Study Techniques for Planning Freeway Surveillance and Control

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Four study techniques, found to be quite useful in planning the peak period freeway surveillance and control activities on the Gulf Freeway in Houston, are presented: (a) entrance ramp origin-destination studies, (b) input-output studies of closed freeway subsystems, (c) aerial photography, and (d) input-output studies of critical intersections in the study area. Data from these studies can be used to plan peak period ramp controls because the demand and capacity can be estimated at each bottleneck (both on the freeway and on the frontage roads and streets) and to plan arterial street controls to provide for diverted traffic because the travel patterns of freeway interchange traffic can be determined. The duration and severity of control at each ramp which are required to prevent congestion can be estimated. The data are also useful in before-and-after comparisons.

•THE INCREASING severity of peak period freeway congestion has led to the establishment of freeway surveillance projects to study this problem. In addition, many other operational studies have been undertaken to determine the causes of peak period congestion. Because of the increasing severity of peak period freeway congestion and the increasing interest in its remedies, a need exists for a means or technique of studying a system composed of one direction of a freeway, perhaps several miles in length. Specifically, it must be possible to locate the critical bottlenecks in the system and to develop a control plan or geometric design changes to alleviate the problem of congestion. In addition, a need exists for a means of measuring completely the effect on the freeway system of any control. This evaluation should be made very quickly after the end of the peak period.

Traditionally, data collection procedures have used point studies, such as time-lapse photography, to determine operational characteristics of the traffic stream at a point. In some cases, several point studies have been used to study a length of freeway but, in these, primary interest has been devoted to the behavior at each individual point. Aerial photography can be used to study a length of freeway and is very useful to determine certain characteristics (especially density), but it is difficult to obtain flow rates and volume counts from the air photos. Few attempts have been made to study a length of freeway as a system.

When considering one direction of a congested freeway during the peak period and attempting to determine operational controls to prevent or reduce this congestion, several things are of interest. Freeway congestion sets in at a location when the demand exceeds the capacity. Hence, for a freeway which is regularly congested during the peak periods, one fact is already established. It is known that the demand exceeds the capacity somewhere on the freeway under consideration during its congested period. The problem is to determine at which locations and by how much this occurs.

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On many congested freeways the area of congestion extends for several miles. In these cases there are probably several bottlenecks and several exit and entrance ramps in the congested area. The operation at any location is a function of the operation at many other locations, so the problem is really that of studying a system of interdependent locations.

The need, therefore, exists for a technique of (a) identifying the bottlenecks, (b) estimating the capacity of each bottleneck, and (c) estimating the demand at each bottleneck so the magnitude and duration of the excess demand can be determined. This is needed to develop a rational peak period control system which can hold the demand at each bottleneck less than or equal to its capacity. However, the freeway cannot be considered independently of other traffic arteries in the same area when developing a peak period control system for the freeway traffic. The traffic operation on the frontage roads and major arterials that intersect the freeway may be affected as much or more than the operation on the freeway itself. Therefore, the same requirements that were set forth for studying a one-directional freeway system apply equally well to studying those streets that accommodate the freeway interchange traffic (i.e., traffic that enters and/or leaves the freeway within the system of interest) as well as the local or non-freeway traffic; namely, to locate critical bottlenecks and to estimate the demand and capacity of the bottlenecks. Also the development of a control system requires the reassignment in time or space of a portion of the freeway interchange traffic, and the calculation of new estimates of demand rates at all of the interchange locations on the freeway and streets. This reassignment requires some knowledge of the travel patterns on the surface street systems, the available alternate routes and the capacity restrictions on these routes.

SCOPE AND OBJECTIVES

The primary objective of this report is to present some study techniques which have proved valuable in planning a peak period freeway surveillance and control project. Some of these techniques were developed especially for use in the study of freeway operations of the inbound Gulf Freeway system as part of the Gulf Freeway Surveillance Project in Houston, but they all have general applications to the field of freeway surveillance and control. Some data and applications of the Houston data are presented to illustrate the methods, but this should not detract from the generality of the approach to the problem and the methods discussed herein.

