Gulf Freeway had a 4-ft concrete median with 6-in. barrier-type curbs; the Central Expressway had an 11-ft grassed median with 6-in. mountable curbs. In the survey section of the Gulf Freeway, there were full width acceleration lanes for entering traffic; in the survey section of the Central Expressway, a $7\frac{1}{2}$-deg curve joined the entrance ramp directly to the freeway lanes, with no acceleration lanes provided.

The study site on the East-West Freeway in Fort Worth had two lanes in each direction, two-way frontage roads which were not continuous through the study area, three entrance ramps of different designs, one diamond-type interchange and one combination type. Figure 6 shows the general layout of the study area.

In order to obtain a sufficient amount of data on the operating characteristics of vehicles for varying sets of conditions and with various types of freeway designs, a total of nine motion picture studies was made (Table 1). Six of these studies were performed on the Gulf Freeway in Houston, two on the Central Expressway in Dallas, and one on the East-West Freeway in Fort Worth. Specific discussion on the various conditions and characteristics covered in these studies will be presented in other sections of this report.

In addition to the motion picture studies, a number of surveys were conducted in cooperation with the Bureau of Public Roads using their electronic traffic analyzer. The results of these studies are being presented in a report on freeway medians.

OPERATION AND CAPACITY

Speed-volume relationships have been used extensively to express operating conditions and capacity, and as a measure of the efficiency of traffic facilities. It has been difficult to determine the limits of efficiency desired on freeways. However, one fact is quite evident; certain hourly volumes do not adequately express operating conditions experienced on freeways except during very low volume conditions. This is illustrated in Figure 7. Platooning of traffic, momentary overcrowding

Figure 3. Time-motion study projector used in analysis of motion pictures.

of one or more lanes, and headway adjustments in the traffic stream are always present except for extremely low volume conditions.

The 5-min volume or rate of flow appears to be a fairly reliable time interval for the expression of freeway traffic volume. Even this short time interval, however, fails to reflect the extremely poor operating conditions experienced during periods when the demand exceeds the capacity of the facility.

The location at which speed and volume measurements are made also has a great deal to do with the adequate description of operating conditions. For example, traffic data taken just beyond an entrance ramp may reflect smooth and uniform operation when actually the traffic behind the ramp may be operating under stop-and-go conditions. Because congestion at one point may cause congestion for a great distance back along the freeway, a survey made at a point behind this critical ramp area will reflect poor conditions without direct association of the cause of the congestion.

Study Method

Data for this section on speeds and volumes were obtained from viewing motion pictures of actual freeway operation. Vehicle speeds were determined by observing each vehicle and recording a frame count as the rear wheel of the vehicle crossed a transverse white line painted on the pave-

Figure 4. Gulf Freeway, Houston.

Figure 5. Central Expressway, Dallas.

ment. A second frame count was recorded for the same vehicle as its rear wheels crossed a second line 176 ft in advance of the first line. Because the camera was operated at a constant speed, it was possible to determine the time required for the vehicle to travel the 176 ft and to compute the speed of the vehicles in miles per hour.

Tabulations of volumes were made for each 1-min period and combined to show 5-min volumes.

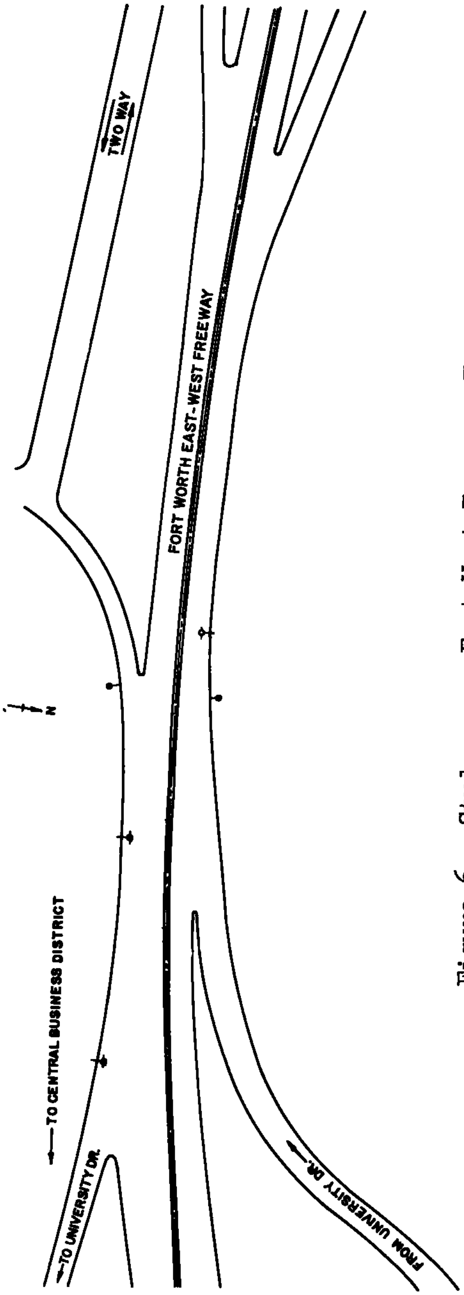


Figure 6. Study area, East-West Freeway, Fort Worth.

Volume-Speed Relationships

In the preliminary report of this study (HRB Bulletin 170, 1958) a number of volume-speed relationships were discussed for the freeways studied. The conclusion was drawn that speeds of 40 to 50 mph could be maintained in the inside (median lane) and middle lanes provided the 5-min lane volume did not exceed 150 (1,800 vph), and in the outside (right) lane provided the 5-min volume did not exceed 125 (1,500 vph). Typical volume-speed relationships are given in Tables 2 through 8. (The 5-min volumes are expressed throughout this report in terms of equivalent hourly rate of flow. These values were obtained by multiplying the 5-min volume by 12. They are shown in terms of vehicles per hour (vph) but are not to be confused with total hourly volume.)

The volume-speed relationships have been plotted in a different manner in Figure 8. For these plots successive 5-min volumes have been plotted in relation to the 5-min average speed. Successive points have been joined in sequence to trace the average speed reduction as volume increases and the increase in average speed after the peak flow has passed. Each of these graphs, developed from data taken in the vicinity of an entrance ramp, shows a characteristic loop resulting from the decrease in speed at high

TABLE 1

FREEWAY MOTION PICTURE STUDIES

Study	Date	Time	Type of Study
Houston I	5-22-56	7:00-8:35 A.M. 9:30-10:30 A.M. 4:15-5:52 P.M.	Motion Picture
Houston II	9-11-56	7:00-8:35 A.M. 9:30-10:30 A.M. 4:15-5:50 P.M.	Motion Picture
Houston III (a)	9-25-56	7:00-8:10 A.M.	Motion Picture
Houston III (b)	9-26-56	7:00-8:30 A.M. 4:15-5:50 P.M.	Motion Picture
Houston IV	7-8-58	7:00-8:30 A.M. 9:30-10:30 A.M. 4:00-6:00 P.M.	Motion Picture
Houston V	7-22-58	7:00-8:15 A.M.	Motion Picture
Dallas I	8-14-56	7:10-8:45 A.M. 9:30-10:30 A.M. 4:00-6:00 P.M.	Motion Picture
Dallas II	11-26-57	4:30-6:05 P.M.	Motion Picture
Fort Worth II	2-20-58	7:45-8:40 A.M. 4:15-5:30 P.M.	Motion Picture

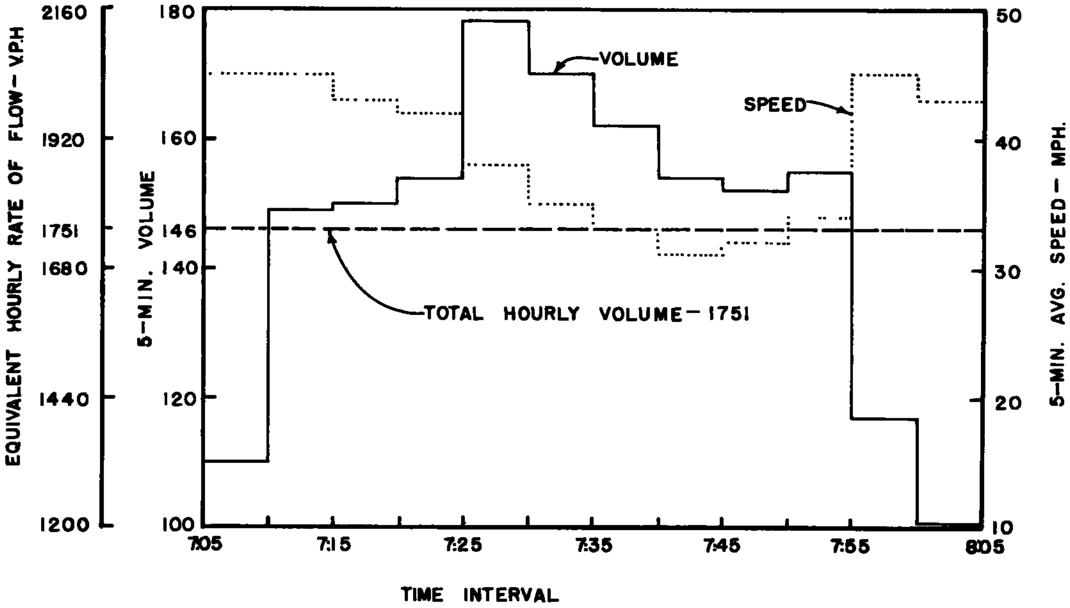


Figure 7. Speed-volume relationship before ramp—Houston II, inside lane, inbound—7:05-8:05 A.M. (5-min time intervals).

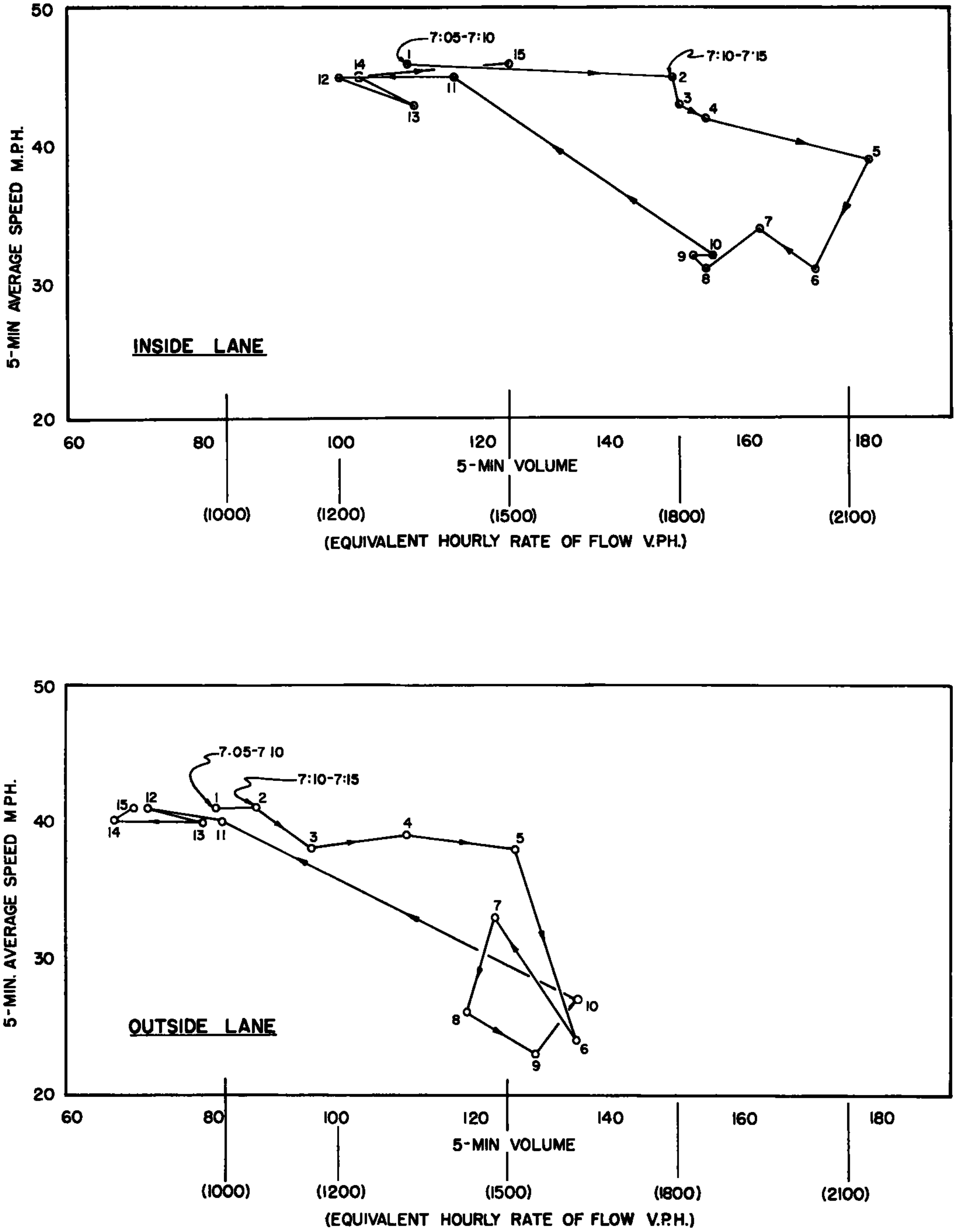
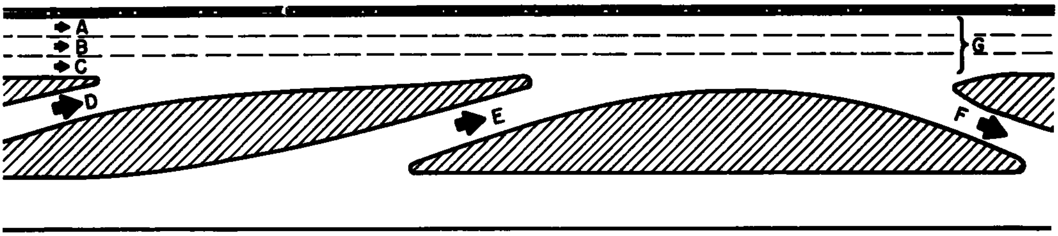


Figure 8. Speed-volume relationships, inside and outside lanes, ahead of exit ramp—Gulf Freeway (Houston II).

TABLE 2
VOLUME-SPEED DATA FOR HOUSTON I, GULF FREEWAY
5-MIN INTERVALS, MORNING PEAK PERIOD



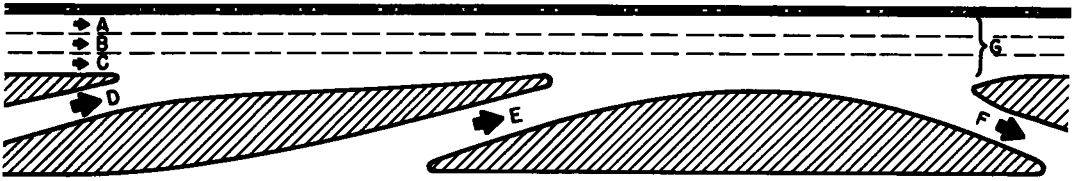
Time	Inside Lane Speed	5-Min Volumes			Outside Lane Speed	Total Vol 3 Lanes	Equiv Hourly Rate of Flow (vph)	5-Min Volumes			Calculated Total Vol 3 Lanes	Equiv Hourly Rate of Flow (vph)
	A	A	B	C	C	at A		D	E	F	at G	
7:00-7:05	40	119	120	70	42	309	3,708	35	18	15	347	4,164
7:05-7:10	44	134	151	78	40	363	4,365	36	31	19	411	4,932
7:10-7:15	43	149	151	88	38	388	4,656	37	25	12	438	5,256
7:15-7:20	40	158	170	114	--	442	5,304	29	31	14	488	5,856
7:20-7:25	33	163	169	110	30	442	5,304	39	17	14	484	5,808
7:25-7:30	32	174	150	105	--	429	5,148	27	33	8	481	5,772
7:45-7:50	--	138	128	127	--	393	4,716	26	30	23	426	5,112
7:50-7:55	--	141	140	130	--	411	4,932	21	26	36	422	5,064
7:55-8:00	29	140	132	127	16	399	4,788	17	23	25	414	4,968
8:00-8:05	34	115	137	92	27	344	4,128	31	17	23	369	4,428
8:05-8:10	44	104	116	62	39	282	3,384	39	31	18	334	4,008
8:10-8:15	--	117	136	66	--	319	3,828	40	23	20	362	4,344
8:15-8:20	44	109	109	65	41	283	3,396	41	27	12	339	4,068
8:20-8:25	45	116	126	54	39	296	3,552	41	20	9	348	4,176
8:25-8:30	47	68	100	42	40	210	2,520	42	20	10	262	3,144
8:30-8:35	47	76	77	43	--	196	2,352	40	21	12	245	2,940

volumes. Examining successive 5-min intervals along the trace demonstrates that as the peak flow builds up, the 5-min average speed drops and generally does not recover to the original relationship with volume until the peak flow or demand has passed. These graphs, however, do not adequately describe the operating conditions experienced during these periods of heavy flow. Momentary overcrowding, adjustments of speed, stoppages and the resulting "backlashes" along the freeway, although clearly visible in the motion pictures, are not adequately described by data taken at a point or within a short length of the freeway. Stoppage conditions "backlash" or progress along a lane so rapidly that average speeds or even individual speeds which have been determined by measuring the time required for each vehicle to move through a distance of 176 ft, indicate only a low speed and do not show the momentary stoppage of some vehicles.

As the rate of flow becomes critically heavy, vehicles weaving from one lane to another, or vehicles entering from a ramp may cause an adjustment in headways in the traffic stream. For example, if an entering vehicle causes a vehicle on the through lane to momentarily reduce speed to adjust its headway, some headway adjustment will probably be necessary for each trailing vehicle in the traffic stream until a sufficiently long headway is available to absorb the shock. The severity of a "backlash effect" is dependent on the compactness or density of the traffic stream and the length of delay created by the headway adjustment. Freeway volume control studies, which will be discussed in a later section of this report, indi-

TABLE 3

VOLUME-SPEED DATA FOR HOUSTON II, GULF FREEWAY 5-MIN INTERVALS, MORNING PEAK PERIOD



Time	Inside Lane Speed A	5-Min Volumes			Outside Lane Speed C	Total Vol 3 Lanes at A	Equiv Hourly Rate of Flow (vph)	5-Min Volumes			Calculated Total Vol 3 Lanes at G	Equiv Hourly Rate of Flow (vph)
		A	B	C				D	E	F		
7:05-7:10	46	110	139	82	41	331	3,972	35	31	9	388	4,656
7:10-7:15	45	149	149	88	41	386	4,632	44	33	11	452	5,424
7:15-7:20	43	150	172	96	38	418	5,016	43	21	19	463	5,556
7:20-7:25	42	154	163	110	39	427	5,124	40	27	19	475	5,700
7:25-7:30	39	178	174	126	38	478	5,736	37	39	19	535	6,420
7:30-7:35	31	170	172	135	24	477	5,724	36	32	20	525	6,300
7:35-7:40	34	162	158	123	33	443	5,316	36	34	16	497	5,964
7:40-7:45	31	154	154	119	26	427	5,124	43	32	13	489	5,868
7:45-7:50	32	152	154	129	23	435	5,220	31	41	19	488	5,856
7:50-7:55	32	155	156	135	27	446	5,352	40	35	19	502	6,024
7:55-8:00	45	117	131	83	40	331	3,972	32	18	11	370	4,440
8:00-8:05	45	100	140	72	41	312	3,744	48	27	13	374	4,488
8:05-8:10	43	111	129	80	40	320	3,840	35	28	16	367	4,404
8:10-8:15	45	103	123	67	40	293	3,516	42	40	19	356	4,272
8:15-8:20	46	125	121	70	41	316	3,792	42	26	11	373	4,476

cate that smooth operating conditions were maintained by eliminating the conditions which created these stoppages during heavy flow conditions.

The point at which volume and speed surveys are made on a freeway is quite critical. Surveys, during peak flow conditions, taken just past an entrance ramp will often reflect operating conditions quite different from a survey taken just ahead of the ramp. Vehicles leaving a congested entrance ramp area may be free to proceed with little restriction ahead of them, while at the same time vehicles behind the same entrance ramp are operating under a stop-and-go condition of severe congestion. The congestion from one entrance ramp area may cause congestion for a great distance back along the freeway. This same condition often exists at critical exit ramp areas. An illustration of the change in volume through an area is given in Tables 2 through 8.

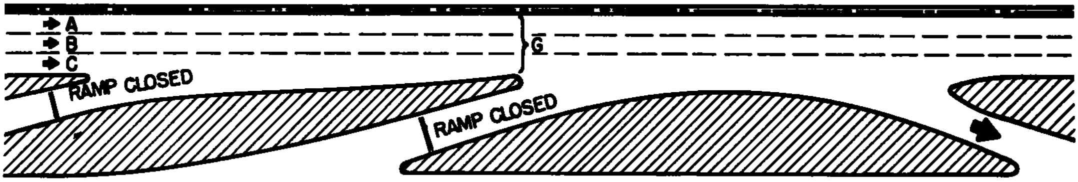
It is difficult from a spot survey to determine the cause of congestion. Congestion observed at one study area may actually be caused by conditions existing at a point some distance ahead of the study area. The motion picture survey method provides some possibility of continually examining conditions ahead of the study area for possible influencing factors.

