## TTECHNICAL REFERENCE CENTER TEXAS TRANSPORTATION INSTITUfE

A STUDY OF FREEWAY TRAFFIC OPERATION

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## A STUDY OF FREEWAY TRAFFIC OPERATION

Synopsis
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 was presented to the 36th Annual Meeting of the Highway Research Board. The data presented herewith represents additional studies and analysis 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 recreate traffic situations for more thorough study. Traffic operations were recorded on approximately 22,000 feet of 16 mm film during the course of nine separate studies made on freeways in Houston, Dallas, and Fort Worth, Texas.

Research was conducted in the following areas: 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 is needed in this area.

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

## INTRODUCTION

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 upon 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.


Figure I. Portable Tower Used in Filming Freeway Traffic.


Figure 2. Sample of Motion Picture Film From Freeway Studies.


Figure 3. Time-Motion Study Projector Used in Analysis of Motion Pictures.

## 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 eight frames per second; after a camera was acquired for the research project, pictures were made at a speed of ten frames per second. Both camera speeds allowed the accurate determination of vehicle speeds, headways and other desirable traffic characteristics.

A l2-inch 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 feet apart to provide reference points for speed, headways and other timedistance determinations.

Two projectors were used to analyse 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, as shown in Figure 3, was especially constructed so that it could be stopped for "still" or single-frame viewing. Since 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 inage at a fixed magnification which could be scaled. Both projectors provided the advantage of being able to replay or recreate 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



Figure 4. Gulf Freeway, Houston.


Figure 5. Central Expressway, Dallas, Texas.


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

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SPEED - VOLUME RELATIONSHIP
    BEFORE RAMP
HOUSTON II - INSIDE LANE- INBOUND
                        7:05 A.M.- 8:05 A.M.
    5-MIN. TIME INTERVALS
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FIGURE 7
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 freaway traffic.

Continuous motion pictures were taken of each test section for approximately one hour and thirty minutes during the moming and evening peak periods (7:00-8:30 a.m., 5:00-6:30 p.m.) and for one hour (9:3010:30 a.m.) during off-peak conditions.

## 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, continuovs one-way frontage roads through the study area and the same type pavement. Figures 4 and 5 show the general layout of the freeways.

Though similar in overall 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 four-foot concrete median with six-inch barrier type curbs; the Central Expressway had an eleven-foot grassed median with six inch 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 $7^{\circ} 30^{\prime}$ 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 cbtain 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 were 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.

| Study | Date | Time | Type of Study |
| :---: | :---: | :---: | :---: |
| Houston I | 5-22-56 | $\begin{aligned} & 7: 00-8: 35 \text { A.M. } \\ & 9: 30-10: 30 \text { A.M. } \\ & 4: 15-5: 52 \text { P.M. } \end{aligned}$ | Motion Picture |
| Houston II | 9-11-56 | $\begin{aligned} & 7: 00-8: 35 \text { A.M. } \\ & 9: 30-10: 30 \text { A. } M_{.} \\ & 4: 15-5: 50 \mathrm{P}, \mathrm{M}_{9} \end{aligned}$ | Motion Picture |
| Houston III (a) | 9-25-56 | 7:00-8:10 A.M. | Motion Picture |
| Houston III (b) | 9-26-56 | $\begin{aligned} & 7: 00-8: 30 \text { A.M. } \\ & 4: 15-5: 50 \text { P. } . \end{aligned}$ | Motion Picture |
| Houston IV | 7-8-58 | $\begin{aligned} & 7: 00-8: 30 \text { A. M. } \\ & 9: 30-10: 30 \text { A. M. } \\ & 4: 00-6: 00 \text { P.M. } \end{aligned}$ | Motion Picture |
| Houston V | 7-22-58 | 7:00-8:15 A.M. | Motion Picture |
| Dallas I | 8-14-56 | $\begin{aligned} & 7: 10-8: 45 \text { A.M. } \\ & 9: 30-10: 30 \text { A.M. } \\ & 4: 00-6: 00 \text { P.M. } \end{aligned}$ | Motion Picture |
| Dallas II | 11-26-57 | 4:30-6:05 P.M. | Motion Picture |
| Fort Worth II | 2-20-58 | $\begin{aligned} & 7: 45-8: 40 \text { A. M. } \\ & 4: 15-5: 30 \text { P. } \end{aligned}$ | Motion Picture |

Table 1

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

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

Tabulations of volumes were made for each one-minute period and combined to show 5 -minute volumes.

## Volume-Speed Relationships

In the preliminary report of this study (Highway Research Board Bulletin Number 170, 1958) a number of volume-speed relationships were discussed for the freeways studied. The conclusion was drawm that speeds of 40 to 50 mph could be maintained in the inside (median lane)







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B6:
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## SPEED-VOLUME RELATIONSHIPS <br> INSIDE \& OUTSIDE LANES-AHEAD OF EXIT RAMP gULF FREEWAY (HOUSTON II)



FIGURE NO. 8

figure 9

CONSECUTIVE FIVE-MINUTE VOLUMES
MIDDLE LANE, MORNING PEAK PERIOD, ALL HOUSTON STUDIES

figure 10
and middle lanes provided the 5 -minute lane volume did not exceed 150 ( $1800 \mathrm{vph}^{*}$ ), and in the outside (right) lane provided the 5 -minute volume did not exceed 125 ( $1500 \mathrm{Vph}^{*}$ ). Typical volume-speed relationships are shown in Tables 2 through 8.

The volume-speed relationships have been plotted in a different manner in Figure 8. For these plots, successive 5-minute volumes have been plotted in relation to the 5 -minute 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 volumes. Examining successive 5-minute intervals along the trace demonstrates that as the peak flow builds up, the 5 -minute 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 feet, 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 upon the compactness or density of the traffic stream and the length of delay created by the headway adjustment. Freeway volumecontrol studies, which will be discussed in a later section of this report, indicate 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 Ilow 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
*The 5 -minute volumes are expressed throughout this report in terms of equivalent hourly rate of flow. These values were obtained by multiplying the 5 -minute volume by 12. They are shown in terms of vehicles per hour but are not to be confiused with total hourly volume.