The techniques presented, when used in combination, fulfill the following objectives:

1. To locate the critical bottlenecks on the freeway and arterial streets;
2. To determine the capacity flow rates at each bottleneck;
3. To determine the demand pattern at each freeway entrance ramp;
4. To determine the demand pattern at each critical freeway bottleneck;
5. To determine by how much and for how long the demand exceeds the capacity at each bottleneck;
6. To provide data suitable for interpretation in terms of the type of control systems required to prevent freeway congestion;
7. To provide data that are suitable for use in before-and-after studies to be used for evaluating control experiments and can be analyzed immediately after the data are collected each day;
8. To provide data suitable for predicting the effect of a control and/or geometric change;
9. To determine the travel patterns of the freeway interchange traffic on the city street system; and
10. To provide data suitable for estimating the effects of a control system on the demand pattern at each freeway entrance ramp.

ORIGIN-DESTINATION STUDIES

Study Technique

The study of travel patterns on city streets is generally developed from a flow diagram or flow map of the traffic volumes using the city street system. These flow

maps are developed from a series of spot counts at major intersections and along major thoroughfares which give point data for the total number of vehicles using a particular street. These volumes are then combined to determine the demand of traffic on these various arterials. At some of the major intersections turning movement counts are made to indicate the demand for separate turning lanes, separate signal indications, or control for turning movements. These data do not give the entire picture of the travel patterns in that there is no way to separate short trips from through movements, or to distinguish the traffic that is destined for the freeway from the other traffic. To better understand the travel patterns of the portion of the interchange traffic which enters the freeway in the system of interest, origin and destination (O-D) survey techniques were selected to determine not only the location of the origin and destination of this interchange traffic but also the routes used to approach the freeway and to exit from the freeway.

All study techniques designed to give information on the origin and destination of motor vehicle trips were considered for use in this survey. Two requirements of the study affecting the design of the technique were (a) that interference of traffic must be minimized when working with freeway traffic; and (b) that the survey is made for a specific group of motorists, namely, the interchange traffic.

The "lights-on" technique was considered because it can be applied to a specific segment of the traffic such as entrance ramp traffic (1). This procedure instructs the motorists in the traffic stream to be studied to turn on their headlights. Observers stationed at various locations record the lane in which the vehicles are traveling and the time of day as they pass. This technique was rejected because the data would be limited only to travel patterns of the interchange traffic on the freeway lanes.

The roadside interview technique was rejected because of the delay and inconvenience to the motorist and the possible distraction to the freeway traffic. Home or business interviews would require a very large sample to obtain efficient data from the particular segment of freeway traffic being studied.

A technique which combines the use of field observations and mailed questionnaires was developed for use in a Los Angeles freeway study and later adopted for use in a study in Chicago (2, 3). This procedure requires that the license plate numbers of all

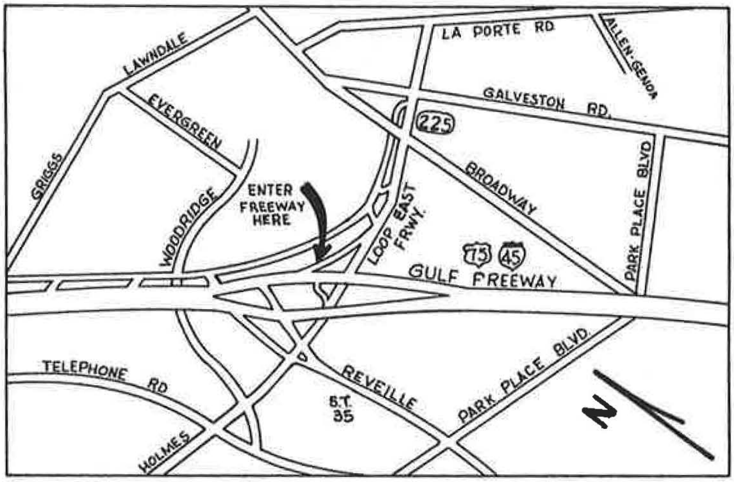
of the vehicles' owners are then obtained from the motor vehicle registration records and questionnaires with return postage guaranteed envelopes inclosed are mailed to these persons. Since favorable returns were received in these studies in Los Angeles and Chicago, the same type of questionnaire form and mail return procedure was selected for this study.

However, the method of distribtuion of the questionnaires was changed. Each motorist entering the ramp during the study period was stopped and issued a questionnaire, a return postage guaranteed envelope and a letter of explanation (Figs. 1 and 2). The forms could usually be issued at a rate faster than the vehicles could merge into the freeway so the motorists experienced little additional delay. This technique also reduces the possibility of vehicles queueing at the ramp and thus distracting the attention of the freeway motorists. This procedure has several advantages:

1. Hundred percent distribution is assured. This means that 100 percent of the traffic of interest has an opportunity to complete and return the questionnaires. When forms are distributed by mail, the owner of each vehicle is contacted and he is not necessarily the driver of the vehicle.