Freeway Volume Control

In order to determine the over-all effect of entering traffic on operation in the through lanes of the freeway, studies were made both with entrance ramps open and with the ramps closed. These studies have been

TABLE 4

VOLUME-SPEED DATA FOR HOUSTON III, GULF FREEWAY 5-MIN INTERVALS, MORNING PEAK PERIOD



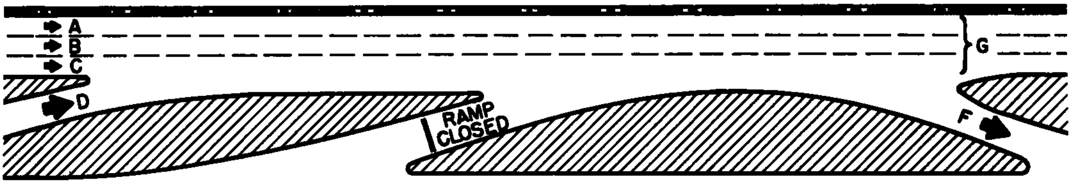
Time	Inside Lane Speed A	5-Min Volumes			Outside Lane Speed C	Total Vol 3 Lanes at A	Equiv Hourly Rate of Flow (vph)
		A	B	C			
(a) Houston III A							
7:00-7:05	46	105	121	60	45	286	3,482
7:05-7:10	46	121	125	68	44	314	3,768
7:10-7:15	46	145	144	85	44	374	4,488
7:15-7:20	43	152	163	109	40	424	5,088
7:20-7:25	40	166	160	115	39	441	5,292
7:25-7:30	40	171	175	129	39	475	5,700
7:30-7:35	36	149	164	-	-	313	3,756
7:35-7:40	35	156	149	140	36	445	5,340
7:40-7:45	34	154	149	128	33	431	5,172
7:45-7:50	37	152	146	138	33	436	5,232
7:50-7:55	36	165	157	138	35	460	5,520
7:55-8:00	40	140	133	82	47	355	4,260
8:00-8:05	44	109	127	78	43	314	3,768
8:05-8:10	45	102	112	58	41	272	3,264
(b) Houston III B							
7:00-7:05	46	116	130	83	45	329	3,948
7:05-7:10	45	128	135	79	44	342	4,104
7:10-7:15	44	156	166	91	40	413	4,956
7:15-7:20	43	163	158	106	42	427	5,124
7:20-7:25	44	177	177	118	40	472	5,664
7:25-7:30	41	165	167	118	41	450	5,400
7:30-7:35	38	162	155	126	37	443	5,316
7:35-7:40	38	154	153	132	36	439	5,268
7:40-7:45	41	148	165	127	37	440	5,280
7:45-7:50	41	161	150	120	39	431	5,172
7:50-7:55	38	146	139	103	40	388	4,656

termed "volume control" studies because a second objective was to control the amount of traffic using the freeway in an attempt to keep this volume below practical capacity. It was found that the volumes during the studies exceeded practical capacity, but a marked improvement of operating conditions was noted and a significant amount of travel time was saved as a result of freeway volume control.

The influence of traffic entering the freeway lanes from a ramp can be compared to water flowing into a main stream channel from a side channel. With no side channel flow, the main channel flow is uniform, but when a side flow is introduced, turbulence is created causing a backwater curve on both the main channel and the side channel. The flow in the main channel only a short distance below the point of entry of the side channel again becomes uniform. If the main channel is widened and the side flow introduced parallel to the main channel flow, the turbulence is virtually eliminated.

TABLE 5

VOLUME-SPEED DATA FOR HOUSTON IV, GULF FREEWAY
5-MIN INTERVALS, MORNING PEAK PERIOD



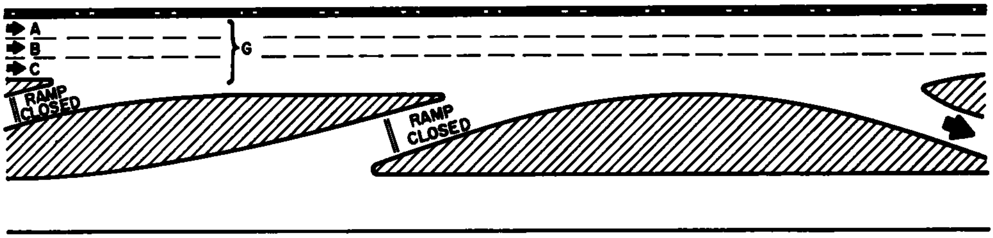
Time	Inside Lane Speed	5-Min Volumes			Outside Lane Speed	Total Vol 3 Lanes at A	Equiv Hourly Rate of Flow (vph)	5-Min Volumes		Calculated Total Vol 3 Lanes at G	Equiv Hourly Rate of Flow (vph)
	A	A	B	C	C			D	F		
7:00-7:05	47	147	164	77	45	388	4,656	39	10	417	5,004
7:05-7:10	46	133	157	92	41	382	4,584	35	13	404	4,848
7:10-7:15	43	144	171	87	41	402	4,824	53	16	439	5,268
7:15-7:20	43	150	167	129	38	446	5,352	38	21	463	5,556
7:20-7:25	39	159	169	116	36	444	5,328	48	21	471	5,652
7:25-7:30	39	136	147	131	33	414	4,968	39	17	436	5,232
7:30-7:35	38	155	182	107	30	444	5,352	47	14	477	5,724
7:35-7:40	35	156	154	137	31	447	5,364	45	25	467	5,604
7:40-7:45	39	151	175	105	33	431	5,172	55	21	465	5,580
7:45-7:50	41	156	152	110	29	418	5,016	50	33	435	5,220
7:50-7:55	41	146	164	103	36	413	4,956	54	25	442	5,304
7:55-8:00	45	114	132	77	40	323	3,876	67	31	359	4,308
8:00-8:05	45	114	125	66	41	305	3,660	42	19	328	3,936
8:05-8:10	46	117	112	74	41	303	3,636	58	15	346	4,152
8:10-8:15	46	100	124	53	43	277	3,324	70	14	333	3,996
8:15-8:20	46	103	129	53	43	285	3,420	49	12	322	3,864

Many freeways are becoming congested during certain peak periods of the day. Often during these periods, more vehicles attempt to utilize the freeways than can be accommodated. When these conditions occur, only a few vehicles entering from a ramp can cause turbulence in the freeway lanes which results in congestion or stoppage because both through and entering traffic are forced to wait their turn to pass through this critical area. This accumulation or "head" of traffic creates very undesirable operating conditions on the through freeway lanes. The number of vehicles thus forced to operate under these undesirable conditions is many times greater than the number of vehicles causing the turbulence by entering from the ramp.

Two studies were made on the Gulf Freeway in Houston, and one study on the Central Expressway in Dallas, to determine the practicability of controlling freeway volumes by closing entrance ramps near the freeway terminal or dispersal system. On the Gulf Freeway in Houston, all inbound entrance ramps located a distance of approximately $1\frac{1}{4}$ mi back of the downtown dispersal system were closed during morning peak periods. On the Central Expressway in Dallas, the ramps were closed for approximately $1\frac{1}{2}$ mi back of the downtown terminal. All "short-trip traffic" normally entering the freeway was diverted to the frontage road or other parallel facility. Motion picture surveys and travel-time evaluations were made of conditions with the ramps open and with the ramps closed to determine the effect of this denial of access to the freeways on the operation of the facilities.

TABLE 6

VOLUME-SPEED DATA FOR HOUSTON V, GULF FREEWAY 5-MIN INTERVALS, MORNING PEAK PERIOD



Time	Inside Lane Speed A	5-Min Volumes			Outside Lane Speed C	Total Vol 3 Lanes at A	Equiv Hourly Rate of Flow (vph)
		A	B	C			
7:10-7:15	42	172	176	124	42	472	5,664
7:15-7:20	42	160	160	120	41	440	5,280
7:20-7:25	41	159	167	119	41	445	5,340
7:25-7:30	40	154	167	119	41	440	5,280
7:30-7:35	37	166	167	127	35	460	5,520
7:35-7:40	37	164	172	119	36	455	5,460
7:40-7:45	41	151	158	129	39	438	5,256
7:45-7:50	42	151	158	117	40	426	5,112
7:50-7:55	43	148	161	122	41	431	5,172
7:55-8:00	47	120	134	76	43	330	3,960
8:00-8:05	47	117	138	79	44	334	4,008
8:05-8:10	46	106	117	83	45	306	3,672
8:10-8:15	46	111	133	67	43	311	3,732

Volume Control Studies—Gulf Freeway, Houston

Studies designated Houston IIIa, Houston IIIb, and Houston V, were made with the inbound entrance ramps closed from the study area to the dispersal system during the morning peak periods.

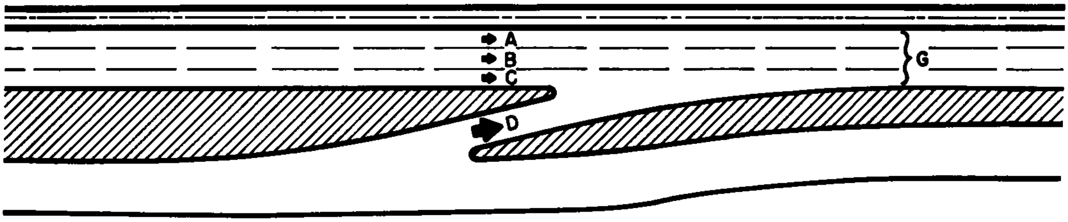
Five-minute volumes by lanes are shown in Figures 9, 10, and 11. Total peak-hour volumes are given in Table 9 including both freeway and frontage road traffic. Values given in this table indicate that the increase in frontage road volume was approximately the same as the decrease in volume on the through lanes.

The effect of volume control on the speed of traffic using the through lanes is shown in Figure 12. As mentioned earlier, 5-min average speeds do not adequately describe the poor operating conditions experienced during the Houston I and Houston II studies. The interference of ramp traffic caused reductions in speed, momentary stoppages, and stop-and-go operation during peak flow periods of both studies. Traffic flow during the studies made with the ramps closed was quite smooth and uniform with slightly higher speeds.

The speed of traffic in one freeway lane has a great influence on the speed in adjacent lanes. This influence of the speed of one lane on the speed of another is termed "speed sympathy." As shown in Figures 13 and 14, the differential in 5-min average speeds was never more than 5.5 mph between any of the through lanes during either the Houston II or Houston IIIa study. The reason for this "speed sympathy" is quite evident from viewing the motion pictures. When a stoppage or speed reduction oc-

TABLE 7

VOLUME-SPEED DATA FOR DALLAS I, CENTRAL EXPRESSWAY 5-MIN INTERVALS, MORNING PEAK PERIOD



Time	Inside Lane Speed	5-Min Volumes			Outside Lane Speed	Total Vol 3 Lanes at A	Equiv Hourly Rate of Flow (vph)	5-Min Volumes	Calculated Total Vol 3 Lanes at G	Equiv Hourly Rate of Flow (vph)
	A	A	B	C	C			D		
7:10-7:15	45	103	121	65	41	289	3,468	24	313	3,756
7:15-7:20	47	115	111	74	40	300	3,600	22	322	3,864
7:20-7:25	45	137	141	65	41	343	4,116	38	381	4,572
7:25-7:30	44	174	163	103	38	440	5,280	33	473	5,676
7:30-7:35	40	156	146	112	36	414	4,968	14	428	5,136
7:35-7:40	36	166	170	130	32	466	5,592	38	504	6,048
7:40-7:45	35	161	147	129	29	437	5,244	23	460	5,520
7:45-7:50	32	163	150	128	27	441	5,292	37	478	5,736
7:50-7:55	35	155	156	140	23	451	5,412	27	478	5,736
7:55-8:00	39	145	137	110	36	392	4,704	34	426	5,112
8:00-8:05	42	133	128	84	39	345	4,140	32	377	4,524
8:05-8:10	44	154	146	97	33	397	4,764	35	432	5,184
8:10-8:15	39	128	139	111	36	378	4,536	24	402	4,824
8:15-8:20	41	150	144	90	37	384	4,608	44	428	5,136
8:20-8:25	42	132	144	94	38	370	4,440	21	391	4,692
8:25-8:30	43	126	126	89	39	341	4,092	24	365	4,380
8:30-8:35	42	127	122	76	39	325	3,900	25	350	4,200
8:35-8:40	44	112	100	56	41	268	3,216	23	291	3,492
8:40-8:45	45	86	110	43	38	239	2,868	23	262	3,144

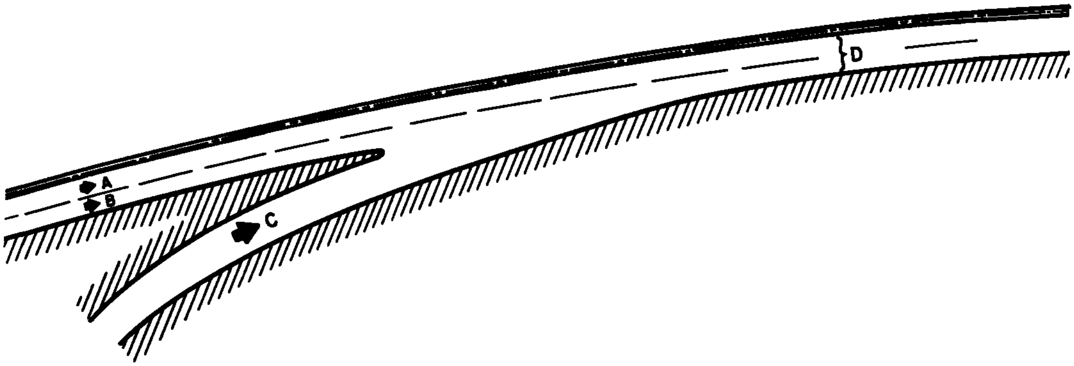
curs in one freeway lane, trailing vehicles in this lane begin weaving to other lanes in an effort to maintain their desired speeds. This quickly absorbs the available gaps in the other streams which results in headway adjustments and a corresponding decrease in speed. "Speed sympathy" is an important consideration because a forced reduction in speed in the outside lane directly affects traffic operation in the adjacent through lanes. Thus by eliminating interference to outside lane traffic by volume control, the average speed of all lanes was increased.

Both sections of freeway studies had 50 mph maximum and 40 mph minimum speed limits in effect during all of the studies. The effect of these speed limits is evidenced by the fact that less than 3 percent of the vehicles in all lanes traveled at a speed greater than 50 mph and only one vehicle traveled at a speed of over 60 mph during any of the studies. The 5-min average speed during the offpeak periods was approximately 45 mph.

Speed-volume relationships given in Tables 2 through 8 indicate that even with the ramps closed in the study area, volumes on the through lane were sufficiently high to cause a reduced speed of operation of the through lanes. These 5-min average values, although not adequately showing the

TABLE 8

VOLUME-SPEED DATA FOR FORT WORTH I, EAST-WEST FREEWAY 5-MIN INTERVALS, MORNING PEAK PERIOD



Time	Inside Lane Speed A	5-Min Volumes A	5-Min Volumes B	Outside Lane Speed B	Total Vol 2 Lanes at A	Equiv Hourly Rate of Flow (vph)	5-Min Volumes C	Calculated Total Vol 2 Lanes at D	Equiv Hourly Rate of Flow (vph)
7:45-7:50	50	102	74	43	176	2,112	47	223	2,676
7:50-7:55	48	79	83	41	162	1,944	30	192	2,304
7:55-8:00	52	53	52	44	105	1,260	46	151	1,812
8:00-8:05	52	49	48	48	97	1,164	36	133	1,596
8:05-8:10	51	38	39	45	77	924	22	99	1,188
8:10-8:15	51	39	31	45	70	840	39	109	1,308
8:15-8:20	53	40	32	47	72	864	24	96	1,152
8:20-8:25	49	48	31	43	79	948	39	118	1,416
8:25-8:30	52	39	43	46	82	984	27	109	1,308
8:30-8:35	51	39	31	45	70	840	23	93	1,116
8:35-8:40	52	37	38	45	75	900	27	102	1,224

poor conditions with the ramps open, indicate improved speed-volume relationships when the ramps were closed.

The following data give a comparison of the worst operating condition observed during the before-and-after volume control studies:

Houston II - Outside Lane - Before Study

5-min average speed - 23 mph
5-min volume - 127 - equivalent hourly rate of flow - 1,524 vph

Houston IIIa - Outside Lane - After Study

5-min average speed - 33 mph
5-min volume - 128 - equivalent hourly rate of flow - 1,536 vph

Houston IIIb - Outside Lane - After Study

5-min average speed - 36 mph
5-min volume - 132 - equivalent hourly rate of flow - 1,584 vph

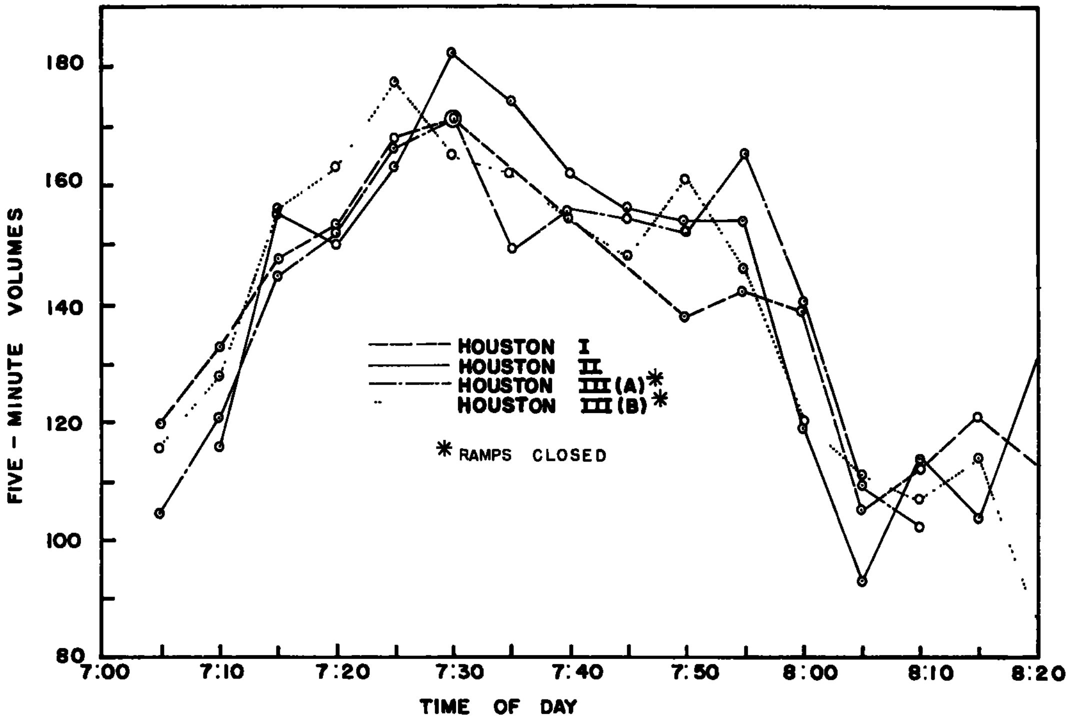


Figure 9. Consecutive 5-min volumes, inside lane, morning peak period, all Houston studies.

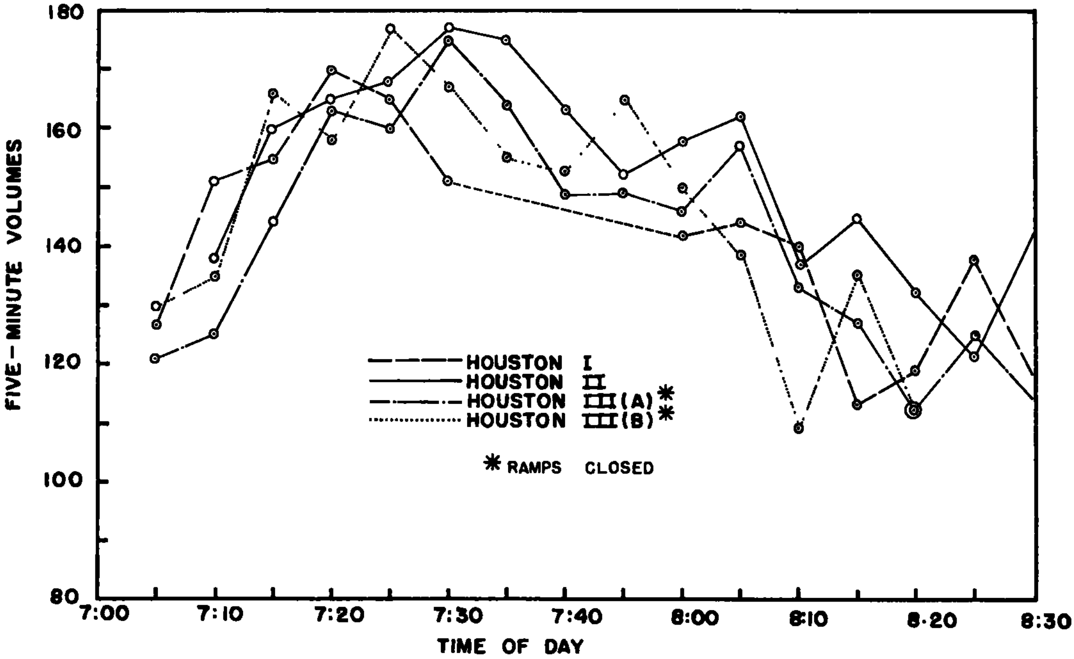


Figure 10. Consecutive 5-min volumes, middle lane, morning peak period, all Houston studies.