## HOUSTON I <br> GULF FREEWAY


houstor I

| TIME | INSIDE LAAE SPEED (A) | 5-MIN. voluries |  |  | $\qquad$ | TOTAI VOL. 3-LARIES <br> AT (A) | $\begin{aligned} & \text { EQUIV. HOURLX } \\ & \text { RATE OF PLOW } \\ & \text { VPH } \end{aligned}$ | 5-MIN. voljers |  |  | CALCULATED total vol. 3-lanes at G | EQUIV. RATE OF FLON VPH |
| :---: | :---: | :---: | :---: | :---: | :---: | :---: | :---: | :---: | :---: | :---: | :---: | :---: |
|  |  | A | B | c |  |  |  | D | E | F |  |  |
| 7:00-7:05 | 40 | 119 | 120 | 70 | 42 | 309 | 3708 | 35 | 18 | 15 | 347 | 4164 |
| 7:05-7:10 | 44 | 134 | 151 | 78 | 40 | 363 | 4365 | 36 | 31 | 19 | 411 | 4932 |
| 7:10-7:15 | 43 | 149 | 151 | 88 | 38 | 388 | 4656 | 37 | 25 | 12 | 438 | 5256 |
| 7:15-7:20 | 40 | 158 | 170 | 114 | -- | 442 | 5304 | 29 | 31 | 14 | 488 | 5856 |
| 7:20-7:25 | 33 | 163 | 169 | 110 | 30 | 442 | 5304 | 39 | 17 | 14 | 484 | 5808 |
| 7:25-7:30 | 32 | 174 | 150 | 105 | -- | 439 | 5148 | 27 | 33 | 8 | 481 | 5772 |
| 7:45-7:50 | -- | 138 | 128 | 127 | -- | 393 | 4716 | 26 | 30 | 23 | 426 | 5112 |
| 7:50-7:55 | -- | 141 | 140 | 130 | -* | 411 | 4932 | 21 | 26 | 36 | 422 | 5064 |
| 7:55-8:00 | 29 | 140 | 132 | 127 | 16 | 399 | 4788 | 17 | 23 | 25 | 414 | 4968 |
| 8:00-8:05 | 34 | 115 | 137 | 92 | 27 | 344 | 4128 | 31 | 17 | 23 | 369 | 4428 |
| 8:05-8:10 | 44 | 104 | 116 | 62 | 39 | 282 | 3384 | 39 | 31 | 18 | 334 | 4008 |
| 8:10-8:15 | -- | 117 | 136 | 66 | -- | 319 | 3828 | 40 | 23 | 20 | 362 | 4344 |
| 8:15-8:20 | 44 | 109 | 109 | 65 | 41 | 283 | 3396 | 41 | 27 | 12 | 339 | 4068 |
| 8:20-8:25 | 45 | 116 | 126 | 54 | 39 | 296 | 3552 | 41 | 20 | 9 | 348 | 4176 |
| 8:25-8:30 | 47 | 68 | 100 | 42 | 40 | 210 | 2520 | 42 | 20 | 10 | 262 | 3144 |
| 8:30-8:35 | 47 | 76 | 77 | 43 | - | 196 | $235 ?$ | 40 | 21 | 12 | 245 | 2940 |

TABIE 2

## HOUSTON II gulf freeway



HOUSTON II

| TDEE | $\begin{gathered} \text { INS IDE } \\ \text { LANE } \\ \text { SPEBD } \\ \text { A } \end{gathered}$ | 5 - min. volume |  |  | $\begin{gathered} \text { OUTSIDE } \\ \text { LANE } \\ \text { SPEED } \\ \hline \end{gathered}$ | $\begin{gathered} \text { TOTAL VOL. } \\ \text { THREE LANES } \\ \text { AT } \\ \hline \end{gathered}$ | $\begin{gathered} \text { EqUIVALENT } \\ \text { HOURLY RATE } \\ \text { OF FLOW } \\ \text { YPH } \\ \hline \end{gathered}$ | S-min. VOLume |  |  | $\begin{gathered} \text { Calclulated } \\ \text { TOTAL vol, } \\ 3 \text { LANES AT } \\ \text { G } \end{gathered}$ | $\begin{gathered} \text { EQUIVALENT } \\ \text { HOURLY RATE } \\ \text { OF FLOW } \\ \text { VRH } \\ \hline \end{gathered}$ |
| :---: | :---: | :---: | :---: | :---: | :---: | :---: | :---: | :---: | :---: | :---: | :---: | :---: |
|  |  | A. | B | c |  |  |  | D | E | F |  |  |
| 7:05-7:10 | 46 | 110 | 139 | 82 | 41 | 331 | 3972 | 35 | 31 | 9 | 388 | 4656 |
| 7:10-7:15 | 45 | 149 | 149 | 88 | 41 | 386 | 4632 | 44 | 33 | 11 | 452 | 5424 |
| 7:15-7:20 | 43 | 150 | 172 | 96 | 38 | 418 | 5016 | 43 | 21 | 19 | 463 | 5556 |
| 7:20-7:25 | 42 | 154 | 163 | 110 | 39 | 427 | 5124 | 40 | 27 | 19 | 475 | 5700 |
| 7:25-7:30 | 39 | 178 | 174 | 126 | 38 | 478 | 5736 | 37 | 39 | 19 | 535 | 6420 |
| 7:30-7:35 | 31 | 170 | 172 | 135 | 24 | 477 | 5724 | 36 | 32 | 20 | 525 | 6300 |
| 7:35-7:40 | 34 | 162 | 158 | 123 | 33 | 443 | 5316 | 36 | 34 | 16 | 497 | 5964 |
| 7:40-7:45 | 31 | 154 | 154 | 119 | 26 | 427 | 5124 | 43 | 32 | 13 | 489 | 5868 |
| 7:45-7:50 | 32 | 152 | 154 | 129 | 23 | 435 | 5220 | 31 | 41 | 19 | 488 | 5856 |
| 1:50-7:55 | 32 | 155 | 156 | 135 | 27 | 446 | 5352 | 40 | 35 | 19 | 502 | 6024 |
| 1:55-8:00 | 45 | 117 | 131 | 83 | 40 | 331 | 3972 | 32 | 18 | 11 | 370 | 4440 |
| 8:00-8:05 | 45 | 100 | 140 | 72 | 41 | 312 | 3744 | 48 | 27 | 13 | 374 | 4488 |
| 8:05-8:10 | 43 | 111 | 129 | 80 | 40 | 320 | 3840 | 35 | 28 | 16 | 367 | 4404 |
| 8:10-8:15 | 45 | 103 | 123 | 67 | 40 | 293 | 3516 | 42 | 40 | 19 | 356 | 4272 |
| 8:15-8:20 | 46 | 125 | 121 | 70 | 41 | 316 | 3792 | 42 | 26 | 11 | 373 | 4476 |