2. Recording and addressing errors are eliminated. The requirement to record the license number of each vehicle entering the freeway increases the possibility of not contacting the driver of the vehicle, either by recording the wrong license number, by looking up the wrong license number, or by copying down the wrong address from the records.

3. Motorists may fill out the form immediately after the trip is completed, thus eliminating some of the problems of incomplete forms and bad data. The motorist is able to recall more accurately the details of the trip and to give good information on such questions as the time of arrival and time of departure for the trip, which are



The following questions concern the trip being made at the time you receive this questionnaire.

1. Please draw a line directly on the above street map showing the route you followed in reaching the indicated entrance ramp. If the origin of the trip is not included in the area shown, extend the route to the border of the map.

2. Where did this trip begin?

____

Street Address City Time of Day

3. Where did this trip end?

____

Street Address City Time of Day

4. What exit ramp did you use to leave the freeway? (Check One)

___Exit No. 7-Wayside	___Exit No. 4-Calhoun-Elgin	___Exit No. 1-Sampson
___Exit No. 6-Telephone	___Exit No. 3-Cullen	___Pease Street
___Exit No. 5-Lombardy	___Exit No. 2-Scott	___US 75 North-Calhoun St.

5. How often is this trip made between 6:30 and 8:30 a.m. (Check One)

___Seldom	___Twice per week	___Four times per week
___Once per week	___Three times per week	___Five or more times per week

6. Do you ever use other routes to make this trip? ____yes ____ no.

If yes, what major streets are used?______________________________

____

After you have completed this questionnaire, please mail it back to us in the addressed envelope at your earliest convenience to the Texas Highway Department, Research Project, P. O. Box 26656, Houston, Texas 77032.

THANK YOU FOR YOUR COOPERATION

Figure 1. Questionnaire for O-D study, Gulf Freeway.

sometimes difficult to recall when related to a trip that occurred one or more days past.

4. Time of arrival for each vehicle can easily be determined by taking periodic time checks and noting the number of the questionnaire being distributed. By issuing the questionnaires in order, the numbering system can indicate the rate of flow for the metered input to the freeway and permits the data to be analyzed for shorter time periods.

As the questionnaires are returned through the mails, the forms can be coded and the origins and destinations can be assigned zone numbers according to the official zoning index of the city being studied so that the information obtained from this survey will complement that obtained in metropolitan O-D surveys of the city. This is helpful in expanding the sample of questionnaires that are returned to the study. Since there are several parameters and many questionnaires involved, the data should be translated to punch cards so that machine sortings and tabulations can be made.

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IN REPLY REFER TO
FILE NO.

Dear Motorist:

We need your help in a Special Traffic Study of the Gulf Freeway which is being conducted in cooperation with the Texas Transportation Institute. This study has the objective of providing safer and more efficient operation on the Gulf Freeway. In order to develop better traffic operation on freeways, it is necessary to learn how the individual motorist uses them.

You are not required to sign any form and the information provided by you will be kept confidential. We would appreciate your completing the attached questionnaire as accurately as possible and returning it to our office.

Your participation and cooperation in this survey will be greatly appreciated.

Figure 2. Letter of explanation.

Analyses

The analysis of the data consists primarily of arranging the dat[illegible] as possible. The first step in preparing the data for presentation is to determine the reliability of the data and to expand them for 100 percent return. It was found in studies conducted on the Gulf Freeway inbound traffic for the morning peak period that more than 90 percent of the traffic using the entrance ramps within the study area were repeat drivers who made the same trip five or more times a week (4). This indicated that it was not necessary to repeat the study more than one day. The percent return was exceptionally good on most of the eleven ramps being studied. A 40 percent return for a mailed questionnaire is considered good, and the results received in Houston were in the range of 45 to 65 percent return for individual ramps and averaged 55 percent for the entire study. A breakdown of the percent return by time period or by section of the area observed indicated a uniform rate of return from all segments of the traffic so that a straight expansion based on percent return was considered reliable.

The following sections show how the information can be analyzed and tabulated for application to the planning and development of a control system.