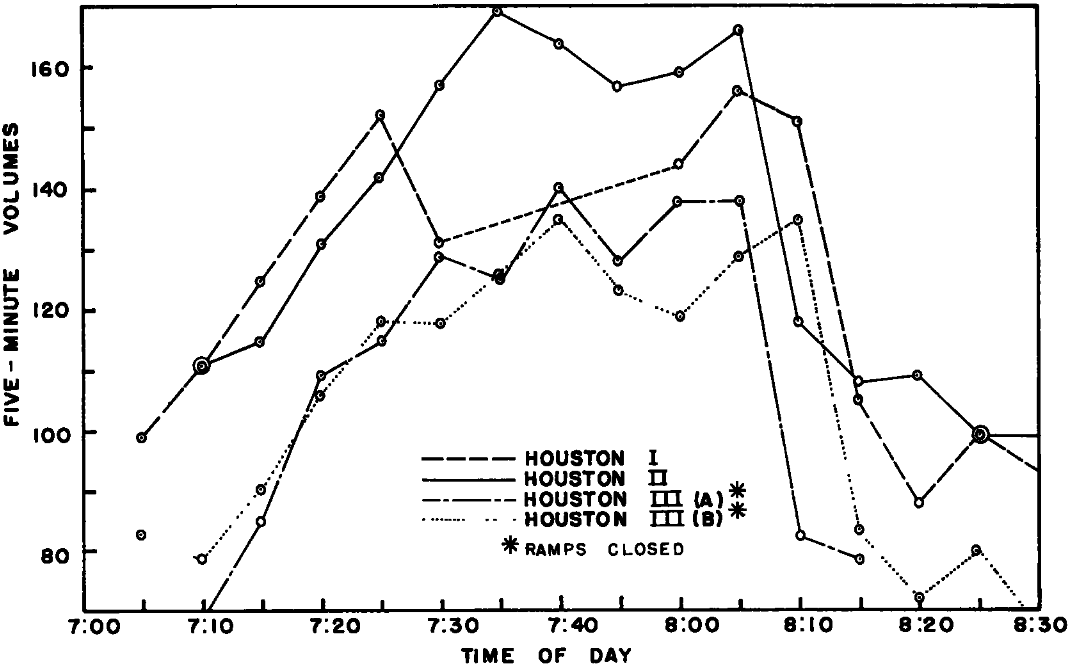


Figure 11. Consecutive 5-min volumes, outside lane, morning peak period, all Houston studies.

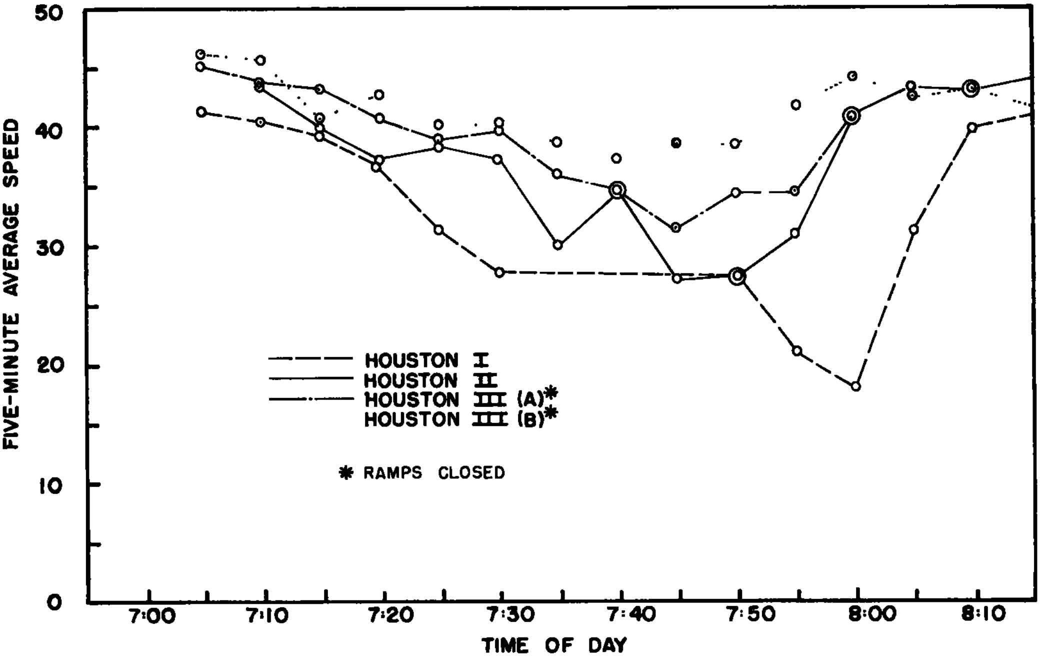


Figure 12. Consecutive 5-min average speeds, outside lane, morning peak period, all Houston studies.

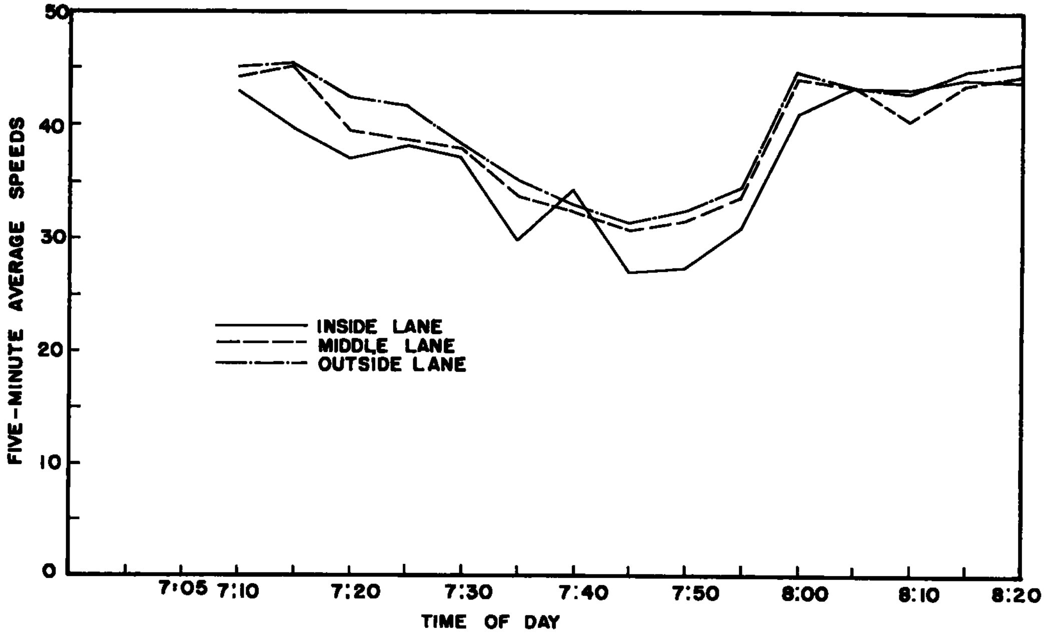


Figure 13. Consecutive 5-min average speeds, all lanes, Houston II.

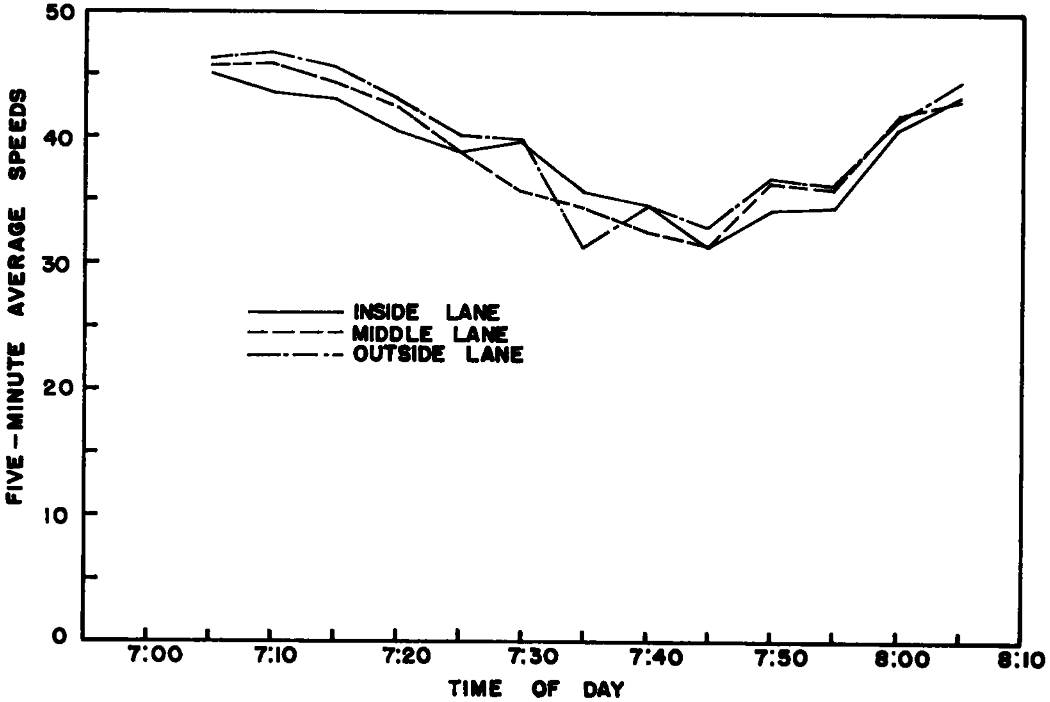


Figure 14. Consecutive 5-min average speeds, all lanes, Houston III(A)—ramps closed.

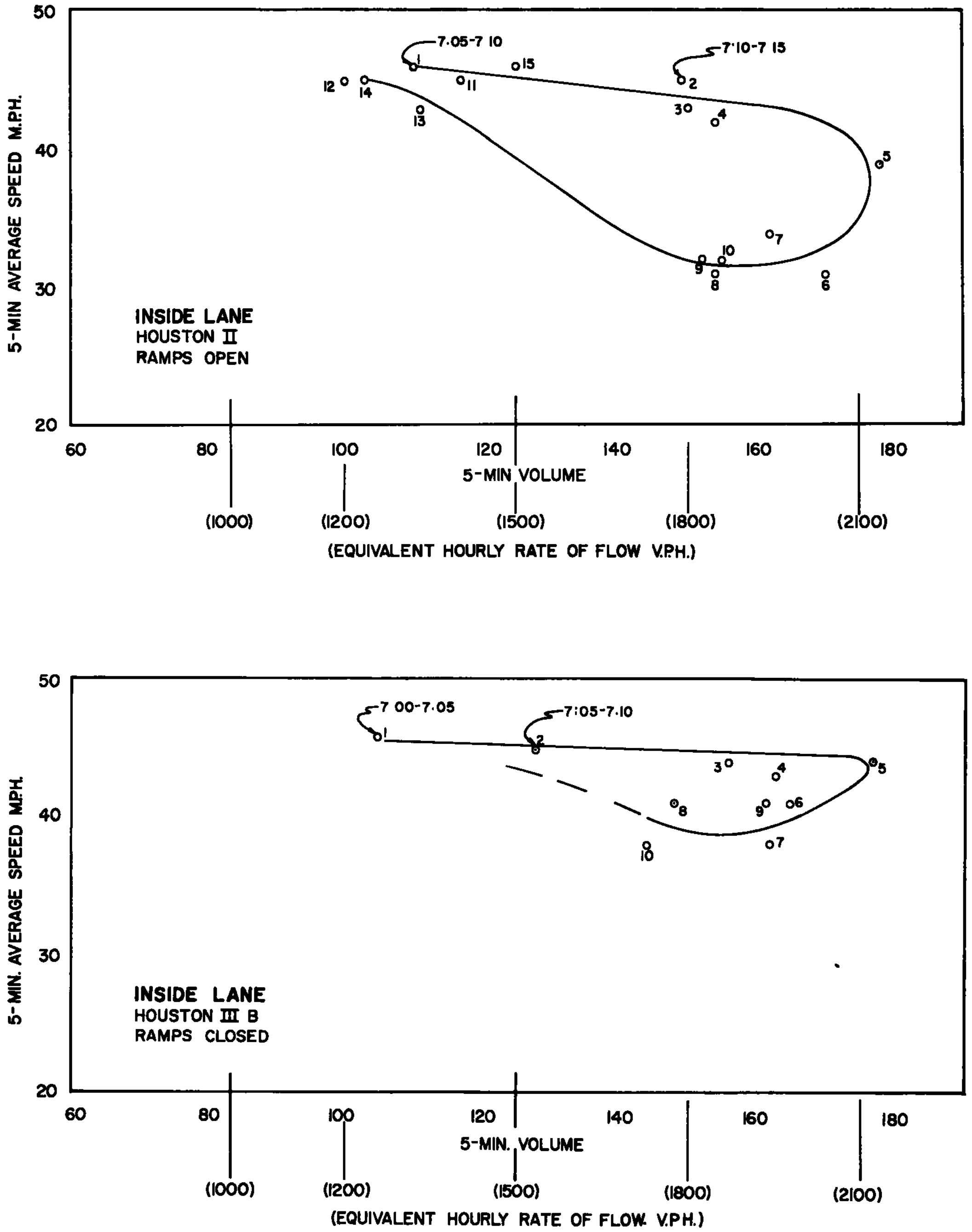


Figure 15. Speed-volume relationships before and after volume control—Gulf Freeway, Houston.

TABLE 9

TOTAL VOLUMES AND LANE VOLUMES ON FREEWAY, INCLUDING FRONTAGE ROAD VOLUMES, FOR PEAK HOUR AND PEAK PERIOD

Study	Freeway Lanes			Frontage Road	Total
	Inside	Middle	Outside		
	Peak Hour Volumes—7:10-8:10 A.M.				
Houston II	1,752	1,723	1,564	652	5,691
Houston III (a)[a]	1,761	1,779	1,320	964	5,824
Houston III (b)[a]	1,770	1,786	1,279	937	5,772
	Peak Period Volumes—7:20 to 7:55 A.M.				
Houston II	1,125	1,131	1,140	238	3,634
Houston III (a)[a]	1,100	1,113	908	450	3,571
Houston III (b)[a]	1,106	1,113	844	614	3,677

[a] Ramp closed.

Houston V - Outside Lane - After Study

5-min average speed - 35 mph
5-min volume - 127 - equivalent hourly rate of flow - 1,524 vph

From these data it may be seen that with the ramps closed the average speed in the critical outside lane never dropped below 33 mph. With the entrance ramps open, the average speed dropped to 23 mph while carrying approximately the same volume of traffic. Several complete stoppages of traffic regularly occurred during the peak periods of flow with the ramps open, while none were observed during the volume control studies.

Volume-speed relationships for the inside lane are shown in Figure 15 for the Houston II and Houston IIIb studies. Smooth curves have been drawn to illustrate the characteristic loop of speed reduction with volume increase and recovery to normal speed after passage of peak flow.

Comparison of these two curves shows that the effect of the entrance ramp was reflected on the operation in the inside lane. Comparisons of the two curves with the data above indicate that volume control had the similar effect on improving the operation in the inside lane as well as the outside lane.

Travel Time Studies—Gulf Freeway, Houston

Travel time studies were made on the Gulf Freeway before and during the volume control studies on both the freeway through lanes and the frontage roads. Because these studies were taken at random, both as to time and lane traveled, it was not practical to use less than 15-min periods for comparison.

The studies were compared by computing the time consumed by the total

TABLE 10

TIME CONSUMED IN VEHICLE MINUTES
FOR 15-MIN TIME PERIODS

Time	Through Lanes	Frontage Road	Ramp	Total
		Before Studies (Ramps Open)		
7:15-7:30 A.M.	3,400	624	107	4,131
7:30-7:45 A.M.	3,030	660	1,131	4,822
7:45-8:00 A.M.	2,566	720	211	3,498
				12,451
		After Studies (Ramps Closed)		
7:15-7:30 A.M.	2,044	772		2,816
7:30-7:45 A.M.	2,350	953		3,303
7:45-8:00 A.M.	2,550	951		3,501
				9,620

inbound traffic (through lanes and frontage road) from a point in the study area to a point at the beginning of the dispersal system—a distance of approximately 1 mi. This time expressed in vehicle minutes, is based on the average travel time during a 15-min period (through lanes and frontage road) and the delay experienced by ramp traffic during the before study. This comparison is given in Table 10.

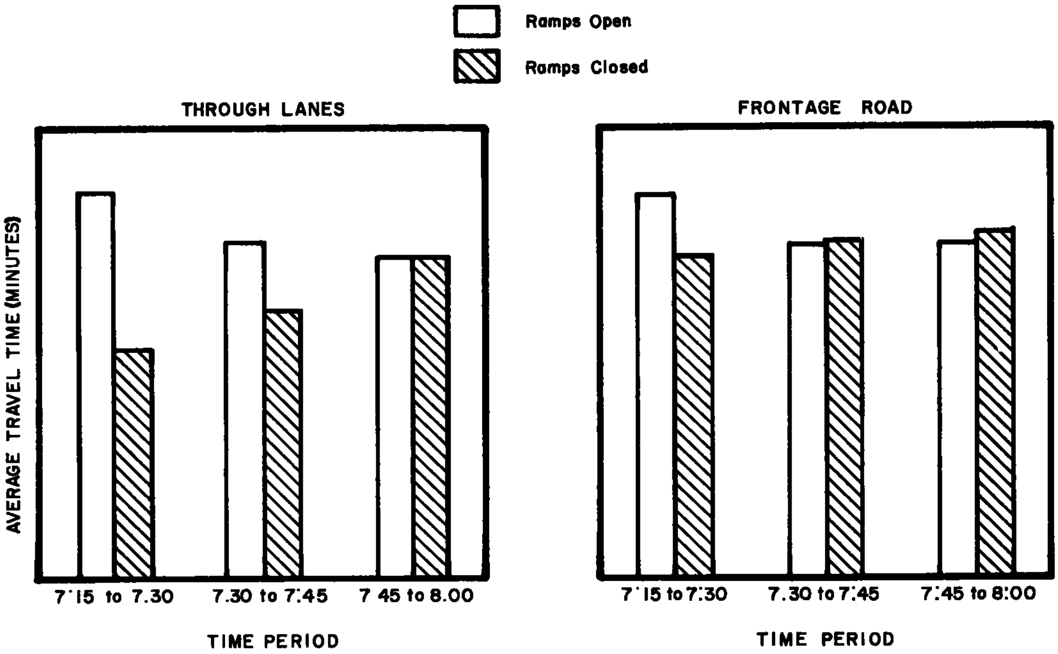


Figure 16. Comparison of average travel time, volume control study—Gulf Freeway.

Figure 16 shows the average travel time by 15-min periods for the through lanes and frontage road. Travel time through the study area on the through lanes was reduced from 2 min 35 sec with the entrance ramps open to 1 min 31 sec with the entrance ramps closed during the period 7:15 to 7:30 A.M. and from 2 min 15 sec to 1 min 47 sec during the period 7:30 to 7:45 A.M. There was no difference for the period from 7:45 to 8:00 A.M.

Comparison of the before and after studies in Table 9 shows that volume control resulted in a saving to the total inbound traffic of 2,831 veh-min or 47.2 veh-hr.

The delay experienced by entering ramp traffic was added to the time consumed by through lane traffic because this delay was caused by congestion on the through lanes. The maximum delay occurred during the 7:30 to 7:45 A.M. period, when 1,131 veh-min, or nearly 25 percent of the vehicle-minutes for this period, was consumed by vehicles waiting to enter the through lanes.

Inbound Gulf Freeway traffic is dispersed in the central business district by a pair of one-way streets which provides adequate capacity to accommodate maximum possible flow on the through lanes and frontage road.

Volume Control Study—Central Expressway, Dallas

Studies similar to those made on the Gulf Freeway in Houston were made on the Central Expressway in Dallas to determine the effect of volume control on the operation of that facility. There were two major differences between the Houston and Dallas studies. First, the ramps were closed only one morning in Dallas, whereas in Houston the ramps were closed each morning for two weeks prior to the study. The second and more significant difference was the fact that an adequate dispersal system was not completed for the Central Expressway. The freeway section ended at the edge of the central business district. The facility through the central business district was a surface street with no access control.

An electronic traffic survey device designed for monitoring freeway operations continuously over long periods of time was installed at the Fitzhugh Street overpass on the Central Expressway in Dallas. The field installation consisted of two radar vehicle detectors located above the center of the inside and the middle inbound lanes, and a radar speed meter installed on the right shoulder of the inbound freeway lanes as shown in Figure 17.