TABLE 3

VOLUME - SPEED TABUEATIONS
5-Minute Time Intervals -- Morning Peak Period

## HOUSTON III

 gULIF FREEWAY
houston III A

| TIME | $\begin{gathered} \text { INS LḊE } \\ \text { LANE } \\ \text { SPEED } \\ \hline \end{gathered}$ | 5 - MIN. VOLUME |  |  | $\begin{gathered} \text { OUTS IDE } \\ \text { LANE } \\ \text { SPEED } \\ \hline \end{gathered}$ | total vol. three lanes AT A | EQUIVALENT hourly rate <br> OF FLOW VPH |
| :---: | :---: | :---: | :---: | :---: | :---: | :---: | :---: |
|  |  | A | 13 | c |  |  |  |
| 7:00-7:05 | 46 | 105 | $1: 31$ | 60 | 45 | 286 | 3482 |
| 7:05-7:10 | 46 | 121 | 125 | 68 | 44 | 314 | 3768 |
| 7:10-7:15 | 46 | 145 | $1 / 4$ | 85 | 44 | 374 | 4488 |
| 7:15-7:20 | 43 | 152 | 163 | 109 | 40 | 424 | 5088 |
| 7:20-7:25 | 40 | 166 | 160 | 115 | 39 | 441 | 5292 |
| 7:25-7:30 | 40 | 171 | 175 | 129 | 39 | 475 | 5700 |
| 7:30-7:35 | 36 | 149 | 164 | - | - | 313 | 3756 |
| 7:35-7:40 | 35 | 156 | 149 | 140 | 36 | 445 | 5340 |
| 7:40-7:45 | 34 | 154 | 149 | 128 | 33 | 431 | 5172 |
| 7:45-7:50 | 37 | 152 | 146 | 138 | 33 | 436 | 5232 |
| 7:50-7:55 | 36 | 165 | 157 | 138 | 35 | 460 | 5520 |
| 7:55-8:00 | 40 | 140 | 1.33 | 82 | 47 | 355 | 4260 |
| 8:00-8:05 | 44 | 109 | 1.27 | 78 | 43 | 314 | 3768 |
| 8:05-8:10 | 45 | 102 | :112 | 58 | 41 | 272 | 3264 |

TABLE 4A


TABLE 4 B

## HOUSTON II <br> gulf freeway


houston IV

| TIME | $\begin{gathered} \text { INS IDE } \\ \text { LANE } \\ \text { SPEED } \\ \hline \end{gathered}$ | 5 - MIN. Volume |  |  | $\begin{gathered} \text { OUTS IDE } \\ \text { LANE } \\ \text { SPEED } \\ \hline \end{gathered}$ | $\begin{gathered} \text { TOTAL VOL, } \\ \text { THREE LANES } \\ \text { AT } \\ A \\ \hline \end{gathered}$ | EQUIVALENT hourly rate OF FLOW VPH | 5-min. VOlume |  | $\begin{gathered} \text { CALCULATED } \\ \text { TOTAL VOL. } \\ \text { AT } \\ G \\ \hline \end{gathered}$ | Equivalent hoURIY RATE of fLow VPH |
| :---: | :---: | :---: | :---: | :---: | :---: | :---: | :---: | :---: | :---: | :---: | :---: |
|  |  | A | B | c |  |  |  | D | F |  |  |
| 7:00-7:05 | 47 | 147 | 164 | 77 | 45 | 388 | 4656 | 39 | 10 | 417 | 5004 |
| 7:05-7:10 | 46 | 133 | 157 | 92 | 41 | 382 | 4584 | 35. | 13 | 404 | 4848 |
| 7:10-7:15 | 43 | 144 | 171 | 87 | 41 | 402 | 4824 | 53. | 16 | 439 | 5268 |
| 7:15-7:20 | 43 | 150 | 167 | 129 | 38 | 446 | 5352 | 38 | 21 | 463 | 5556 |
| 7:20-7:25 | 39 | 159 | 169 | 116 | 36 | 444 | 5328 | 48 | 21 | 471 | 5652 |
| 7:25-7:30 | 39 | 136 | 147 | 131 | 33 | 414 | 4968 | 39 | 17 | 436 | 5232 |
| 7:30-7:35 | 38 | 155 | 182 | 107 | 30 | 444 | 5352 | 47 | 14 | 477 | 5724 |
| 7:35-7:40 | 35 | 156 | 154 | 137 | 31 | 447 | 5364 | 45 | 25 | 467 | 5604 |
| 7:40-7:45 | 39 | 151 | 175 | 105 | 33 | 431 | 5172 | 55 | 21 | 465 | 5580 |
| 7:45-7:50 | 41 | 156 | 152 | 110 | 29 | 418 | 5016 | 50 | 33 | 435 | 5220 |
| 7:50-7:55 | 41 | 146 | 164 | 103 | 36 | 413 | 4956 | 54 | 25 | 442 | 5304 |
| 7:55-8:00 | 45 | 114 | 132 | 77 | 40 | 323 | 3876 | 67 | 31 | 359 | 4308 |
| 8:00-8:05 | 45 | 114 | 125 | 66 | 41 | 305 | 3660 | 42 | 19 | 328 | 3936 |
| 8:05-8:10 | 46 | 117 | 112 | 74 | 41 | 303 | 3636 | 58 | 15 | 346 | 4152 |
| 8:10-8:15 | 46 | 100 | 124 | 53 | 43 | 277 | 3324 | 70 | 14 | 333 | 3996 |
| 8:15-8:20 | 46 | 103 | 129 | 53 | 43 | 285 | 3420 | 49 | 12 | 322 | 3864 |