Traffic Assignment. —The route used to approach the freeway can be determined from a sketch made on the questionnaire by the driver and from the location of the origin of the trip with respect to the entrance ramp used. This information is tallied for each trip on a map of the major arterial streets leading to the freeway. Since the time period in which each questionnaire was distributed is known, these data can be obtained for any time period to indicate the volumes of interchange traffic on the street system at any time of day. As the questionnaires are tabulated, volumes of interchange traffic using each of the various streets leading to the freeway are calculated. These volume counts can be used to determine the percent of turning movements at major intersections involving interchange traffic. These data can be summarized for each entrance ramp, or a combination of several entrance ramps, and by time of day for one or more entrance ramps. Figure 3 shows a summary of the number of vehicles

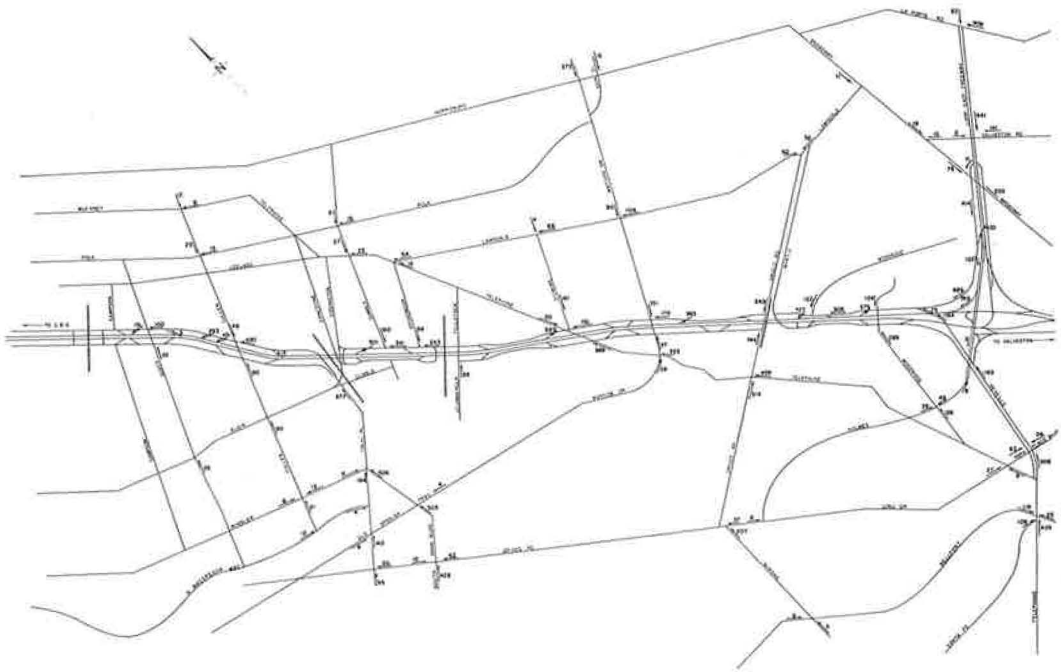

Figure 3. Interchange traffic assignment, 6:45 to 8:30 a.m. volumes.

entering the freeway during the entire study period of 6:45 to 8:30 a.m. for the Gulf Freeway survey. Figure 4 indicates the same information for a single ramp.

The volumes shown at some distance away from the freeway are assigned to the system by engineering judgment based on the knowledge of the street system and location of the trip origins. These estimates can be misleading due to the omission of minor streets that can be used as feeders to the major street system. However, the estimate becomes more reliable at the arterial streets closer to the freeway because most traffic uses the major arterial system to approach the freeway, and the sketches included on the questionnaires provide some information on the approach routing.

Summary Tables.—Some of the data can be summarized in tables for one or more entrance ramps (Table 1). The data on the percent return, the exit ramp used, the frequency of use, and the use of alternate routes can be presented in time intervals compatible with the study control time. The distance in miles between the entrance ramp and every downstream exit ramp can be included on this form to indicate the number of short freeway trips that are generated from each of the entrance ramps in the study area.

Of particular interest in the estimation of demand at the freeway bottlenecks is the percent of vehicles entering the freeway at any entrance ramp which exit at each downstream exit ramp. Table 2 shows a summary of these data obtained from the studies on the inbound Gulf Freeway (4).