Impulses from the detectors were transmitted over telephone wires to the office of the Department of Traffic Control in the Dallas City Hall. The instantaneous impulses for both lanes were averaged and 67 percent of the change in volume from the previous averaging interval was added or subtracted and the resultant plotted on a time graph, as shown in Figure 18. Because the instrumentation of the monitor equipment was based on a constant rate of flow, and because traffic flow was intermittent rather than constant, it was determined that there was no exact correlation between the actual freeway volume and the indicated value. However, it was determined that the indicated values would reflect the general pattern of volume change.

The radar speed meter was aligned and adjusted to record the speed

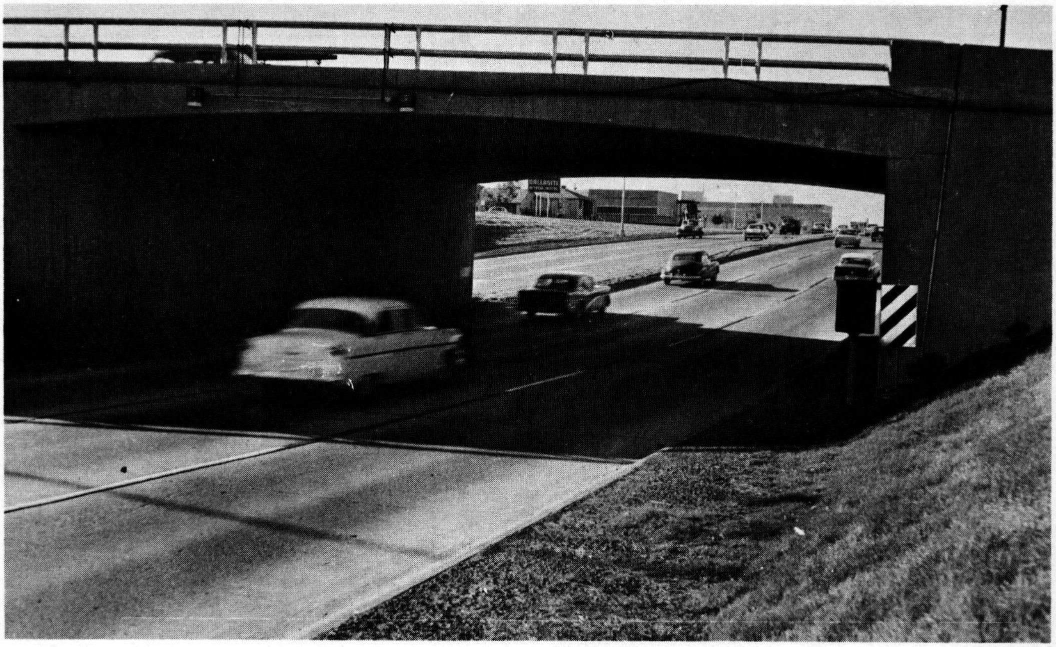


Figure 17. Field installation of freeway monitor.

of traffic on all three inbound lanes. During low volume conditions, the speed of almost every vehicle was recorded individually. However, the speeds of only the fastest vehicles were detected when vehicles passed in closely spaced groups. The speed data were transmitted over telephone lines and were recorded on a time graph. The volume and speed graphs were coordinated so that the data for any specific time period could be taken from the two graphs. Data taken by this process are referred to as "Monitor Data" to distinguish them from data taken by the motion picture survey method which was used during both the Dallas I study and the Dallas II (volume control) study.

Table 11 is a tabulation of the peak period volumes in the inside, middle, and outside lanes for the Dallas I and Dallas II studies and the indicated volumes taken from the monitor graphs. As given in this table, there was no significant change in volume between the Dallas I and Dallas II studies.

Because motion pictures were not taken continuously during the Dallas II study, speed-volume curves were not drawn for this study. However, speed-volume curves were drawn from the data taken from the monitor time graphs as shown in Figure 19.

The results of these studies were quite similar to those of the volume control studies on the Gulf Freeway. Volume-speed relationships through the study area were greatly improved by closing the ramps during the heavy inbound peak flow. However, because the dispersal system in existence at the time of these studies was inadequate to accommodate the increased load on the frontage road, the advantage gained for traffic in the study area when the entrance ramps were closed was partially offset by the increased congestion at the end of the freeway section. Inadequate

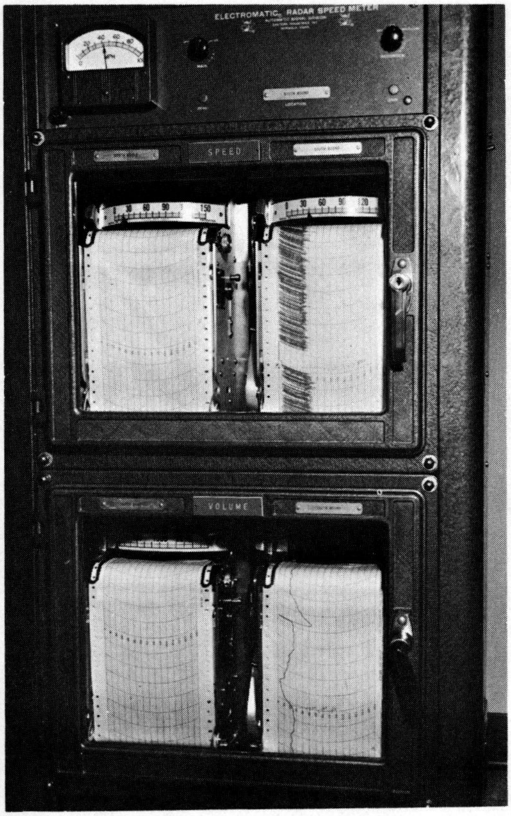


Figure 18. Time graphs of freeway monitor.

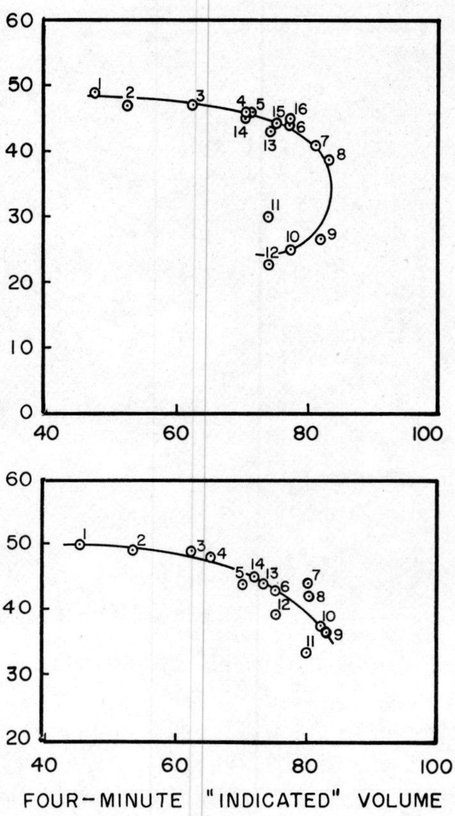


Figure 19. Speed-volume relationships—Dallas "Monitor Data."

TABLE 11

PEAK PERIOD VOLUME ON CENTRAL EXPRESSWAY

Study	Inside Lane	Middle Lane	Outside Lane	Total
Film Data 7:20 A.M. to 7:55 A.M.				
Dallas I	783	754	714	2,251
Dallas II	786	765	639	2,190

Study	Indicated Average Lane Volume (Middle and Inside Lanes)
Monitor Data 7:18 A.M. to 7:54 A.M.	
Dallas, Before	690
Dallas II	705

capacity at the freeway terminal caused severe congestion of both the through lanes and the frontage road at this point.

Summary

1. The results of these studies agree with the findings of previously reported studies 1 and 2 in regard to freeway operation and capacity, and that 5-min volumes are more indicative of freeway traffic flow conditions than are total hourly volumes.

2. The point at which a freeway survey is made should be carefully selected to avoid misleading interpretations of the results of the survey.

3. Many major operational difficulties on the freeways studied were found to be directly associated with the entrance ramps. Additional research is needed for a wide range of conditions to fully evaluate the effect of entrance ramps on freeway operation and capacity.

4. Volume control increased the efficiency of the freeway by:
   (a) Decreasing travel time on the through lanes.
   (b) Eliminating congestion created by vehicles entering the through lanes during peak periods.
   (c) Creating conditions for smoother flow and better operation.
   (d) Decreasing the speed differential between vehicles.
   (e) Increasing the average speed of all vehicles.

5. These studies indicate that volume control is necessary only during periods of peak flow which are normally less than 1 hr. During the other 23 hr of the day, the efficiency of the freeway is increased by permitting short trip use.

6. Freeway volume control is feasible and practical to improve operational efficiency on existing freeways where adequate capacity is available on parallel facilities such as continuous frontage roads or major streets.

LANE USE AND PLACEMENT

This section provides general information on freeway lane use and placement. The data were obtained from film studies made on the Houston and Dallas freeways which are 6-lane controlled-access facilities.

Lane volumes were taken at a point 176 ft in advance of an entrance ramp at each location. A white transverse line painted on the pavement was used as a reference point from which to measure volume and placement. The traffic studied was the inbound flow and the studies were made during the morning peak (7:00-8:30 A.M.), morning offpeak (9:00-10:30 A.M.), and the afternoon peak (4:00-6:00 P.M.).

Lane Use

The volume data indicated that the middle lane of the three inbound lanes on both the Gulf Freeway in Houston and Central Expressway in Dallas usually carried the greatest percentage of the total inbound flow, the inside or median lane the second highest, and the outside lane the smallest percentage.

Figures 20 (Houston) and 21 (Dallas) show typical lane usage during the offpeak hours. During these periods the inside lane carried approximately 32 percent of the inbound volume, the middle lane approximately 44 percent and the outside lane approximately 24 percent.

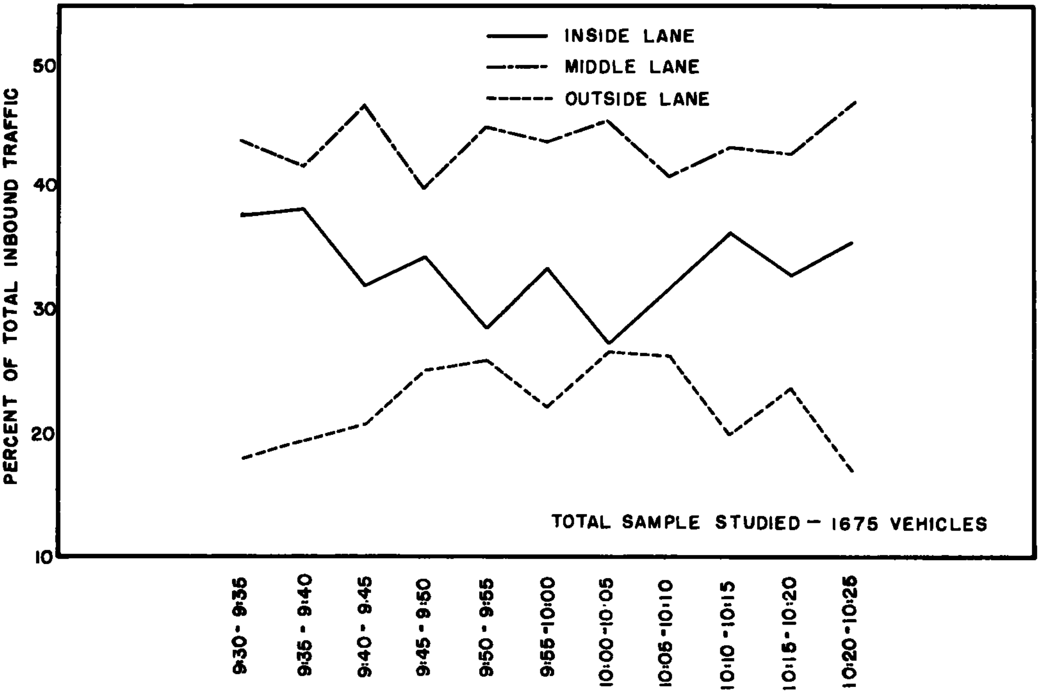


Figure 20. Lane usage—Gulf Freeway, Houston (offpeak—inbound).

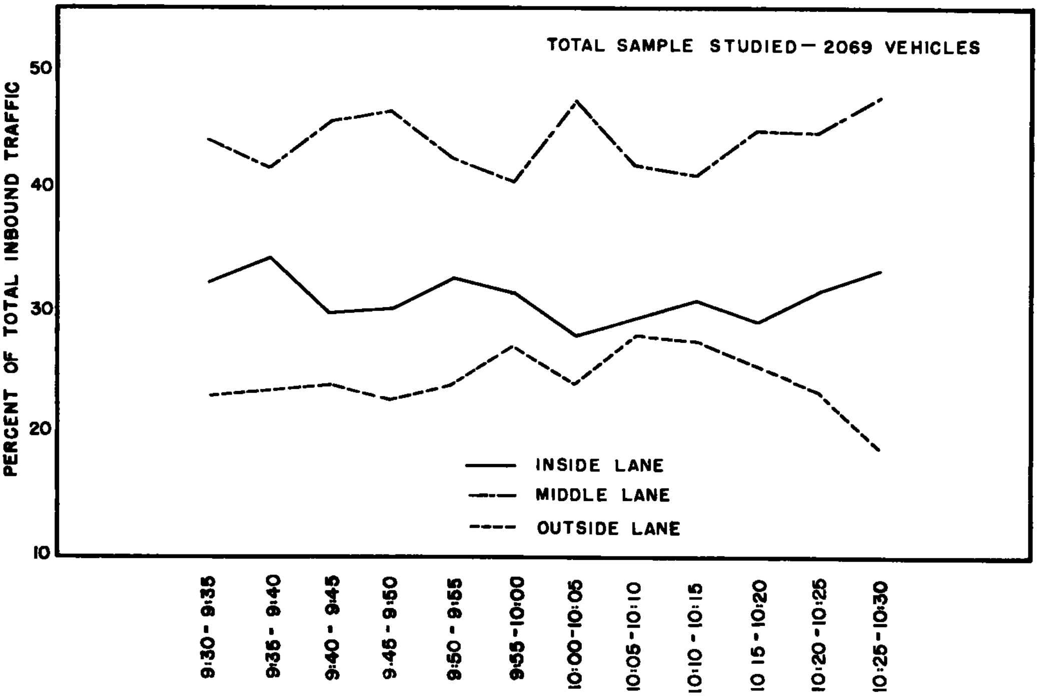


Figure 21. Lane usage—Central Expressway, Dallas (offpeak—inbound).

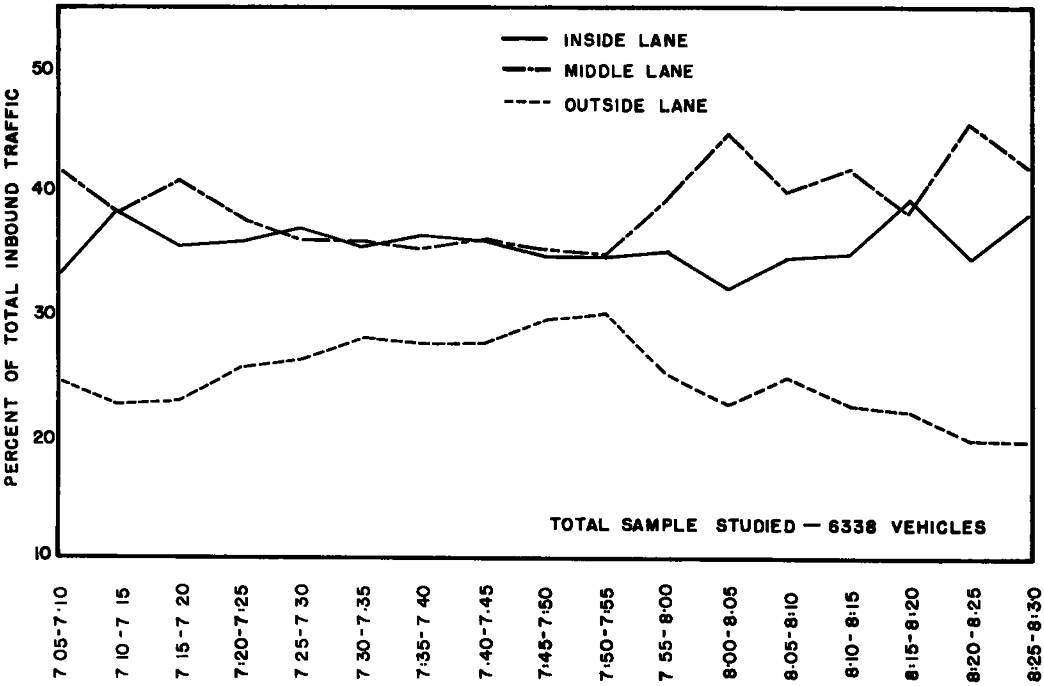


Figure 22. Lane usage—Gulf Freeway, Houston (A.M. peak—inbound).

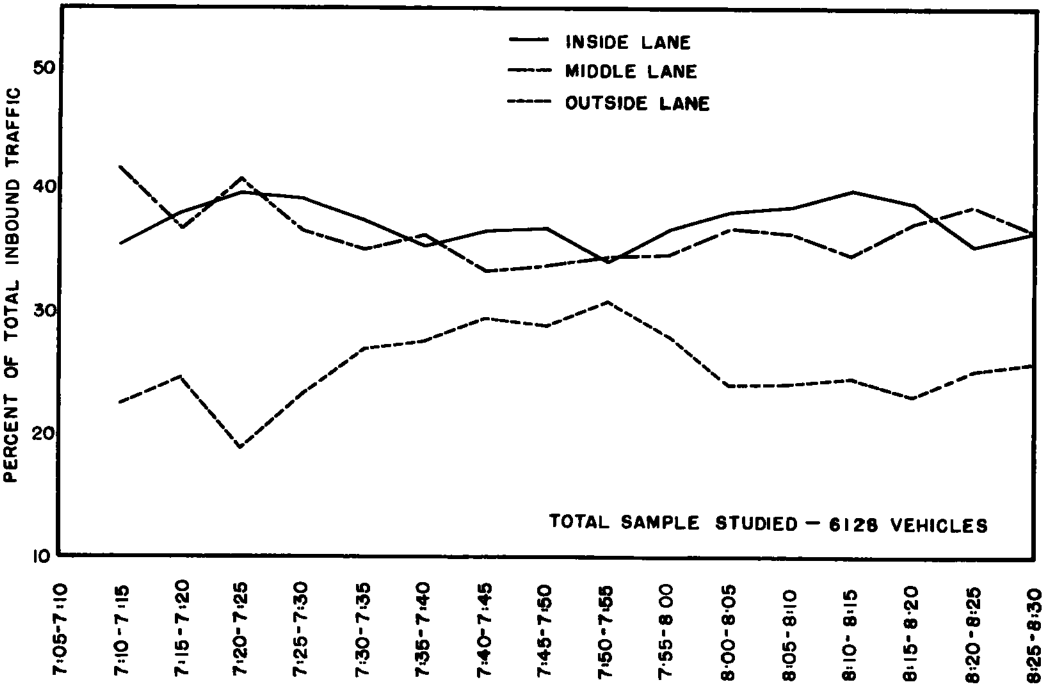


Figure 23. Lane usage—Central Expressway, Dallas (A.M. peak—inbound).

During the periods of peak traffic flow, the inside and middle lanes adjusted to the greater volumes and carried approximately the same volume of traffic. Volumes in the outside lane were slightly lower. Figures 22 (Houston) and 23 (Dallas) show typical lane usage for the morning peak periods of flow on the two freeways. For several 5-min intervals during the peak period of flow, the inside lane volume was greater than the volume in the middle lane.

For the Houston III study, during which the entrance ramps in the study area were closed to control freeway volumes, better usage of all three lanes was realized. Although the inside and middle lanes still carried the largest percentage of the total inbound traffic, the percentage carried by the outside lane was increased as shown in Figure 24.

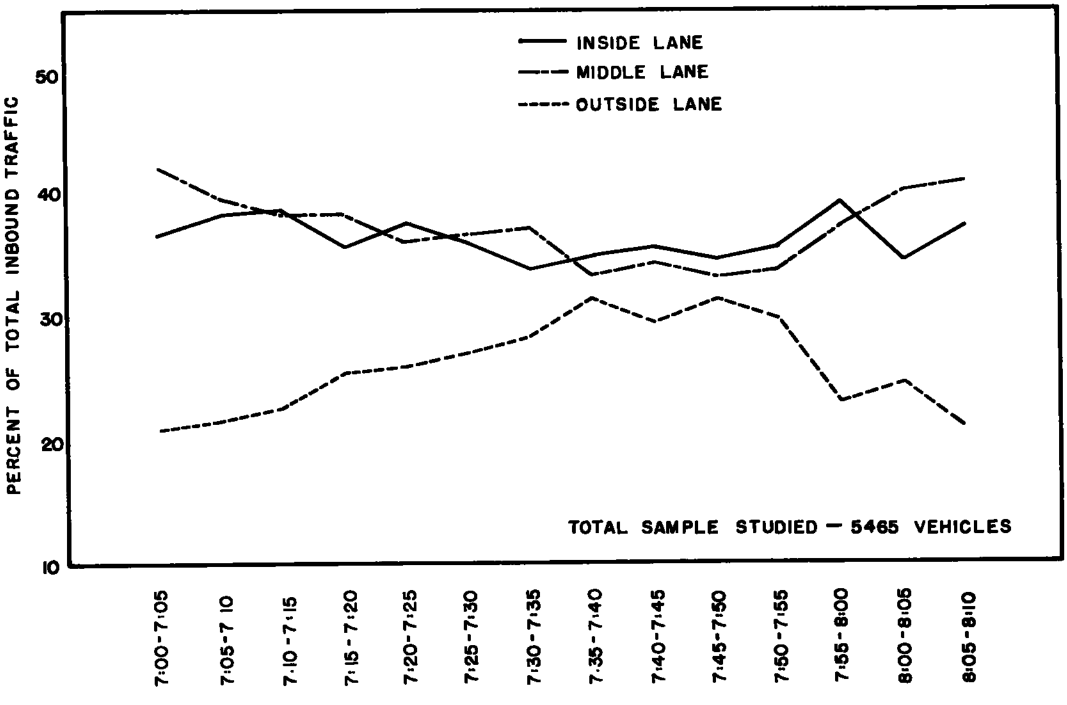


Figure 24. Lane usage—Gulf Freeway, Houston—volume control studies (ramps closed) (A.M. peak—inbound).