TABLE 5

VOLUME - SPEED TABULATIONS
5 - Minute Time Intervals -- Moming Peak Period

## HOUSTON ㅍ gULF FREEWAY



HOUSTON V

| TIME | INS IDE LANE SPEED | 5 - MIN. VOLUME |  |  | OUTSIDE <br> LANE S PEED $\mathrm{C}$ | total vol. THREE LANES$\qquad$ | bquivalent hourly rate <br> OE FLOH VPH |
| :---: | :---: | :---: | :---: | :---: | :---: | :---: | :---: |
|  |  | A | B | c |  |  |  |
| 7:10-7:15 | 42 | 172 | 176 | 124 | 42 | 472 | 5664 |
| 7:15-7:20 | 42 | 160 | 160 | 120 | 41 | 440 | 5280 |
| 7:20-7:25 | 41 | 159 | 167 | 119 | 41 | 445 | 5340 |
| 7:25-7:30 | 40 | 154 | 167 | 119 | 41 | 440 | 5280 |
| 7:30-7:35 | 37 | 166 | 167 | 127 | 35 | 460 | 5520 |
| 7:35-7:40 | 37 | 164 | 172 | 119 | 36 | 455 | 5460 |
| 7:40-7:45 | 41 | 151 | 158 | 129 | 39 | 438 | 5256 |
| 7:45-7:50 | 42 | 151 | 158 | 117 | 40 | 426 | 5112 |
| 7:50-7:55 | 43 | 148 | 161 | 122 | 41 | 431 | 5172 |
| 7:55-8:00 | 47 | 120 | 134 | 76 | 43 | 330 | 3960 |
| 8:00-8:05 | 47 | 117 | 138 | 79 | 44 | 334 | 4008 |
| 8:05-8:10 | 46 | 106 | 117 | 83 | 45 | 306 | 3672 |
| 8:10-8:15 | 46 | 111 | 133 | 67 | 43 | 311 | 3732 |

DALLAS I
CENTRAL EXPRESSWAY

dallas I

| TIME | $\begin{array}{\|c} \hline \text { INSIDE } \\ \text { LANE } \\ \text { SPEED } \\ \hline \end{array}$ | 5-min. volunes |  |  | OUTSIDELANESPEED(C) | total vol. 3-LANES <br> AT (A) | $\begin{aligned} & \text { EQUIV. HOURLY } \\ & \text { RATE OF FLOW } \\ & \text { YPH } \end{aligned}$ | 5-MIN. VOLUMES 0 | $\begin{aligned} & \text { CALCULATED } \\ & \text { TOTAL VOL. } \\ & \text { 3-LANES AT } \\ & \text { (G) } \\ & \hline \end{aligned}$ | EQUIV. RATE OF FLOW VPH |
| :---: | :---: | :---: | :---: | :---: | :---: | :---: | :---: | :---: | :---: | :---: |
|  |  | A | B | C |  |  |  |  |  |  |
| 7:10-7:15 | 45 | 103 | 121 | 65 | 41 | 289 | 3468 | 24 | 313 | 3756 |
| 7:15-7:20 | 47 | 115 | 111 | 74 | 40 | 300 | 3600 | 22 | 322 | 3864 |
| 7:20-7:25 | 45 | 137 | 141 | 65 | 41 | 343 | 4116 | 38 | 381 | 4572 |
| 7:25-7:30 | 44 | 174 | 163 | 103 | 38 | 440 | 5280 | 33 | 473 | 5676 |
| 7:30-7:35 | 40 | 156 | 146 | 112 | 36 | 414 | 4968 | 14 | 428 | 5136 |
| 7:35-7:40 | 36 | 166 | 170 | 130 | 32 | 466 | 5592 | 38 | 504 | 6048 |
| 7:40-7:45 | 35 | 161 | 147 | 129 | 29 | 437 | 5244 | 23 | 460 | 5520 |
| 7:45-7:50 | 32. | 163 | 150 | 128 | 27 | 441 | 5292 | 37 | 478 | 5736 |
| 7:50-7:55 | 35 | 155 | 156 | 140 | $\cdot 23$ | 451 | 5412 | 27 | 478 | 5736 |
| 7:55-8:00 | 39 | 145 | 137 | 110 | 36 | 392 | 4704 | 34 | 426 | 5112 |
| 8:00-8:05 | 42 | 133 | 128 | 84 | 39 | 345 | 4140 | 32 | 377 | 4524 |
| 8:05-8:10 | 44 | 154 | 146 | 97 | 33 | 397 | 4764 | 35 | 432 | 5184 |
| 8:10-8:15 | 39 | 128 | 139 | 111 | 36 | 378 | 4536 | 24 | 402 | 4324 |
| 8:15-8:20 | 41 | 150 | 144 | 90 | 37 | 384 | 4600 | 44 | 428 | 5136 |
| 8:20-8:25 | 42 | 132 | 144 | 94 | 38 | 370 | 4440 | 21 | 391 | 4692 |
| 8:25-8:30 | 43 | 126 | 126 | 89 | 39 | 341 | 4092 | 24 | 365 | 4380 |
| 8:30-8:35 | 42 | 127 | 122 | 76 | 39 | 325 | 3900 | 25 | 350 | 4200 |
| 8:35-8:40 | 44 | 112 | 100 | 56 | 41 | 268 | 3216 | 23 | 291 | 3492 |
| 8:40-8:45 | 45 | 86 | 110 | 43 | 38 | 239 | 2堅 | 23 | 262 | 3164 |

volume - speed tabulations
5 - Minute Tinie Intervals -- Morning Peak Period

FORT WORTH I


FORT WORTR

| TIME | INSIDE LaRE SPEED (A) | 5-min. volumes |  | OUTSIDE LaNE SPEED <br> (B) | $\begin{gathered} \text { TOTAL VOL. } \\ \text { 2-LANRS } \\ \text { AT } \\ \text { (A) } \\ \hline \end{gathered}$ | $\begin{aligned} & \text { EQUIV. HOURLY } \\ & \text { RATE OF FLOW } \\ & \text { VPB } \end{aligned}$ | $\begin{gathered} \text { S- MIN. vOLUMES } \\ \text { AT } \\ \hline \text { (C) } \\ \hline \end{gathered}$ | calculated total vol. 2-Lanes at <br> (D) | EQUIV. RATE OF FLOH VPH |
| :---: | :---: | :---: | :---: | :---: | :---: | :---: | :---: | :---: | :---: |
|  |  | , | 8 |  |  |  |  |  |  |
| 7:45-7:50 | 50 | 102 | 74 | 43 | 176 | 2112 | 47 | 223 | 2676 |
| 7:50-7:55 | 48 | 79 | 83 | 41 | 162 | 1944 | 30 | 192 | 2304 |
| 7:55-8:00 | 52 | 53 | 52 | 44 | 105 | 1260 | 46 | 151 | 1812 |
| 8:00-8:05 | 52 | 49 | 48 | 48 | 97 | 1164 | 36 | 133 | 1596 |
| 8:05-8:10 | 51 | 38 | 39 | 45 | 77 | 924 | 22 | 99 | 1188 |
| 8:10-8:15 | 51 | 39 | 31 | 45 | 70 | 840 | 39 | 109 | 1308 |
| 8:15-8:20 | 53 | 40 | 32 | 47 | 72 | 864 | 24 | 96 | 1152 |
| 8:20-8:25 | 49 | 48 | 31 | 43 | 79 | 948 | 39 | 118 | 1416 |
| 8:25-8:30 | 52 | 39 | 43 | 46 | 82 | 984 | 27 | 109 | 1308 |
| 8:30-8:35 | 51 | 39 | 31 | 45 | 70 | 840 | 23 | 93 | 1116 |
| 8:35-8:40 | 52 | 37 | 38 | 45 | 75 | 900 | 27 | 102 | 1224 |

TABLE 8
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 shown 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 overall 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 termed "volume-control" studies since 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 unjform. If the main channel is widened and the side flow introduced parallel to the main channel flow, the turbulence is virtually eliminated.

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 accormodated. 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 since both through and entering traffic are forced to wait their turn to pass through this critical area. This accummulation 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 $1 \frac{1}{4}$ miles back of the downtown dispersal system were closed during morning peak periods. On the Central Expressway in Dallas, the ramps were closed for approximately $1 \frac{1}{2}$ miles back of the downtown terminal. All "short-trip traffic" normally


CONSECUTIVE FIVE-MINUTE AVERAGE SPEEDS outside lane, morning peak period, all houston studies


FIGURE 12

CONSECUTIVE FIVE-MINUTE AVERAGE SPEEDS ALL LANES, HOUSTON II


FIGURE 13

CONSECUTIVE FIVE-MINUTE AVERAGE SPEEDS
ALL LANES, HOUSTON \#(A)-RAMPS CLOSED


FIGURE 14
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.

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 shown in Table 9 including both freeway and frontage road traffic. Values shown 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-minute 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 upon the speed of another is termed "speed sympathy". As shown in Figures 13 and 14 , the differential in five-minute 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 speedreduction occurs 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 since 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 three 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 -minute average speed during the offpeak periods was approximately 45 mph .

Speed-volume relationships shown 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 -minute average values, although not adequately


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

Peak Hour Volumes

7:10 to 8:10 A.M.


Table 9

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

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

```
Houston II - Outside Lane - Before Study
    5-minute average speed - 23 mph
    5-minute volume - 127 - equivalent hourly rate of
                                    flow - }1524\textrm{vph
Houston IIIa - Outside Lane - After Study
    5-minute average speed - 33 mph
    5-minute volume - 128 - equivalent hourly rate of
                                    flow - 1536 vph
Houston IIIb - Outside Lane - After Study
    5-minute average speed - 36 mph
    5-minute volume - 132 - equivalent hourly rate of
                                    flow - 1584 vph
Houston V - Outside Lane - After Study
    5-minute average speed - 35 mph
    5-minute volume - 127 - equivalent hourly rate of
                                    flow - }1524\mathrm{ 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 show 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. Since these studies were taken at random, both as to time and lane traveled, it was not practical to use less then i5minute periods for comparison.


FIGURE NO. I5

```
COMPARISON OF AVERAGE TRAVEL TIME
VOLUME-CONTROL STUDY - GULF FREEWAY
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FIGURE 16


Figure 17. Field Installation of Freeway Monitor.


Figure 18. Time Graphs of Freeway Monitor.

SPEED-VOLUME RELATIONSHIPS DALLAS "MONITOR - DATA"



The studies were compared by computing the time consumed by the total 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 one mile. This time expressed in vehicleminutes, is based on the average travel time during a 15 -minute period (through lanes and frontage road) and the delay experienced by ramp traffic during the before study. This comparison is shown in Table 10.

Figure 16 shows the everage travel time by 15 -minute periods for the through lanes and frontage road. Travel-time through the study area on the through lanes was reduced from 2 -minutes 35 -seconds with the entrance ramps open to 1 -minute 31 -seconds with the entrance ramps closed during the period 7:15 to 7:30 А.M. and from 2-minutes 15 -seconds to l-minute 47 -seconds during the period 7:30 to 7:45 A.M. There was no difference for the time 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 2831 vehicle-minutes or 47.2 vehicle-hours.

The delay experienced by entering ramp traffic was added to the time consumed by through lane traffic since 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 l, 131 vehicle-minutes, or nearly one-fourth of the vehicle-minutes for this time 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 oneway streets which provide adequate capacity to accomodate 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 we.s 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

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## TIME CONSUMED IN VEHICLE -MINUTES <br> FOR FIFTEEN-MINUTE 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 | 3,030 | 660 | 1,131 | 4,822 |
| 7:45-8:00 | 2,566 | 720 | 211 | $\frac{3,498}{12,451}$ |
|  | After Studies (Ramps Closed) |  |  |  |
| 7:15-7:30 | 2,044 | 772 |  | 2,816 |
| 7:30-7:45 | 2,350 | 953 |  | 3,303 |
| 7:45-8:00 | 2,550 | 951 |  | 3,501 |
|  |  |  |  | 9,620 |

Table 10
sixty-seven 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. Since 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 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 transinitted 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 is referred to as "Monitor Data" to distinguish it 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 shown in this table, there was no significant change in volume between the Dallas I and Dallas II studies.