Vehicle Placement

Vehicle placement was measured by viewing each single frame of the film projected vertically to a table-top screen. The distance from an outside curb to either the left or right rear wheel of the vehicle was measured with a special scale when the vehicle tire was directly over the transverse line on the pavement 176 ft in advance of the entrance ramp.

To develop typical values of vehicle placement on the freeways, data on this phase of the study were tabulated for each of the three inbound lanes during each of the study periods. The average placements for these three periods for the Dallas study are shown graphically in Figures 25,

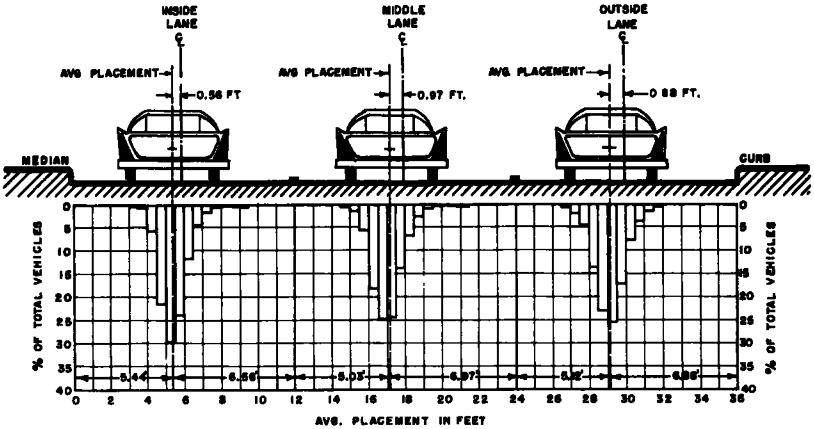


Figure 25. Vehicle placement—Dallas—inbound traffic (7:00-8:30 A.M.).

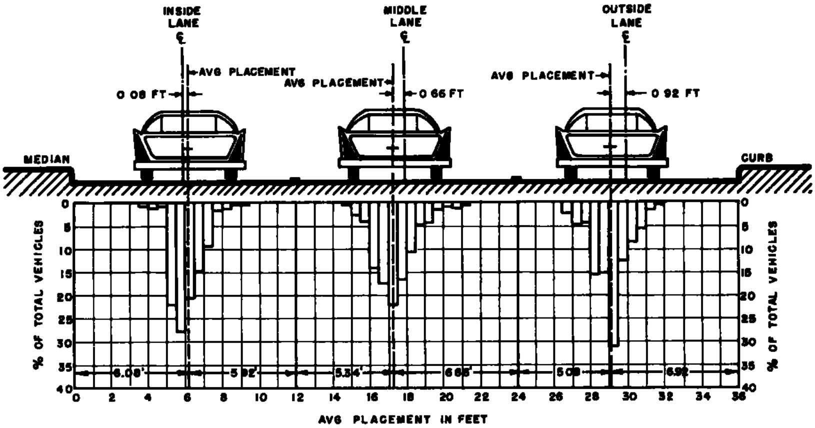


Figure 26. Vehicle placement—Dallas—inbound traffic (9:00-10:30 A.M.).

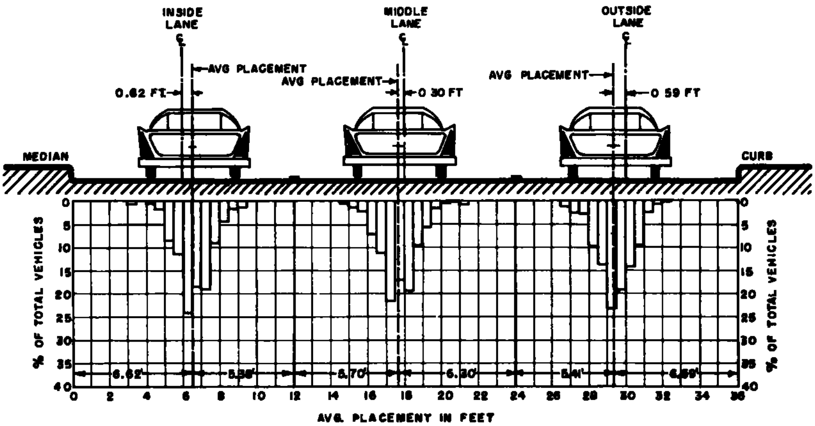
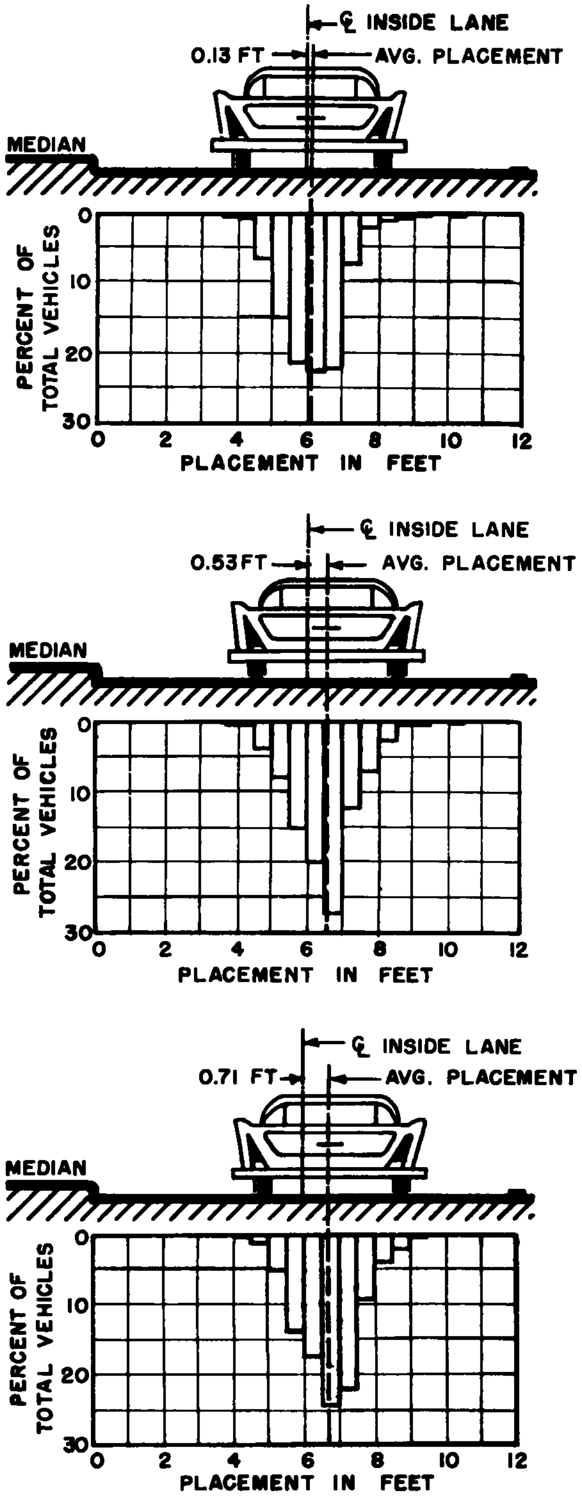


Figure 27. Vehicle placement—Dallas—inbound traffic (4:00-6:00 P.M.).



TIME
7:00 TO 8:30 AM

AVG. PLACEMENT
FROM MEDIAN TO
℄ OF VEHICLE = 6.13'

TIME
9:00 TO 10:30 AM

AVG. PLACEMENT
FROM MEDIAN TO
℄ OF VEHICLE = 6.53'

TIME
4:00 TO 5:30 PM

AVG. PLACEMENT
FROM MEDIAN TO
℄ OF VEHICLE = 6.71'

Figure 28. Average placements in median lane—Gulf Freeway.

26 and 27. These placements are typical of the results obtained in all of the placement studies.

Statistical analysis of placement data with respect to median design shows that freeway volumes have a large influence on placement at sections near entering ramps. If the average placements for inbound traffic during the morning, mid-day and afternoon periods (Figs. 25, 26, and 27) are compared, a shift is noted in vehicle placement toward the median during the morning peak flow and away from the median during the afternoon peak flow. This shift is also apparent on the Gulf Freeway in Houston as seen in Figure 28 which shows the inside or median lane placement for inbound traffic for the morning peak, offpeak, and afternoon peak periods. These data show that vehicle placements are affected by the volume of traffic flow on both sides of the median. During the morning peak, the average placement in the inside-inbound lane is approximately at the center of the lane. In the offpeak period, the average placement shifts to the right of the center of the lane and during the period of heavy flow in the opposing lanes (P.M. peak) inside-inbound lane traffic shifts further to the right. Placements in all three lanes are affected in a similar manner; therefore, a shift in placements in one lane will be reflected to the other lanes.

It is interesting to note that average vehicle placements in the outside lane are to the left of the center of the lane (Figs. 25, 26, and 27). This was found to be true in studies conducted both in the vicinity of entrance ramps and in areas distantly removed from entrance ramps. Indications are that drivers have a tendency to reference their driving, or vehicle position, by the left side of the vehicle emphasizing the need for maintaining adequate lane lines.

Summary

The study of lane use and placement data indicated the following:

1. During offpeak periods, the middle lane of three inbound traffic lanes carries the largest percentage of traffic with the outside lane carrying the smallest percentage. For peak periods of flow, the inside or median lane and the middle lane carry approximately the same percentage of traffic with the outside lane carrying a smaller percentage.
2. Vehicle placements were influenced by volume of flow on both sides of the median. Placements were noted to shift during various periods of the day and this shift was reflected in all three lanes.
3. Observations indicate that drivers have a tendency to reference their driving to their left side.
4. Vehicle placements are of little consequence in freeway operation and 12-ft lanes are adequate in width.

WEAVING

Predicted freeway volumes will demand that future freeways be designed to accommodate tremendous volumes and the number of parallel lanes will undoubtedly increase. Five, six, or possibly more lanes in each direction will be required to adequately accommodate the anticipated traffic volumes. The greater the number of lanes, the more complex will be the problem of routing traffic onto and off the freeway and lane changing will become an even more important problem than it is on existing freeways.

The motion picture studies of freeways in Texas have provided an excellent opportunity to study lane changing maneuvers on 6-lane divided freeways. Because these film studies were not conducted solely for the purpose of studying this single traffic flow characteristic, the precision of some of the measurements was restricted and the variety of conditions limited.

The purposes of this study were to determine as many characteristics of a weaving maneuver as possible from motion pictures of freeway traffic; to determine if these characteristics could be correlated with freeway volumes, speeds, geometric features of the roadway, and entering traffic; and to determine what additional studies could be made on the data taken from the films.

Although a large amount of valuable information has been accumulated, additional studies under various conditions are necessary before definite conclusions can be formulated. Additional comprehensive studies of weaving are desirable in order to provide the designer with criteria relative to the location and design of route and destination signs, spacing of entrance and exit ramps, lane use and capacity, and other design considerations. Data for this study were taken from the four film studies listed below. Each facility was a 6-lane divided freeway with the following distinctions:

1. Houston I - no barrier fence in the 4-ft paved median; entrance ramps open.
2. Houston II - a 4-ft high barrier fence in the 4-ft paved median; entrance ramps open.
3. Houston III - a 4-ft high barrier fence in the 4-ft paved median; entrance ramps from Cullen closed.
4. Dallas - no barrier fence in the 12-ft grassed median; entrance ramps open.

The four film studies are of different lengths of time due to varying conditions in filming procedure. This is reflected in the number of weaving maneuvers recorded for each study as tabulated in Table 12.

TABLE 12

NUMBER OF WEAVING MANEUVERS FOR EACH STUDY

Study	Length of Study in min	No. of Weaving Maneuvers	Average No. of Weaves per min
Houston I	237	532	2.24
Houston II	245	412	1.88
Houston III	145	235	1.62
Dallas	277	711	2.57
Total	904	1,940	2.15

Only 2 hr of observation are included in the Houston III study because the entrance ramps in the study area were closed only during the morning peak periods. The other three studies represent the sum of the morning-peak, morning-offpeak, and afternoon-peak periods.

All Houston studies were made on the same area at the Cullen Street Interchange on the Gulf Freeway (Fig. 4).

The Dallas Study was made on a similar area at the Fitzhugh Interchange on the Central Expressway (Fig. 5).

Only inbound traffic on each freeway was considered.

A 400-ft section of the freeway, which included the entrance ramps, was used for evaluation of speeds, gaps and other traffic flow characteristics necessary for the analysis of weaving maneuvers. Only weaves that began in this 400-ft section were recorded for analysis, but data relative to the weaving maneuver, such as the length and paths of weaves, were, of necessity, obtained over the entire study area.

The weaving maneuvers observed in this report were performed entirely on the 3 inbound "through" freeway lanes. The vehicles on the entrance ramps and exit ramps were not included as weaving vehicles because their maneuvers are considered more precisely in another section of this report.

Method of Study

All information used in this study was secured from 16-mm motion picture film of traffic operations on the freeway. A projectionist read the information from the pictures and recorded it on data sheets by prearranged codes. The information was transferred to punch cards and all calculations necessary to convert the data to the desired units of measure were performed and recorded on the punch cards by the use of an electronic computer. The analysis was then a matter of proper sorting and tabulation.

The code, used in recording the information, was established from several trial observations of weaving maneuvers in the motion pictures. The operator recorded the complete set of data for one weaving vehicle at one time. This required the operator to review only a portion of the film to secure all the information, thus reducing the number of re-runs of the entire length of film. For each weaving vehicle the following information was recorded:

1. Time of day to the nearest minute, read from a clock filmed in the field of view.
2. Type of vehicle (passenger car, truck, bus).
3. Lane in which the vehicle was traveling and the lane into which it weaved.
4. Location of the origin of the weaving maneuver with respect to the three areas mentioned in the description of the study areas.
5. Speed of the vehicle, determined by the frame count between two lines of known spacing and a known camera speed.
6. Length of the weaving maneuver, recorded in number of frames of film and later converted to either distance in feet or duration in time by the electronic computer.
7. Location of vehicles on the entrance ramps.
8. Whether the vehicle left the freeway on the next exit ramp or continued on the freeway.

Because the accuracy of some information depends on the perception and judgment of the projectionist, only two persons were used in an attempt to eliminate varying degrees of perception.

Discussion of Findings

Length of Weaves. Length of weaves as defined for this report, is the forward distance traveled by the weaving vehicle from the time the vehicle first indicates a weaving maneuver until the vehicle is entirely in the lane into which it is weaving. Two features limited the degree of accuracy in determining the length of the weaving maneuvers, as follows:

1. The identification of the point of beginning and the point of ending of the weaving maneuver.
2. The location and length of the area used for speed determination with respect to the location of the weaves.

These two factors are offset by the following facts:

1. Only two operators were used to collect the data.
2. The rates of acceleration for the range of speeds observed are very low.
3. Because 85 to 95 percent of the weaves were completed in only 300 ft or less, a large percentage of each weave occurred in the speed determination area.

Frequency Distribution. The lengths of weaving maneuvers are shown as cumulative frequency distribution curves for the separate studies and for the total study in Figures 29 through 33.

The average length of weave for all observations was 217 ft with lengths ranging from 50 to 900 ft. The frequency distribution curve from

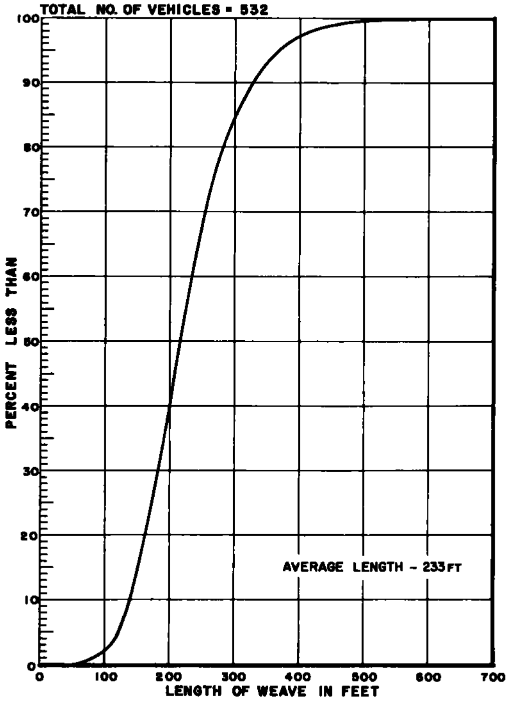


Figure 29. Distribution of weave lengths—Houston I.

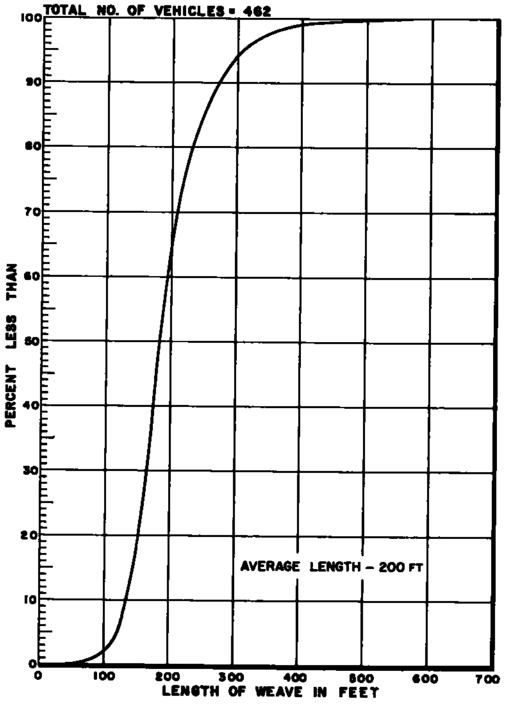


Figure 30. Distribution of weave lengths—Houston II.

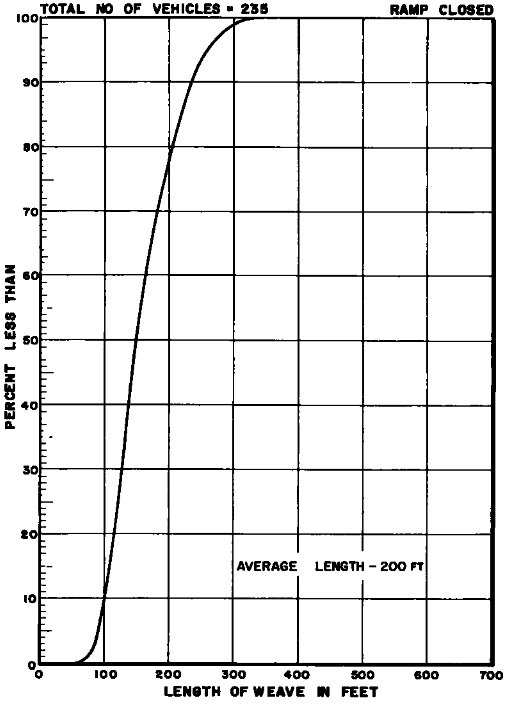


Figure 31. Distribution of weave lengths—Houston III.

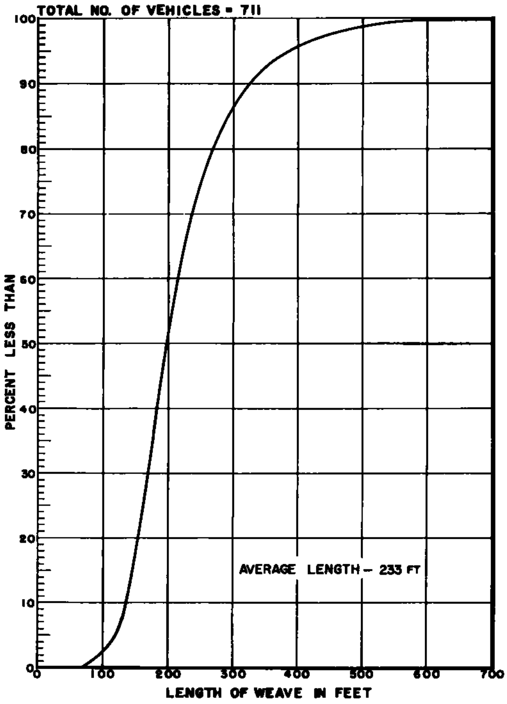


Figure 32. Distribution of weave lengths—Dallas.

the combined study increases uniformly up to 300 ft in Figure 33 and flattens out for longer lengths, indicating that 90 percent of all weaves are 300 ft or less. Using this length as a criteria for comparing the individual studies, the range of "percent less than 300 ft" was 85 percent in Houston I to 99 percent in Houston III.

The average lengths of weaves for the four studies are given in Table 13. The low value for Houston III is probably due to the fact that this study consists of two morning peak periods only, when the volume was high.

Speed-Volume-Length of Weaving Maneuvers. Speed-volume relationships have been determined for the four studies. Using as a reference the time of day recorded as an integral part of the data for each weaving maneuver, it was possible to determine the rate of flow for

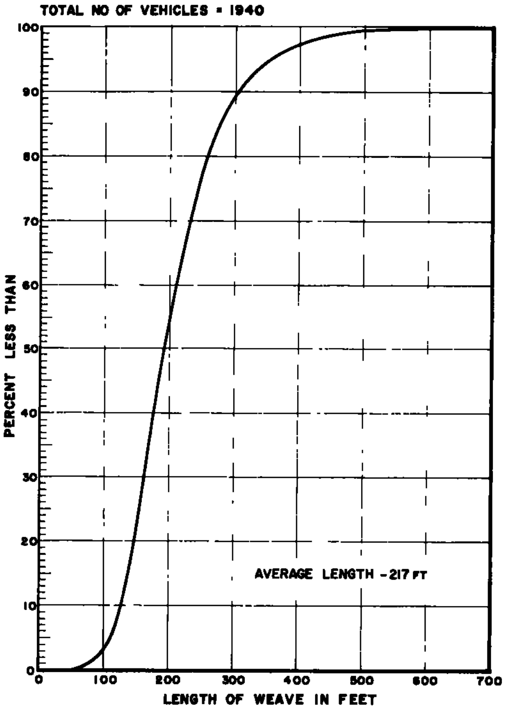


Figure 33. Distribution of weave lengths—all studies.

TABLE 13

AVERAGE LENGTH OF WEAVES

Study	Average Length in ft
Houston I	233
Houston II	200
Houston III	200
Dallas	223
Average	217

the total roadway and by lanes for each weaving maneuver studied. For this analysis 5-min volumes were expanded to equivalent hourly rates of flow and related to the average length of the weaving maneuvers for that 5-min period.

The graph in Figure 34 indicates the trend for the length of weaves for all four studies with respect to traffic flow. The equivalent rates of flow used for this analysis are average lane volumes for all three lanes. Because the outside lane volumes were lower than the middle and inside lanes, additional analyses were run using the average rates of flow for the inside and middle lanes and the rates of flow for the outside lane separately. The volumes for the average length of weaves changed slightly, but the general trend of the length decreasing as the rates of flow increased remained the same, as given in Table 14.

The average roadway speeds for the various volume levels are also shown on Figure 34. The speed decreased as the volume levels increased.

Influence of Entering Vehicles. The classification of weaving maneuvers by location of origin with respect to the entrance ramp produced significant results. The length of the section of the study area in front

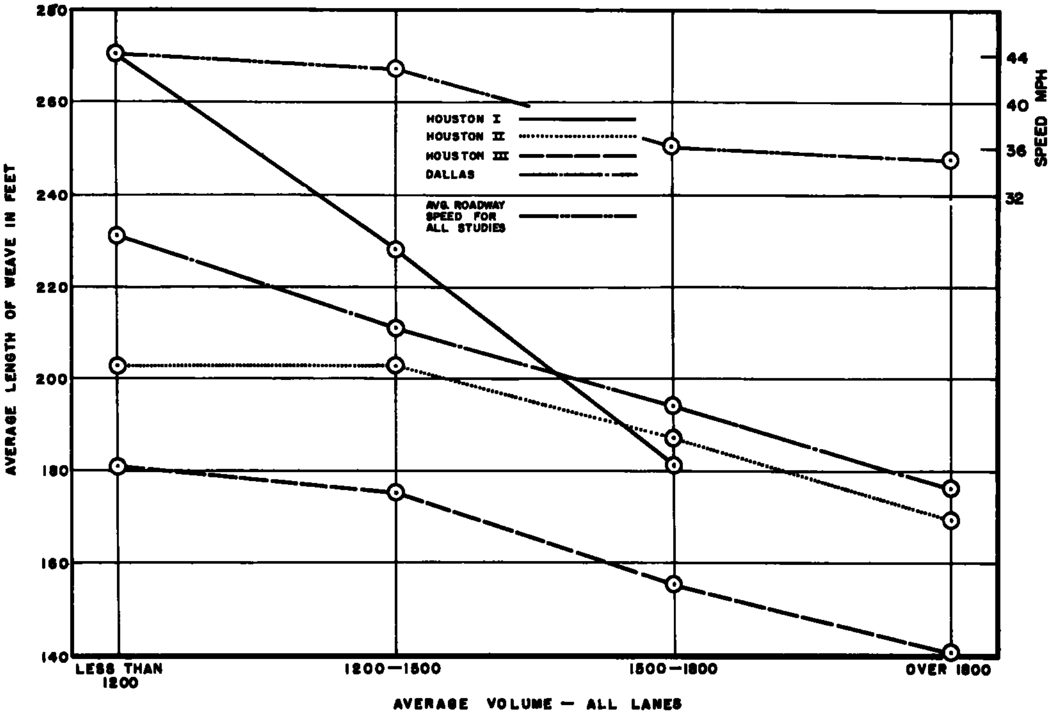


Figure 34. Length of weave as related to volume and speed.

TABLE 14

LENGTHS OF WEAVES AS RELATED TO VOLUME

Average Volume Level	Houston I	Houston II	Houston III	Dallas
Inside & Middle Lanes		Average Length in ft		
Less than 1,200	271	227		
1,200 to 1,500	255	201	181	232
1,500 to 1,800	201	204	166	207
Over 1,800	198	177	150	180
All Lanes				
Less than 1,200	270	203	181	231
1,200 to 1,500	228	203	175	211
1,500 to 1,800	181	187	155	194
Over 1,800		169	140	176
Outside Lane				
Less than 720	284	194	192	
720 to 960	238	209	176	232
960 to 1,200	221	205	172	204
1,200 to 1,440	198	178	159	210
Over 1,440	153	168	144	159
Average length of weaves in ft - 217				

TABLE 15

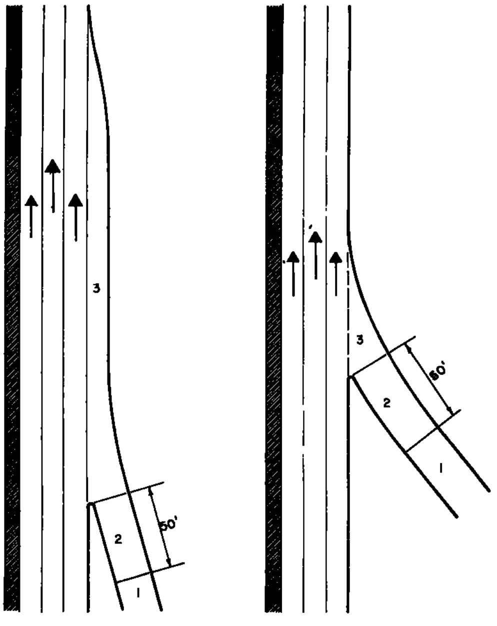
INFLUENCE OF ENTERING VEHICLES ON WEAVING

Study	Total No. of Weaves	No. of Weaves Occurring in Front of Entrance Ramp (% of Total Shown Below)			No. of Weaves Occurring Behind the Entrance Ramp (% of Total Shown Below)		
		Direction of Weave			Direction of Weave		
		Right	Left	Total	Right	Left	Total
Houston I	532	141 (26.5)	319 (60.0)	460 (86.5)	31 (5.8)	41 (7.7)	72 (13.5)
Houston II	462	108 (23.4)	292 (63.2)	400 (86.6)	24 (5.2)	38 (8.2)	62 (13.4)
Houston III	235	126 (53.6)	67 (28.5)	193 (82.1)	20 (8.5)	22 (9.4)	42 (17.9)
Dallas	711	208 (29.2)	328 (46.2)	536 (75.4)	99 (13.9)	76 (10.7)	175 (24.6)
Combined	1,940	583 (30.1)	1,006 (51.8)	1,589 (81.8)	174 (9.0)	177 (9.1)	351 (18.1)

of the entrance ramp was 225 ft, or approximately 56 percent of the total length of the study section. There were 1,589 weaves, which represents 81.8 percent of the total observations, that originated in this area. Of this percentage, 51.8 percent moved to the left away from the entrance ramp and 30 percent to the right. The same pattern is indicated by the individual studies in Table 15; that is, a large percent of weaves originated before the entrance ramp, the majority of which moved to the left. The one exception was the Houston III study, during which the entrance ramps were closed. The Dallas study has the second largest percentage of vehicles weaving to the right. This is explained in part by the large number of vehicles leaving the freeway at the next exit.

In the section of the study area past the nose of the entrance ramp the distribution of lateral movements was almost equal. Again, Dallas had a large percentage of vehicles moving to the right.

The location of vehicles on the entrance ramp was noted as part of the data for the weaving vehicles. Figure 35 shows the two types of entrance ramps involved in these studies. The ramps were divided into three areas and the location of the lead (or first) vehicle on the ramps was recorded in relation to these areas for each weaving maneuver. A notation was also made if no vehicles were on the ramp. A tabulation by study of the number of weaves occurring during each entrance condition is given in Table 16.



HOUSTON DALLAS

Figure 35. Conditions of entry.

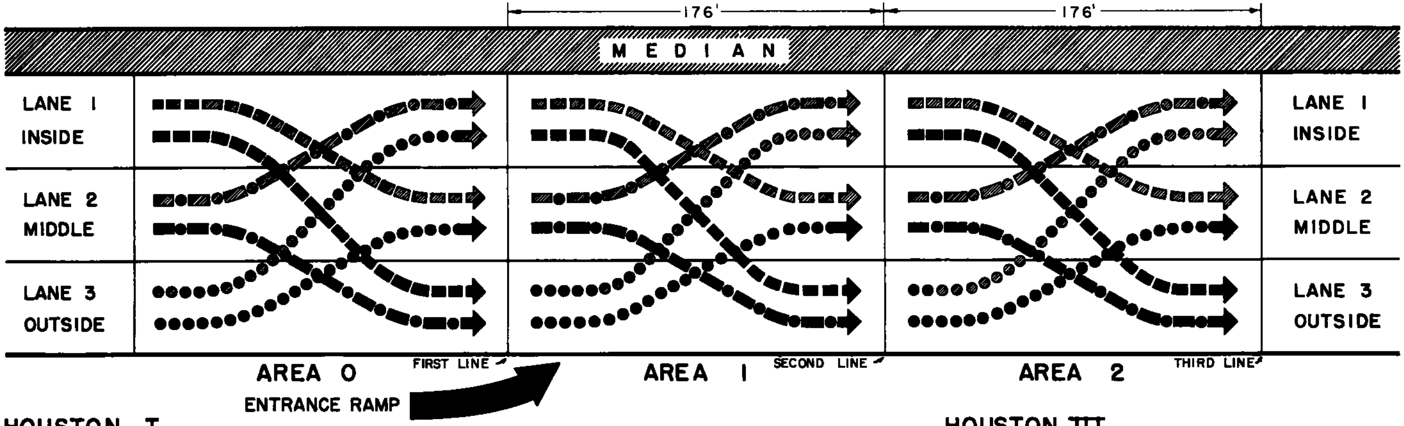
TABLE 16

NUMBER OF WEAVES OCCURRING FOR EACH ENTERING CONDITION

	Position of Entering Vehicles			
Study	0*	1	2	3
Houston I	163	68	79	222
Houston II	62	37	66	128
Houston III	Entrance Ramp Closed			
Dallas	348	67	58	238
Total	573	172	203	588

*No Vehicles on ramp.

Origin-Termination-Distribution of Weaving Vehicles. A total of 1,940 weaves was recorded from the four studies. The total for each study has been tabulated and divided into the lane and area in which the weaving maneuver began and the lane in which the weave terminated (Fig. 36). Because the length of the weaving maneuvers is not shown, this drawing does not present a true picture. However, this method of presentation is particularly useful in relating



NOTE

ARROWS INDICATE THE AREA AND LANE IN WHICH THE WEAVE BEGAN AND THE LANE IN WHICH THE WEAVE ENDED

HOUSTON I

DESIGNATION	TYPE OF WEAVE		POINT OF BEGINNING			TOTAL	% OF TOTAL
	FROM LANE	TO LANE	AREA O	AREA I	AREA 2		
▨▨▨▨	I	2	34	39	14	87	16 35
■■■■	I	3	3	2	0	5	94
●▨●▨	2	I	66	51	29	146	27 44
●■●■	2	3	47	16	17	80	15 05
◍●●◍●	3	I	3	I	0	4	75
●●●●●	3	2	104	94	12	210	39 47
TOTAL			257	203	72	532	100 00
% OF TOTAL			48 31	38 16	13 53	100 00	

HOUSTON III

DESIGNATION	TYPE OF WEAVE		POINT OF BEGINNING			TOTAL	% OF TOTAL
	FROM LANE	TO LANE	AREA O	AREA I	AREA 2		
▨▨▨▨	I	2	17	34	10	61	26 00
■■■■	I	3	0	0	I	I	40
●▨●▨	2	I	19	14	9	42	17 90
●■●■	2	3	22	53	9	84	35 70
●◍◍◍◍	3	I	0	0	0	0	0 00
●●●●●	3	2	21	13	13	47	20 00
TOTAL			79	114	42	235	100 00
% OF TOTAL			33 62	48.51	17 87	100 00	

HOUSTON II

DESIGNATION	TYPE OF WEAVE		POINT OF BEGINNING			TOTAL	% OF TOTAL
	FROM LANE	TO LANE	AREA O	AREA I	AREA 2		
▨▨▨▨	I	2	32	19	12	63	13 64
■■■■	I	3	0	0	0	0	0 0
◍▨◍▨	2	I	51	47	24	122	26 41
●■●■	2	3	33	24	12	69	14 94
◍●●●●	3	I	2	I	0	3	64
●●●●●	3	2	109	82	14	205	44 37
TOTAL			227	173	62	462	100 00
% OF TOTAL			49 13	37 45	13 42	100 00	

COMPOSITE

DESIGNATION	TYPE OF WEAVE		POINT OF BEGINNING			TOTAL	% OF TOTAL
	FROM LANE	TO LANE	AREA O	AREA I	AREA 2		
▨▨▨▨	I	2	155	128	73	356	1835
■■■■	I	3	5	5	4	14	7
●▨◍▨	2	I	238	160	108	506	26 08
●■●■	2	3	165	125	97	387	19 95
◍◍●●◍	3	I	13	2	I	16	85
●●●●●	3	2	344	249	68	661	34 07
TOTAL			920	669	351	1940	100 00
% OF TOTAL			47 43	34 48	18 09	100 00	

DALLAS

DESIGNATION	TYPE OF WEAVE		POINT OF BEGINNING			TOTAL	% OF TOTAL
	FROM LANE	TO LANE	AREA O	AREA I	AREA 2		
▨▨▨▨	I	2	72	36	37	145	20 39
■■■■	I	3	2	3	3	8	I I
◍▨●▨	2	I	102	48	46	196	27 57
●■●■	2	3	63	32	59	154	21 66
◍●◍◍◍	3	I	8	0	I	9	I 30
●●●●●	3	2	110	60	29	199	27 98
TOTAL			357	179	175	711	100 00
% OF TOTAL			50 21	25 18	24 61	100 00	

Figure 36. Origin-termination-distribution of weaving maneuvers.

the effect of entrance ramps on freeway traffic which is presented in detail in the following section of this report on weaving.

On 6-lane divided freeways that introduce the entrance and exit ramps on the right side of the through lanes, almost every vehicle in the middle and inside lanes must perform at least one and possibly two weaving maneuvers that involve the middle lane.

In this survey every weaving maneuver involved the middle lane because only the through lanes were considered. It is significant to note that even though the inside lane was least involved with weaving maneuvers, the operational characteristics of that lane, discussed in another section of this report, were almost identical to those of the middle lane.

Reasons for Weaves. It was assumed at the beginning of this study that several basic reasons for making a lane change could be determined from the motion picture films. These reasons were classified as follows:

1. To position vehicles in the appropriate lane to facilitate leaving the freeway by an exit ramp.
2. To avoid vehicles that stopped or slowed on the freeway lanes.
3. To avoid vehicles entering the freeway from entrance ramps.
4. To pass slow moving vehicles.
5. For no apparent reason.

Preliminary investigations indicated that the classification of weaves in a few of these categories was not possible from this study. Too often it relied on the judgment and speculation of the recorder.

The results of this investigation on reasons for weaves are:

1. A positive classification of purpose of weave was possible for vehicles leaving the freeway at the exit ramp in the test area, Table 17. This was the only exit ramp in view of the camera.
2. Complete lane stoppages on the freeways occurred during the peak periods, but weaving maneuvers were prevented by the increased density of all three lanes.
3. Entering vehicles appeared to have an effect on the number and lateral direction of weaves. This subject was discussed in the preceding sections and the results are presented in Tables 15 and 16.
4. The positive classifications of weaving vehicles passing slower moving vehicles were not possible from this film study. However, many vehicles that appeared to perform this maneuver were classified in one of the more specific categories listed above.

TABLE 17
WEAVING VEHICLES USING NEXT EXIT

Study	Total No. of Weaves	Weaves to the Right		
			Using Next Exit	
		No.	No.	Percent
Houston I	532	172	42	24.4
Houston II	462	132	25	18.9
Houston III	235	146	19	13.0
Dallas	711	307	136	44.3
Total	1,940	757	222	29.3

Frequency of Weaving Maneuvers. The proportion of the total traffic volume that began weaving maneuvers in the 400-ft study section ranged from 2 to 10 percent. There were considerable variations between different time periods and studies. Generally, the percentage increased as the total volume of traffic decreased as given in Table 18.

TABLE 18

FREQUENCY OF WEAVING MANEUVERS

Study	Morning Peak Period			Morning Offpeak Period			Afternoon Peak Period			Total All Periods		
	Total No. Veh.	No. of Veh. That Weaved	%	Total No. Veh.	No. of Veh. That Weaved	%	Total No. Veh.	No. of Veh. That Weaved	%	Total No. Veh.	No. of Veh. That Weaved	%
Houston I	5,506	197	3.60	2,052	107	5.21	4,773	228	4.77	12,331	532	4.31
Houston II	6,298	167	2.65	2,208	126	5.78	4,393	169	3.84	12,899	462	3.58
Houston III A*	4,851	98	2.02	-	-	-	-	-	-	4,851	98	2.02
Houston III B*	5,819	137	2.35	-	-	-	-	-	-	5,819	137	2.35
Dallas	7,070	244	3.47	1,675	147	9.25	3,496	320	9.16	12,241	771	5.81
Total	29,544	843	2.86	5,935	380	6.54	12,662	717	5.66	48,141	1,940	4.02

*Houston III was taken on two separate morning peak periods.

Recommendations for Further Study and Research

Because the study of weaving on freeways is of such broad scope, the complete analysis and correlation of the several factors affecting weaving maneuvers will require several individual investigations on special sections in order to isolate the variables. A combination of three or four of the following factors would constitute an investigation:

1. Location of the beginning of the weaving maneuver with respect to the geometric design features.
2. Length of the weaving maneuver.
3. Path of the weaving maneuver.
4. Speed of the weaving vehicle.
5. Average speed of freeway traffic.
6. Various conditions of entering traffic.
7. Purposes of weaving maneuvers.
8. Comparisons of roadway sections with different geometric design features.
9. The effect on the operational characteristics of the traffic stream by the size and frequency of gaps accepted by weaving vehicles.

Summary

Many of the results of this report are expressed in percentage to gain a common basis for comparisons of unequal study lengths and number of observations.

A summary of the findings of this weaving study is as follows:

1. A total on 1,940 observations were made from the four film studies. This represents 4.02 percent of the total volume of traffic recorded during these studies.
2. As the volume on the freeways decreased, the number of weaving

maneuvers, expressed as a percentage of total volume, increased.

3. The average length of weave for the composite study was 217 ft.

4. The average length of the weaving maneuvers decreased as the volume on the freeway increased.

5. The average length of the weaving maneuvers decreased as the average speed of the freeway traffic decreased.

6. A length of 300 ft was used as a basis for comparisons of the several studies. A study of the frequency distribution curves (Figs. 29 to 33) shows the following percentages of weaving maneuvers to be 300 ft or less:

(a) Combined study, 90 percent.
(b) Houston I, 85 percent.
(c) Houston II, 94 percent.
(d) Houston III, 90 percent.
(e) Dallas, 86 percent.

7. Eighty-two percent of the weaving maneuvers were initiated in the section of the study area in front of the nose of the entrance ramp.