Since 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, since the dispersal system in existance 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 capacity at the freeway terminal caused severe congestion of both the through lanes and the frontage road at this point.

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 -minute 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.
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PEAK PERIOD VOLUNE ON CENTRAL EXPRESSWAY

Film Data 7:20 A.M. to 7:55 A.M.

| Study | Inside Lane | Middle Lane | Outside Lane | Total |
| :---: | :---: | :---: | :---: | :---: |
| Dallas I | 783 | 754 | 714 | 2,251 |
| Dallas II | 786 | 765 | 639 | 2,190 |
| Monitor Data 7:18 A.M. to 7:54 A.M. |  |  |  |  |
| StudyIndicated Average Lane Volume <br> (Middle and Inside Lanes) |  |  |  |  |
| Dallas, Before |  |  | 690 |  |
| Dallas II |  |  | 705 |  |

Table 11

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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 one hour. During the other 23 hours 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.

## IANE 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 six-lane controlled access facilities.

Lane volumes were taken at a point 176 feet 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 off-peak ( $9: 00-10: 30 \mathrm{a.mo}$ ) and the afternoon peak ( $4: 00-6: 00 \mathrm{p} . \mathrm{m}_{\mathrm{s}}$ ).

Iane 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 off-peak 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.

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-minute 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.

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


LANE USAGE
gulf freeway - houston OFF-PEAK - INBOUND


LANE USAGE
CENTRAL EXPRESSWAY - DALLAS
OFF-PEAK - INBOUND


FIGURE




## average placements in median lane

## GULF FREEWAY



## DISTRIBUTION OF WEAVE LENGTHS DISTRIBUTION OF WEAVE LENGTHS HOUSTON I HOUSTON III



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 (Figures 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, off-peak, 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 off-peak period, the average placement shifts to the right of the center of che 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 (Figures 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 off-peak 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 twelve-foot 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 increass. 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 six-lane divided freeways. Since these film studies were not conducted solely for the purpose of studying this single traffic flow characteristic, the precision of some of the measurements were 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 -foot paved median; entrance ramps open.
2. Houston II - a 4 foot high barrier fence in the 4 -foot paved median; entrance ramps open.
3. Houston III - a 4 -foot high barrier fence in the 4 foot paved median; entrance ramps from Cullen closed.
4. Dallas - no barrier fence in the 12-foot 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.

Only two hours of observation are included in the Houston III study since 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 off-peak, and afternoon-peak periods.

All Houston studies were made on the same area at the Cullen Street Interchange on the Gulf Freeway shown in Figure 4.


## DISTRIBUTION OF WEAVE LENGTHS

ALL STUDIES


FIGURE

The Dallas Study was made on a similar area at the Fitzhugh Interchange on the Central Expressway shown in Figure 5.

Only inbound traffic on each freeway was considered.
A 400 -foot 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-foot 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 three inbound "through" freeway lanes. The traffic on the entrance ramps and exjt ramps were not included as weaving vehicles since their maneuvers are consicered 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. The time of day to the nearest minute, read from a clock filmed in the field of view.
2. The type of vehicle -- passenger car, truck, bus.
3. The lane in which the vehicle was traveling and the lane into which it weaved.
4. The location of the origin of the weaving maneuver with respect to the three areas mentioned in the description of the study areas.
5. The speed of the vehicle, determined by the frame count between two lines of known spacing and a known camera speed.
6. The 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. The location of vehicles on the entrance ramps.
8. Whether the vehicle left the freeway on the next exit ramp or continued on the freeway.
$\square$
$\square$

Since the accuracy of some information depends on the perception and judgement 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. There were two features that limited the degree of accuracy in determining the length of the weaving maneuvers:

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 facts that:

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. Since 85 to 95 percent of the weaves were only 300 feet or less, a large percent 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 feet with lengths ranging from 50 to 900 feet. The frequency distribution curve from the combined study increases uniformly up to 300 feet in Figure 33 and flattens out for longer lengths, indicating that 90 percent of all weaves are 300 feet or less. Using this length as a criteria for comparing the individual studies, the range of "percent less than 300 feet" was 85 percent in Houston I to 99 percent in Houston III.

The average lengths of weaves for the four studies are shown 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-Iength 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 the total roadway and by lanes for each weaving maneuver studied. For this analysis 5 -minute volumes were expanded to equivalent hourly rates of flow and related to the average length of the weaving maneuvers for that 5 -minute 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

figure 34
CONDITIONS OF ENTRY


HOUSTON


DALLAS

## ORIGIN - TERMINATION - DISTRIBUTION <br> OF WEAVING MANEUVERS


three lanes. Since the outside lane volumes were lower than the middle and inside lanes, additionel 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 shown 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 of the entrance ramp was 225 feet, or approximately 56 percent of the total length of the study section. There were 1589 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 percent of vehicles moving to the right.

The location of vehicles on the entrance ramps were 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 shown in Table 16.

Origin-Termination-Distribution of Weaving Vehicles - A total of 1940 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, Figure 36. Since the length of the weaving maneuvers are not shown, this drawing does not present a true picture. However, this method of presentation is particularly useful in relating the effect of entrance ramps on freeway traffic which is presented in detail in the following section of this report on weaving.

On six-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 since 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 characieristics 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 judgement 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 ramps in view of the camera.
2. Completelane 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 diroction of weaves. This subject was discussed in the preceeding 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, meny vehicles that appeared to perform this maneuver were classified in one of the more specific categories listed ebove.

Frequency of Weaving Meneuvers - The percent of the total volume of traffic that began weaving meneuvers in the 400 -foot study section ranged from 2 to 10 percent. There were considerable variations between different time-period and studies. Generally, the percent increased as the total volume of traffic decreased as shown in Table 18.

Recommendations for Further Study and Research
Since 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.

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The results of this report indicate several factors that must be considered in future studies. Any combination of three or four of these factors would constitute an individual investigation:

These factors are:

1. Location of the beginning of the weaving maneuver with respect to the geometric design features.
2. Iength of the weaving maneuver.
3. Path of the weaving maneuver.
4. Speed of the weaving vehicle.
5. Average speed of ireeway 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.

Surmary
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 1940 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 feet.
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 feet was used as a basis for comparisons of the several studies. A study of the frequency distribution curves, Figures 29 to 33, show the following percentages of weaving maneuvers to be 300 feet 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.

8a. 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 thirty-eight 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 anytime 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.

## NUMBER OF WEAVING MANEUVERS FOR EACH STUDY

| Study | Length of Study <br> in Minutes | No. of Weaving <br> Maneuvers | Average No. of <br> Weaves per min. |
| :--- | :---: | :---: | :---: |
| Houston I | 237 | 532 | 2.24 |
| Houston II | 245 | 412 | 1.88 |
| Houston III | 145 | 235 | 1.62 |
| Dallas | 277 | 904 | 1,940 |
| Total |  |  | 2.57 |

Table 12


## AVERAGE LENGTH OF WEAVES

| Study | Average Length in Feet |
| :--- | :---: |
| Houston I | 233 |
| Houston II | 200 |
| Houston III | 200 |
| Dallas | 223 |
|  | Average 217 |

Table 13

## LENGTHS OF WEAVES AS RELATED TO VOLUME

Average Volume Level Houston I Houston II Houston III Dallas

Average Length in Feet


Table 14

INFLUENCE OF ENTERING VEHICLES ON WEAVING

|  | Study | Total <br> Number of Weaves | ```Number of Weaves Occurring in Front of Entrance Ramp (Percent of Total Shown Below)``` |  |  | Number of Weaves Occurring <br> Behind the Entrance <br> Ramp <br> (Percent of Total Shown Below |  |  |
| :---: | :---: | :---: | :---: | :---: | :---: | :---: | :---: | :---: |
|  |  |  | Direction of Weave |  |  | Direction of Weave |  |  |
|  |  |  | Right | Left | Total | Right | Left | Total |
|  | Houston I | 532 | $\begin{gathered} 141 \\ (26.5) \end{gathered}$ | $\begin{gathered} 319 \\ (60.0) \end{gathered}$ | $\begin{gathered} 460 \\ (86.5) \end{gathered}$ | $\begin{gathered} 31 \\ (5.8) \end{gathered}$ | $\begin{gathered} 41 \\ (7.7) \end{gathered}$ | $\begin{gathered} 72 \\ (13.5) \end{gathered}$ |
|  | Houston II | 462 | $\begin{aligned} & 108 \\ & (23.4) \end{aligned}$ | $\begin{gathered} 292 \\ (63.2) \end{gathered}$ | $\begin{gathered} 400 \\ (86.6) \end{gathered}$ | $\begin{gathered} 24 \\ (5.2) \end{gathered}$ | $\begin{gathered} 38 \\ (8.2) \end{gathered}$ | $\begin{gathered} 62 \\ (13.4) \end{gathered}$ |
| $\begin{aligned} & 1 \\ & 0 \\ & 0 \end{aligned}$ | Houston III | 235 | $\begin{gathered} 126 \\ (53.6) \end{gathered}$ | $\begin{gathered} 67 \\ (28.5) \end{gathered}$ | $\begin{gathered} 193 \\ (82.1) \end{gathered}$ | $\begin{gathered} 20 \\ (8.5) \end{gathered}$ | $\begin{gathered} 22 \\ (9.4) \end{gathered}$ | $\begin{gathered} 42 \\ (17.9) \end{gathered}$ |
| 1 | Dallas | 711 | $\begin{gathered} 208 \\ (29.2) \end{gathered}$ | $\begin{gathered} 328 \\ (46.2) \end{gathered}$ | $\begin{gathered} 536 \\ (75.4) \end{gathered}$ | $\begin{aligned} & 99 \\ & (13.9) \end{aligned}$ | $\begin{gathered} 76 \\ (10.7) \end{gathered}$ | $\begin{gathered} 175 \\ (24.6) \end{gathered}$ |
|  | Combined | 1940 | $\begin{gathered} 583 \\ (30.1) \end{gathered}$ | $\begin{gathered} 1006 \\ (51.8) \end{gathered}$ | $\begin{gathered} 1589 \\ (81.8) \end{gathered}$ | $\begin{gathered} 174 \\ (9.0) \end{gathered}$ | $\begin{array}{r} 177 \\ (9.1) \end{array}$ | $\begin{gathered} 351 \\ (18.1) \end{gathered}$ |


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NUNBER 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 | $\boxed{67}$ | 172 | 58 |
| Total | 573 |  | 203 | 588 |

*Code 0 - No Vehicles on Ramp

Table 16
-31-
W:

| $5+$ |  |  |  |  |
| :---: | :---: | :---: | :---: | :---: |
|  | ： 8 | 172 | 42 | 24． 4 |
| 玉こustcı $\therefore$ \％ | «6？ | $\therefore 23$ | 25 | 10.9 |
| Hcuston ity | \％e | 149 | 1\％ | 23.0 |
| Dallar： | $\therefore \%$ | $30 \%$ | 133 | $\therefore ¢ 0$ |


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FREQUENCY OF WEAVING MANEUVERS

| Study | Morning Peak Period |  |  | Morning Off-Peak Period |  |  | Afternoon Peak Period |  |  |  | Total All Periods |  |
| :---: | :---: | :---: | :---: | :---: | :---: | :---: | :---: | :---: | :---: | :---: | :---: | :---: |
|  | Total <br> Number- <br> Vehicles | No. of Veh. That Weaved | \% | Total <br> Number <br> Vehicles | $\begin{aligned} & \text { No. of } \\ & \text { Veh. } \\ & \text { That } \\ & \text { Weaved } \end{aligned}$ | \% | Total <br> Number Vehicles | No. of Veh. That Weaved | \% | Total <br> Number Vehicles | $\begin{aligned} & \text { No. of } \\ & \text { Veh. } \\ & \text { That } \\ & \text { Weaved } \end{aligned}$ | \% |
| 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 | --mmen | - $-\cdots$ | $\cdots$ | - - - - | $\cdots$ | $\cdots$ | 4,851 | 98 | 2.02 |
| Houston III B | 5,819 | 137 | 2.35 | $\cdots$ | $\cdots$ | $\cdots$ | ----- | $\cdots$ | $\cdots \cdots$ | 5,819 | 137 | 2.35 |
| Dallas | 7,070 | 244 | 3.47 | I,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 3 was taken on two separate morning peak periods.