8. (a) Sixty-one percent of all the observed weaving maneuvers moved to the left. Entrance ramps and acceleration lanes were located on the right side of the freeway lanes, except during Houston III studies when the ramps were closed.

(b) Thirty-nine percent of all the observed maneuvers moved to the right. Of this group 11.4 percent moved off the freeway at the next exit.

9. In the Houston III study during which both entrance ramps were closed, only 38 percent of the weaving vehicles moved to the left.

10. It is evident from these studies that the motion picture study provides a method for determining characteristics of weaving maneuvers and their relation to geometric features of the freeway. These studies, coupled with the studies of other operational characteristics, indicate that vehicles weave from one lane to another at any time when the lane into which they are weaving appears to offer either a faster speed or less density. This fact tends to keep parallel lanes operating near the speed of the slowest lane.

ENTRANCE RAMP OPERATION

Efficient freeway operation is largely dependent on the facilities provided for vehicle ingress and egress. If efficient operation is to be obtained, the facilities must be designed so that traffic entering or leaving the freeway will have a minimum of influence on through freeway traffic.

One problem encountered in bringing traffic on or off a freeway is the speed differential that exists between through traffic and vehicles entering or leaving the freeway. Some ramp designs take the traffic directly on or off the freeway, while other designs provide speed-change lanes (acceleration and deceleration lanes) on which the speed differential can be absorbed.

In order to compare and evaluate the relative merits of these various types of entrance ramps, studies were made of four different types:

(a) a two-lane, direct-entry ramp;
(b) a one-lane, direct-entry ramp;
(c) a one-lane ramp with a short acceleration lane; and
(d) a one-lane ramp with a long acceleration lane.

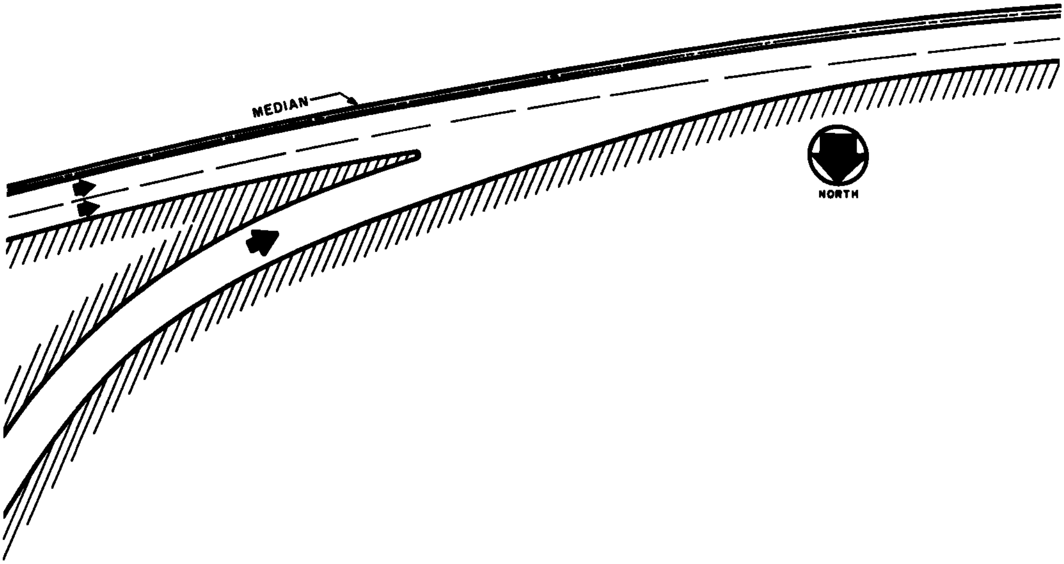


Figure 37. Ramp study section, Ft. Worth East-West Freeway—Study II.

The two-lane, direct-entry ramp was a part of the University Avenue Interchange on the East-West Freeway in Fort Worth. The ramp was up-grade, 24 ft wide, and joined the freeway with a 4-deg curved transition becoming tangent with the freeway curb line at a distance of 365 ft from the nose. The ramp was of sufficient width to accommodate two lanes of traffic but was not marked with lane lines. A view of this ramp is shown in Figure 37.

The one-lane, direct-entry ramp, located on the Central Expressway in Dallas (Fig. 38) was 17 ft wide and was connected to the freeway by a $7\frac{1}{2}$-deg curve.

The one-lane ramp with a short acceleration lane, was located on the Gulf Freeway in Houston. This ramp, the first of two adjacent ramps entering the freeway, was 17 ft wide and during an initial study (Houston I

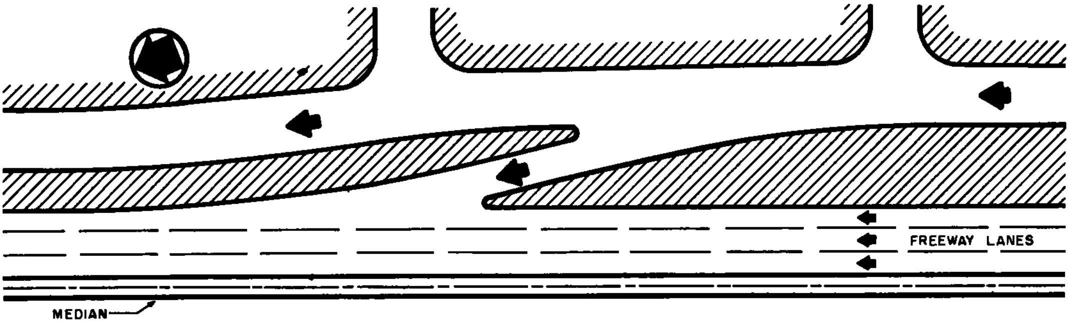


Figure 38. Ramp study section, Dallas Central Expressway (North)—Study I.

and II) was connected to the freeway by a full-width acceleration lane, 12 ft wide and 350 ft in length as shown in Figure 39. In another study (Houston IV), this acceleration lane was modified as shown in Figure 40 to form an auxiliary lane approximately 1,000 ft in length connecting the entrance ramp with the exit ramp.

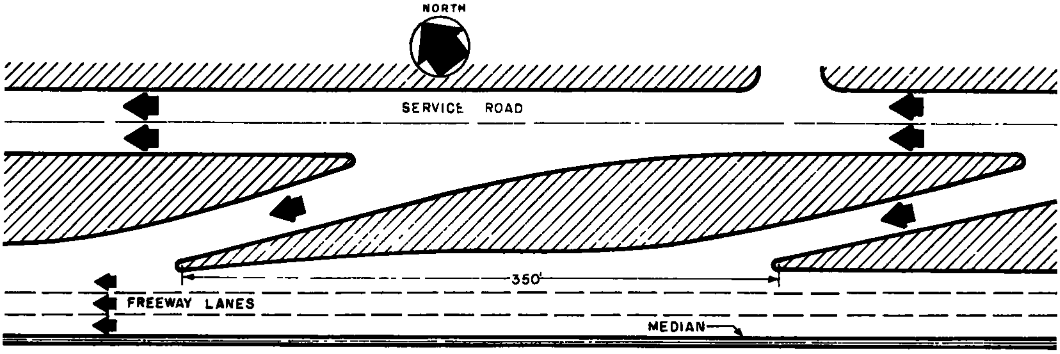


Figure 39. Ramp study section, Gulf Freeway, Houston—Studies I and II.

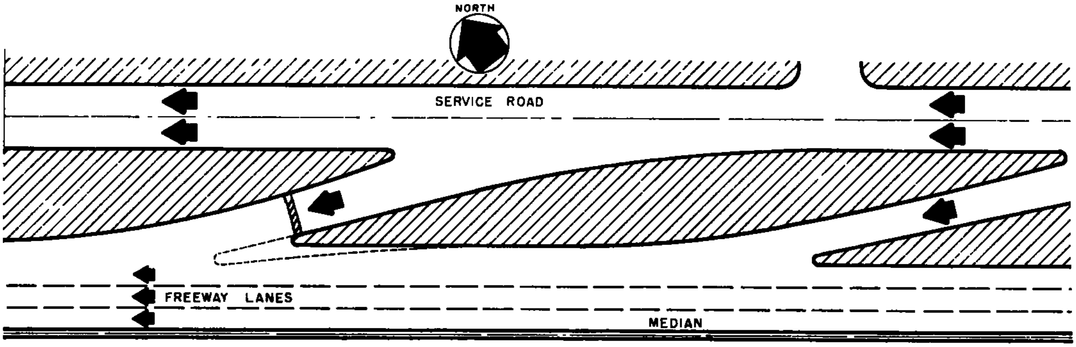


Figure 40. Ramp study section, Gulf Freeway, Houston—Study IV.

Study Procedure

In order to study various characteristics of entering traffic, data on the following items were tabulated:

1. Paths of entry and the extent of use of the acceleration lane for the Houston studies.
2. Paths of entry and the use of the second lane for the Fort Worth study.
3. Vehicle gaps accepted and rejected by the ramp traffic.
4. Delays encountered by the ramp traffic.

The data collected for the ramp study were taken from the following film studies: Houston I, Houston II, Houston IV, Dallas I, and Fort Worth II.

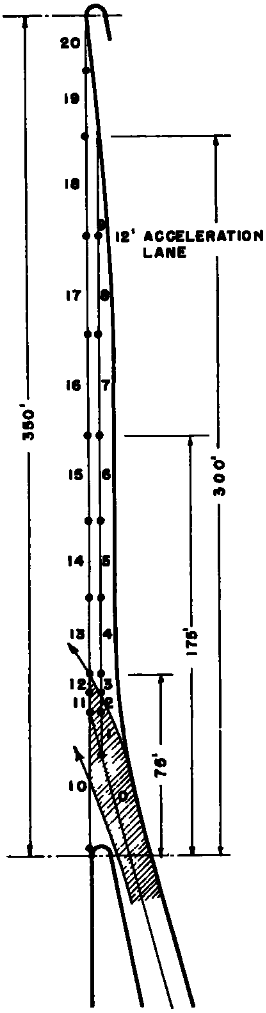
Because the design of the entrance ramp on the Central Expressway in Dallas rigidly fixed the path followed by vehicles entering the freeway, the slight variations in vehicle entry paths were considered insignificant.

To obtain data on paths of entry, a plastic template was designed to indicate the paths shown in Figures 41 through 45. This template was used to overlay the screen of the time motion projector during analysis of the motion pictures. The entrance path of each entering vehicle was determined by observing the position of the right rear wheel in relation to the control points on the template.

The paths were grouped according to the following conditions of entry:

Condition I. Direct entry into the outside lane with no use of the acceleration lane (Fig. 41).

Condition II. Semi-direct entry along a curved path with full entry into the outside lane within 175 ft of the nose (Fig. 42).



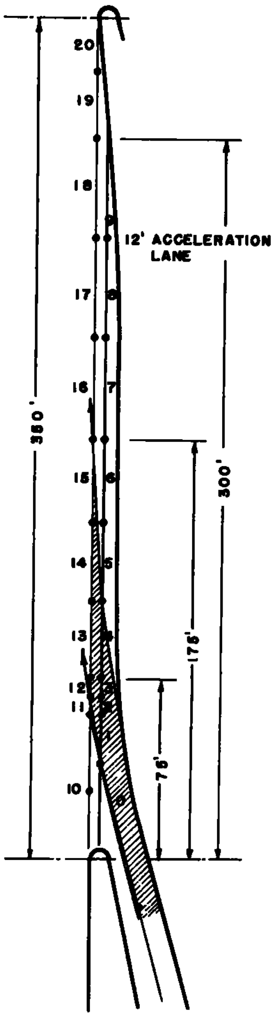
RIGHT REAR WHEEL OF VEHICLE

CONDITION I

PATH TAKEN	NO. OF VEHICLES	% OF TOTAL VEHICLES
0 — 10	12	0. 46
1 — 10	5	0. 19
1 — 11	58	2. 22
1 — 12	63	2. 41
2 — 11	2	0. 08
2 — 12	73	2. 79
TOTALS	213	8. 15

TOTAL NO. OF VEHICLES STUDIED **2615**

Figure 41. Houston I and II paths of entry.



RIGHT REAR WHEEL OF VEHICLE

CONDITION II

PATH TAKEN	NO. OF VEHICLES	% OF TOTAL VEHICLES
1 — 13	32	1.22
1 — 14	8	0.31
2 — 13	164	6.27
2 — 14	215	8.22
2 — 15	171	6.54
2 — 16	62	2.37
3 — 13	5	0.19
3 — 14	73	2.79
3 — 15	221	8.45
3 — 16	288	11.01
4 — 14	2	0.08
4 — 15	8	0.31
4 — 16	64	2.45
TOTALS	1313	50.21

TOTAL NO. OF VEHICLES STUDIED 2615

Figure 42. Houston I and II paths of entry.

Condition III. Partial use of the acceleration lane with full entry into the outside lane from 150 to 250 ft from the nose (Fig. 43).

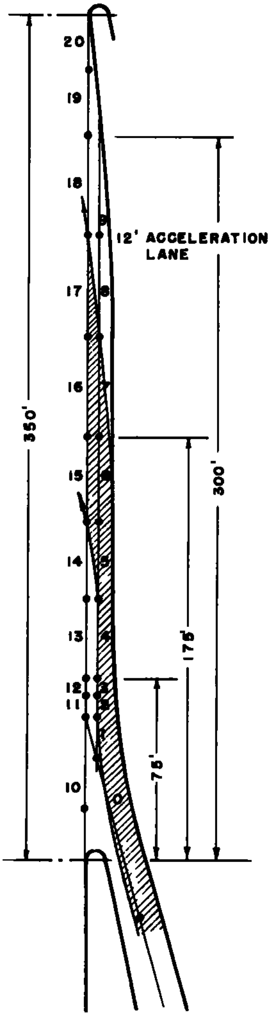
Condition IV. Full use of the acceleration lane (Fig. 44).

Condition V. Combined use of the acceleration lane and outside lane. Encroachment sufficient to insure a gap in the outside lane (Fig. 45).

Paths of Entry—Houston I and II—Short Acceleration Lane

A total of 2,615 entering vehicles were observed in the Houston I and II studies. Entry paths are tabulated below in terms of percentage of total entering vehicles:

Condition or Paths	Percent of Total Entering Vehicles	Condition or Paths	Percent of Total Entering Vehicles
I	8.12	IV	5.69
II	50.03	V	32.86
III	2.96		



RIGHT REAR WHEEL OF VEHICLE

CONDITION III

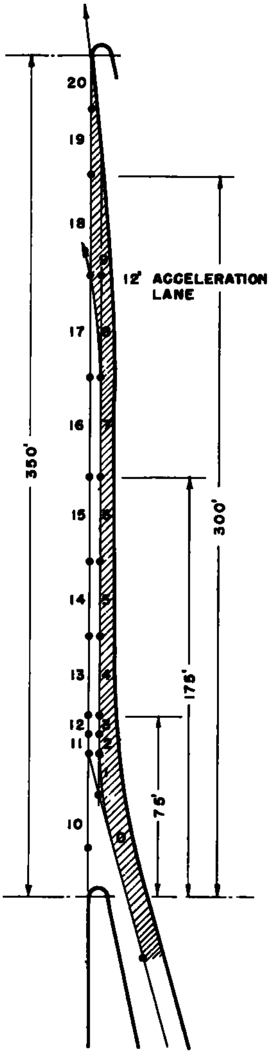
PATH TAKEN	NO. OF VEHICLES	% OF TOTAL VEHICLES
5 — 15	0	0.00
5 — 16	15	0.57
5 — 17	52	1.99
6 — 15	0	0.00
6 — 16	0	0.00
6 — 17	8	0.31
7 — 16	0	0.00
7 — 17	3	0.11
TOTALS	78	2.98

TOTAL NO OF VEHICLES STUDIED 2615

Figure 43. Houston I and II paths of entry.

The tabulation indicates that approximately 58 percent (Condition I and II) made little or no use of the acceleration lane. Observation of the motion pictures indicated that this particular path, or direct-entry, resulted in a significant speed differential between the freeway traffic and entering traffic, requiring the through freeway traffic to adjust speed or change lanes. It was not practical to obtain the speeds of the entering vehicles. Observations indicated that those entering under Conditions III, IV, and V obtained speeds more comparable to that of the freeway traffic before entering the freeway lanes and thus caused little turbulence in the freeway traffic stream.

The paths of entry were further classified according to the rate of flow of traffic in the outside lane, as shown in Figure 46. The rates of flow were taken at a point beyond the acceleration lane and included the entering vehicles. The rates of flow (5-min volumes expanded to equivalent hourly rates of flow) were grouped into three basic levels: less



RIGHT REAR WHEEL OF VEHICLE

CONDITION IV

PATH TAKEN	NO. OF VEHICLES	% OF TOTAL VEHICLES
7 — 18	10	0. 38
7 — 19	23	0. 88
7 — 20	33	1. 26
8 — 18	2	0. 08
8 — 19	12	0. 46
8 — 20	36	1. 38
9 — 19	1	0. 04
9 — 20	32	1. 22
TOTALS	149	5. 70

TOTAL NO. OF VEHICLES STUDIED 2615

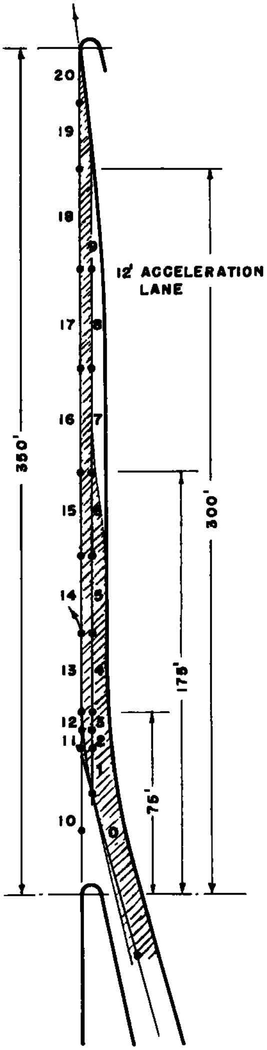
Figure 44. Houston I and II paths of entry.

less than 1,200 vph; 1,200-1,500 vph; and over 1,500 vph.

This classification indicates that as the rate of flow increased, there was a small increase in the percentage of entering vehicles for each of Conditions I through IV while there was a decrease for Condition V (those vehicles protecting a gap in the outside lane by early encroachment).

Houston IV—Long Auxiliary Lane

The Houston IV study was made after modification of the acceleration lane. The second ramp was closed (Fig. 40) and the ramp nose removed to form an auxiliary lane approximately 1,000 ft in length which served as a combination acceleration-deceleration lane for the entering and exiting traffic. Motion pictures made during the morning peak, morning offpeak,



RIGHT REAR WHEEL OF VEHICLE

CONDITION V

PATH TAKEN	NO. OF VEHICLES	% OF TOTAL VEHICLES
1 — 15	8	0.31
1 — 16	4	0 15
1 — 17	2	0.08
1 — 18	1	0 04
1 — 19	0	0.00
1 — 20	2	0.08
2 — 17	20	0.76
2 — 18	9	0.34
2 — 19	3	0.11
2 — 20	2	0 08
3 — 17	169	6.46
3 — 18	59	2.26
3 — 19	20	0.76
3 — 20	4	0.15
4 — 17	137	5.24
4 — 18	103	3 94
4 — 19	28	1.07
4 — 20	5	0 19
5 — 18	101	3.86
5 — 19	47	1.79
5 — 20	11	0.42
6 — 18	44	1 68
6 — 19	60	2 30
6 — 20	23	0.88
TOTALS	862	32.96

TOTAL NO OF VEHICLES STUDIED 2615

Figure 45. Houston I and II paths of entry.

and afternoon peak periods recorded approximately 3 hr and 40 min of traffic operation for this arrangement.

The plastic overlay template used with the time-motion projector to observe the paths of entry of each vehicle was revised from that used in earlier studies to simplify the data tabulation by reducing the number of control points. However, the simplification did not alter the classification of the individual paths into the 5 conditions of entry previously outlined. The paths of entry for the Houston IV study are shown in Figures 47 through 51. It should be noted, that with the exception of paths 1-18, 2-18, and 4-18 classified under Condition V, all vehicle paths which extended past the original nose of the second ramp were classified under Condition IV, full use of the acceleration lane. All other conditions are considered comparable to those outlined in the Houston I and II studies.