## ENTRANCE RAMP OPERATION

Efficient freeway operation is largely dependent upon 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.

Studies were made of four different types of entrance ramps: a two-lane, direct-entry ramp; a one-lane, direct-entry ramp; a one-lane ramp with a short acceleration lane and a one-lane ramp with a long acceleration lane, in order to compare and evaluate the relative merits of these various type entrance ramps.

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 feet wide, and joined the freeway with a $4^{\circ}$ curved transition becoming tangent with the freeway curb line at a distance of 365 feet 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, Figure 38, was 17 feet wide and was connected to the freeway by a $7^{\circ} 30^{\prime}$ 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 feet wide and during an initial study (Houston I and II) was connected to the freeway by a full-width acceleration lane, 12 feet wide and 350 feet 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 feet in length connecting the entrance ramp with the exit ramp.

## 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.



RAMP STUDY SECTION
GULF FREEWAY - HOUSTON
STUDY IV
FIGURE 40




## ENTRANCE RAMP STUDY HOUSTON I \& 프

Path of entry vs. percent of total entering vehicles CLASSIFIED ACCORDING TO VOLUME LEVELS



The data collected for the ramp study were taken from the following film studies:

Houston I
Houston II
Houston IV
Dallas I
Fort Worth II
Since 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 Figure 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 (Figure 41).
Condition II - Semi-direct entry along a curved path with full entry into the outside lane within 175 feet of the nose (Figure 42).
Condition III - Partial use of the acceleration lane with full entry into the outside lane from 150 to 250 feet from the nose (Figure 43).
Condition IV - Full use of the acceleration lane (Figure 44).
Condition V - Combined use of the acceleration lane and outside lane. Encroachment sufficient to insure a gap in the outside lane (Figure 45).

## Paths of Entry - Houston I \& 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 |
| :---: | :---: |
| I ........ | -(.)......................... 8.12 |
| II | $\ldots$ |
| III | (......................... 2.96 |
| IV |  |
| V | -... 32.86 |

The above tabulation indicates that approximately 58\% (Condition I \& II) made little or no use of the acceleration lane. Observation of


PATHS OF ENTRY
CLASSIFIED ACCORDING TO VOLUME LEVELS


TOTAL NO. OF VEHICLES STUDIED 2059

FIGURE 51

HOUSTON IV

figure 52
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 -minute volumes expanded to equivalent hourly rates of flow) were grouped into three basic levels: 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 - Iong Auxiliary Lane

The Houston IV study was made after modification of the acceleration lane. The second ramp was closed, as shown in Figure 40 , and the ramp nose removed to form an auxiliary lane approximately 1,000 feet in length which served as a combination acceleration-- deceleration lane for the entering and exiting traffic. Motion pictures made during the morning peak, morning off-peak, and afternoon-peak periods recorded approximately 3 hours and 40 minutes 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.

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 shown 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 the Houston IV study is shown in Figure 52.



## FORT WORTH

PATHS OF ENTRY
right rear wheel of vehicle
CONDITION

| PATH <br> TAKEN | III <br> VEHICLES |  |
| :---: | :---: | :---: |
| $3-10$ | 3 | $\%$ OF <br> YOTAL <br> VEHICLES |
| $3-11$ | 17 | 0.42 |
| $3-12$ | 74 | 2.36 |
| TOTAL | 94 | 10.29 |

total number of vehicles studied 719

FIGURE 55
FORT WORTH
PATHS OF ENTRY
right rear wheel of vehicle
CONDITION

| PATH <br> TAKEN | NO.OF <br> VEHICLES | \%OF <br> TOTAL <br> 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 <br> TAKEN | NO. OF <br> VEHICLES | \% OF <br> TOTAL <br> VEHIGLES |
| :---: | :---: | :---: |
| $2-10$ | 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
PATH OF ENTRY VS PERCENT OF TOTAL ENTERING VEHICLES classified according to volume levels


Fort Worth II - Two-Iane 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 accomodate 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 six feet of the right curb at a point opposite the nose of the ramp. A vehicle was considered in the inside or left lane of the ramp when the right rear wheel was further than 12 feet from the right curb, Those vehicles encroaching on both lanes used the ramp as single lane.

During this study, $63.5 \%$ of the 719 entering vehicles used the right or outside lane of the ramp, $23.5 \%$ encroached on both lanes and $13 \%$ 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 1500 vph . Therefore, the three rates of flow selected for comparison were less than $1,000 \mathrm{vph} ; 1,000-1,200 \mathrm{vph}$; 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, l-10, decreased as the volume increased, while the more direct or abrupt path of entry, l-1l, increased as the volume increased.

## 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 upon the relationship of instantaneous rates of flow on the freeway and ramp than upon 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.

## Paths of Entry

## A Comparison of the Houston I and Houston IV Studies <br> Houston I and II - Short Acceleration Lane <br> Houston IV - Long Auxiliary Lane

| Condition <br> of <br> Entry | Houston I \& II <br> Percent of Total <br> Entering Vehicles | Houston IV <br> Percent of Total <br> Entering Vehicles | Difference <br> of |
| :--- | :---: | :---: | :---: |
| 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 |

Table 19

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 $58 \%$ 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 $13 \%$ 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 greates 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 off-peak 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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#### Abstract

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Gratitude is also expressed to the personnel of this project for the valuable contribution each has made in the various phases of these studies.


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