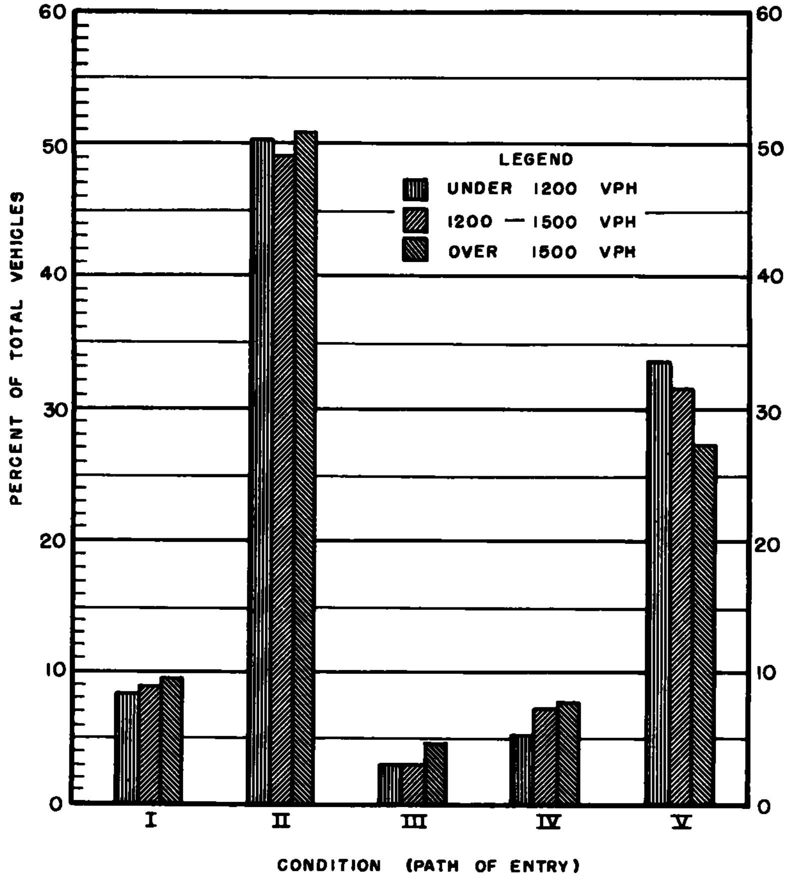


Figure 46. Entrance ramp study, Houston I and II. Percentage of total entering vehicles by path of entry, classified according to volume levels.

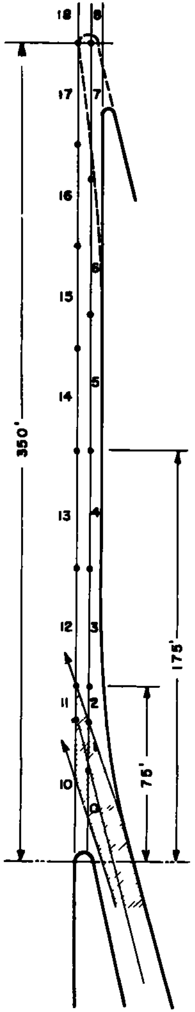
A before-and-after comparison of the paths of entry on a short acceleration lane (Houston I and II) and on a long auxiliary lane (Houston IV) is given in Table 19. The comparison shows some increase in the use of the acceleration lane after modification to the long auxiliary lane.

A classification of paths of entry according to rate of flow for Houston IV study is shown in Figure 52.

Fort Worth II—Two-Lane Ramp

A study of vehicle paths of entry was conducted on a ramp of the University Avenue Interchange in Fort Worth shown in Figure 37. The primary purpose of this study was to observe paths of entry from a ramp of sufficient width to accommodate two lanes of traffic. The plastic template overlay was again used in conjunction with the time-motion projector to determine the entry paths shown in Figures 53, 54, and 55.

A vehicle was considered in the outside lane of the ramp when the right rear wheel was within 6 ft of the right curb at a point opposite the nose of the ramp. A vehicle was considered in the inside or left



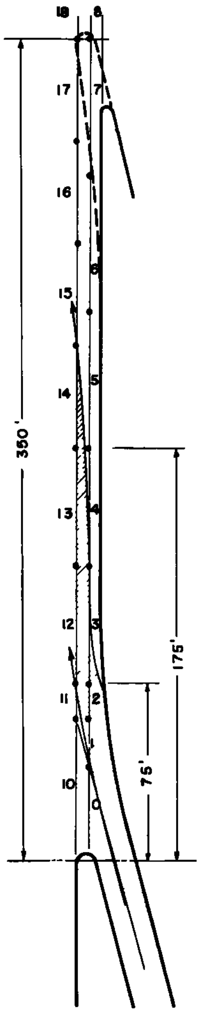
RIGHT REAR WHEEL OF VEHICLE

CONDITION I

PATH TAKEN	NO OF VEHICLES	% OF TOTAL VEHICLES
0 — 10	0	0.00
1 — 10	3	0 14
1 — 11	108	5.25
2 — 11	1	0 05
TOTALS	112	5 44

TOTAL NO. OF VEHICLES STUDIED 2059

Figure 47. Houston IV paths of entry.



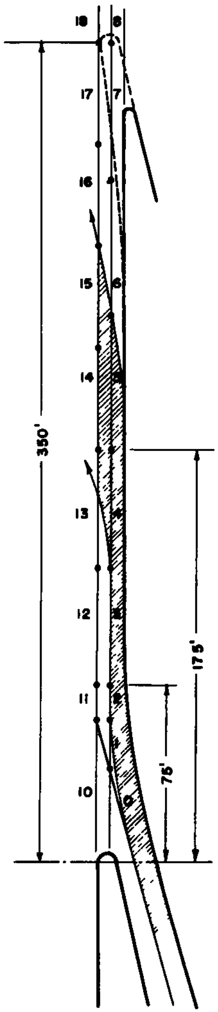
RIGHT REAR WHEEL OF VEHICLE

CONDITION II

PATH TAKEN	NO OF VEHICLES	% OF TOTAL VEHICLES
1 — 12	63	3 06
2 — 12	148	7 19
2 — 13	226	10 98
2 — 14	53	2 57
3 — 12	3	0 14
3 — 13	160	7 77
3 — 14	271	13 16
TOTALS	924	44 87

TOTAL NO OF VEHICLES STUDIED 2059

Figure 48. Houston IV paths of entry.



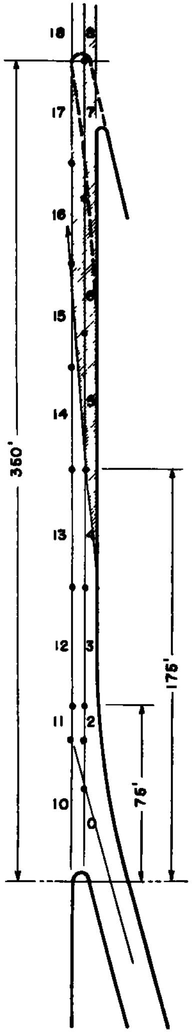
RIGHT REAR WHEEL OF VEHICLE

CONDITION III

PATH TAKEN	NO. OF VEHICLES	% OF TOTAL VEHICLES
4 — 13	0	0.00
4 — 14	27	1.31
4 — 15	147	7.14
5 — 14	0	0.00
5 — 15	6	0.29
TOTALS	180	8.74

TOTAL NO. OF VEHICLES STUDIED 2059

Figure 49. Houston IV paths of entry.



RIGHT REAR WHEEL OF VEHICLE

CONDITION IV

PATH TAKEN	NO OF VEHICLES	% OF TOTAL VEHICLES
5 — 16	47	2 28
5 — 17	53	2.57
5 — 18	62	3 02
6 — 16	5	0 24
6 — 17	22	1.07
6 — 18	77	3 74
7 — 17	0	.00
7 — 18	74	3 59
8 — 18	94	4 57
TOTALS	434	21 08

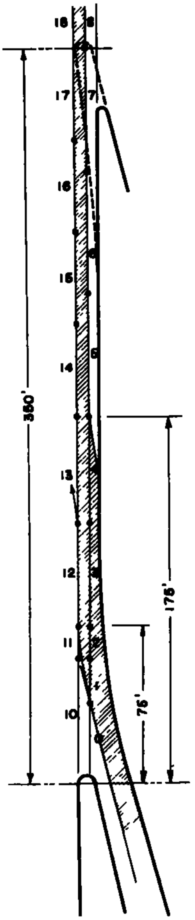
TOTAL NO OF VEHICLES STUDIED 2059

Figure 50. Houston IV paths of entry.

TABLE 19

PATHS OF ENTRY—COMPARISON OF THE HOUSTON I AND HOUSTON IV STUDIES
HOUSTON I AND II—SHORT ACCELERATION LANE
HOUSTON IV—LONG AUXILIARY LANE

Condition of Entry	Houston I & II Percent of Total Entering Vehicles	Houston IV Percent of Total Entering Vehicles	Difference of Percent
I	8.2	5.44	-2.68
II	50.03	44.87	-5.16
III	2.96	8.74	+5.78
IV	5.69	21.08	+15.39
V	32.86	19.87	-12.99
	2,615 vehicles studied	2,059 vehicles studied	



RIGHT REAR WHEEL OF VEHICLE

CONDITION V

PATH TAKEN	NO OF VEHICLES	% OF TOTAL VEHICLES
1 — 13	11	0 53
1 — 14	4	0 19
1 — 15	1	0.05
1 — 16	0	0.00
1 — 17	0	0.00
1 — 18	2	0.10
2 — 15	11	0.53
2 — 16	7	0.34
2 — 17	2	0.10
2 — 18	4	0.19
3 — 15	129	6 27
3 — 16	33	1 60
3 — 17	13	0.63
3 — 18	25	1 22
4 — 16	80	3.89
4 — 17	42	2 04
4 — 18	45	2.19
TOTALS	409	19 87

TOTAL NO. OF VEHICLES STUDIED 2059

Figure 51. Houston IV paths of entry.

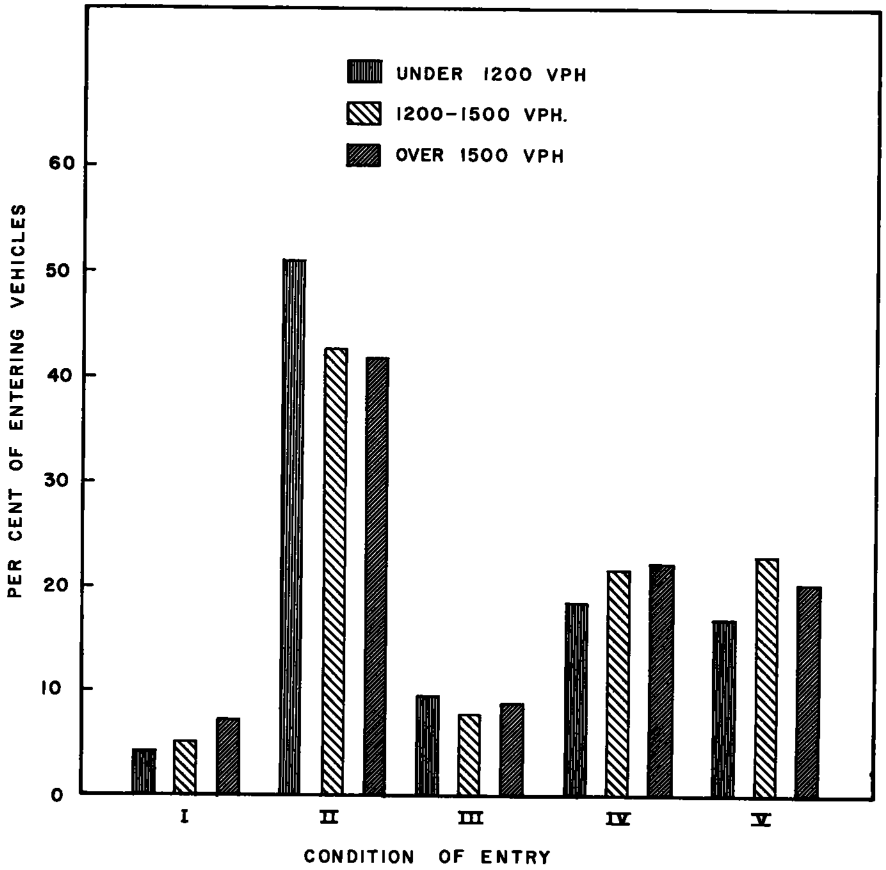


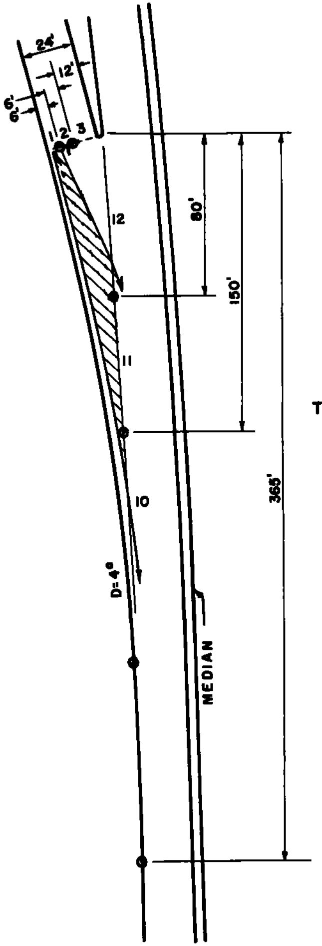
Figure 52. Houston IV paths of entry classified according to volume levels.

lane of the ramp when the right rear wheel was further than 12 ft from the right curb. Those vehicles encroaching on both lanes used the ramp as single lane.

During this study, 63.5 percent of the 719 entering vehicles used the right or outside lane of the ramp, 23.5 percent encroached on both lanes and 13 percent used the inside lane of the ramp.

Paths of entry were classified according to volume in the outside lane of the freeway as shown in Figure 56. During this study, the combined rate of flow of the entrance ramp and the outside lane of the freeway did not exceed 1,500 vph. Therefore, the three rates of flow selected for comparison were less than 1,000 vph; 1,000-1,200 vph; and 1,200-1,500 vph.

These comparisons indicate that paths 1-10 and 1-11 are significantly influenced by the volume level. The small samples occurring in the remaining paths do not reliably indicate any true trend. The long curved path of entry, 1-10, decreased as the volume increased, while the more direct or abrupt path of entry, 1-11, increased as the volume increased.



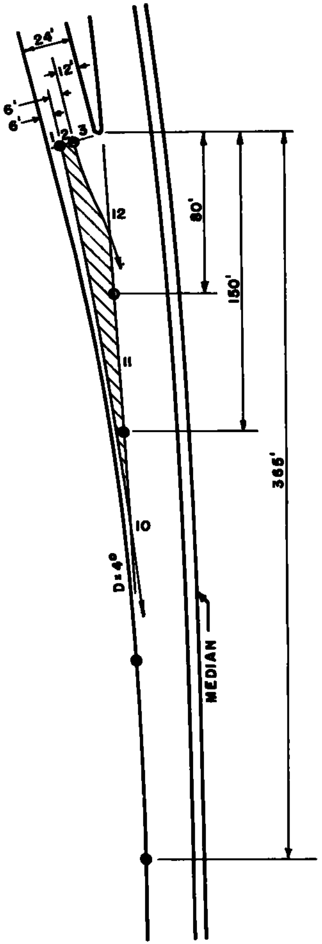
RIGHT REAR WHEEL OF VEHICLE

CONDITION I

PATH TAKEN	NO. OF VEHICLES	% OF TOTAL VEHICLES
1-10	282	39.22
1-11	161	22.39
1-12	13	1.81
TOTAL	456	63.42

TOTAL NUMBER OF VEHICLES STUDIED 719

Figure 53. Fort Worth paths of entry.



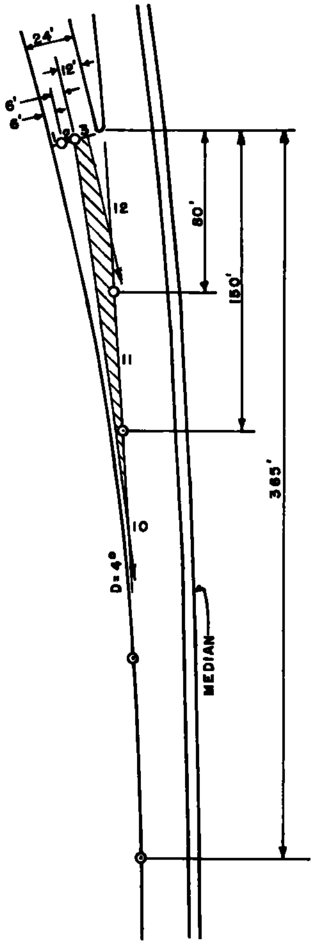
RIGHT REAR WHEEL OF VEHICLE

CONDITION II

PATH TAKEN	NO OF VEHICLES	% OF TOTAL VEHICLES
2-10	60	8.35
2-11	83	11.54
2-12	26	3.62
TOTAL	169	23.51

TOTAL NUMBER OF VEHICLES STUDIED 719

Figure 54. Fort Worth paths of entry.



RIGHT REAR WHEEL OF VEHICLE

CONDITION III

PATH TAKEN	NO OF VEHICLES	% OF TOTAL VEHICLES
3-10	3	0.42
3-11	17	2 36
3-12	74	10 29
TOTAL	94	13 07

TOTAL NUMBER OF VEHICLES STUDIED 719

Figure 55. Forth Worth paths of entry.

Characteristics of Entering Traffic—Research in Progress

Delay to Entering Ramp Traffic. In order to facilitate further comparison of the various ramp types, an analysis is being made of the delay experienced by vehicles entering the freeway as a possible measure of ramp efficiency. Preliminary analyses indicate that delay is related to a number of complex variables and that delay experienced by entering traffic is possibly more dependent on the relationship of instantaneous rates of flow on the freeway and ramp than on the geometric design of the ramp.

Gaps Accepted and Rejected by Ramp Traffic. The motion picture study provided the opportunity to obtain vehicle gap or headway data for vehicles in the through lanes of the freeway and to study the acceptance or rejection of these gaps by entering ramp traffic. Analysis of these data is also a phase of current studies in an effort to facilitate complete analysis of freeway ramp operation.

Analyses of data on the above items are not sufficiently complete for presentation in this report.

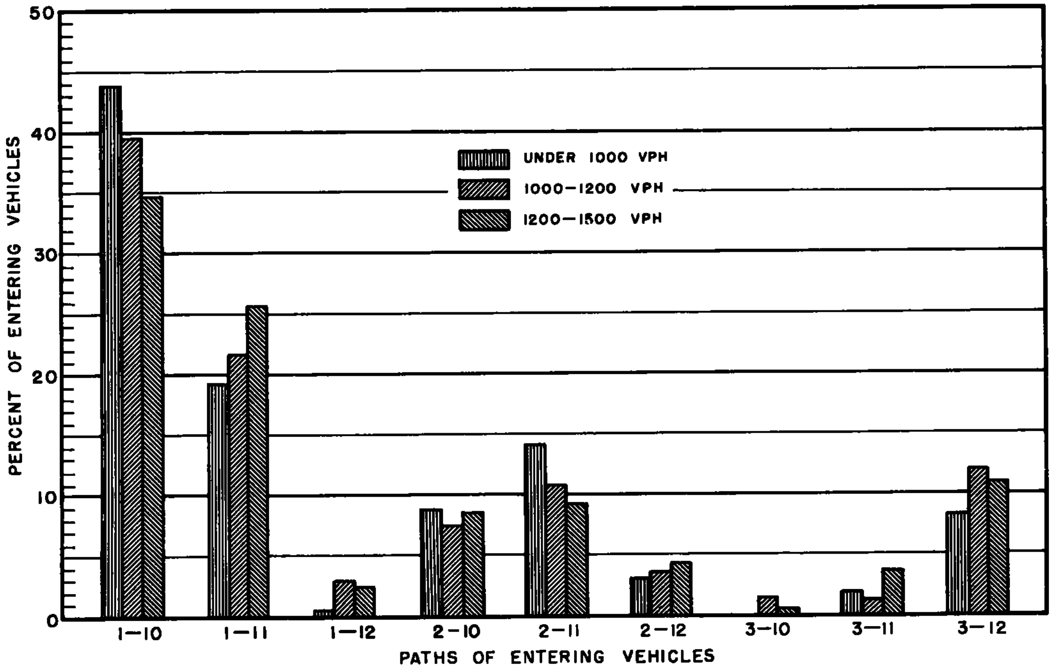


Figure 56. Fort Worth—percentage of total entering vehicles by path of entry, classified according to volume levels.

Summary

The studies of entrance ramp operation may be summarized as follows:

1. Studies of a ramp with a short acceleration lane indicate that approximately 58 percent of the ramp traffic made little or no use of the acceleration lane.

2. Modification of the short acceleration lane to provide a long auxiliary lane for entering traffic resulted in only a slight increase in acceleration lane usage.

3. Studies of two-lane ramp operation indicate minor use of the ramp as a two-lane facility. Only 13 percent of the entering ramp traffic used the second or outside lane.

4. Classifications of paths of entry according to volume in the outside lane of the freeway indicate an increase in the direct or abrupt path of entry with a volume increase. This was true for each of the ramp designs studied.

GENERAL SUMMARY

A summary of findings is presented at the end of each of the sections of this report. Discussions of many of the interrelationships are included throughout the report.

Correlation of the results of the various studies indicates that the design and operation of ramps and interchanges have the greatest effect on freeway operation.

The various studies indicate also that entering traffic along the freeway has an obvious influence on traffic across all parallel unseparated lanes. It is concluded that high-speed express lanes are needed for accommodating longer freeway trips without interference from entering traffic. It is considered that the outer roadway involving the relatively frequent points of access and egress is necessary to efficiently integrate the freeway with the existing major street pattern and to assure greater utilization of the facility during offpeak as well as peak periods.

The studies show that control of freeway access during congested peak periods can be utilized to improve the efficiency of the over-all facility. The same is probably true for egress from the freeway to force better distribution of traffic to the major street system.

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