Freeway Trip Lengths.—Based on the information developed in the preceding tables, the distribution of trip lengths of traffic entering the study section from the entrance ramps can be determined, as well as the average freeway trip from each ramp (3, 4).

Freeway Area of Influence.—With the addresses of the origins and destinations of the interchange traffic trips known, the area of influence of the freeway can be determined. The locations of the origins can either be plotted separately according to street address or can be grouped according to the official zoning system if the zones are broken down into very small areas. A tabulation of the trips from zone of origin to zone of destination can be made, and the desire lines drawn from the centroid of the zones indicate graphically the overall influence of the freeway (Fig. 5).

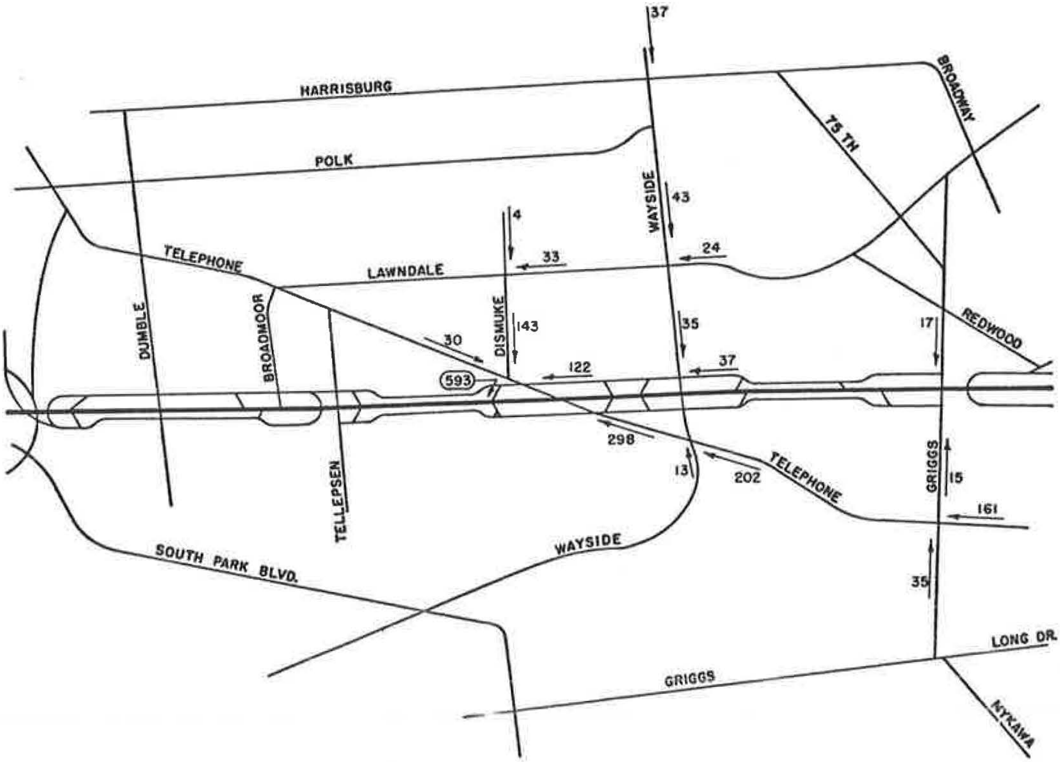

Figure 4. Assignment of interchange traffic entering Gulf Freeway at telephone entrance ramp.

TABLE 1

RESULTS OF QUESTIONNAIRES RECEIVED FROM GRIGGS-MOSSROSE RAMP

Question	Time of Day Traffic Entered Freeway (a. m.)							Total	Expanded Totals
	6:50 to 7:00	7:00 to 7:15	7:15 to 7:30	7:30 to 7:45	7:45 to 8:00	8:00 to 8:15	8:15 to 8:22		
Total distributed	24	145	143	164	179	71	24	750	750
Total returned	14	101	93	113	114	45	13	493	750
Percent return	58.4	69.6	65.0	69.0	63.6	63.5	54.1	65.8	100.0
Exit ramp used:									
No. 9—Woodridge	-	-	-	-	-	-	-	-	-
No. 8—Griggs	-	-	-	-	-	-	-	-	-
No. 7—Wayside	1	15	15	22	40	14	4	111	169
No. 6—Telephone	-	1	7	5	7	3	2	25	38
No. 5—Lombardy	-	4	3	8	8	2	-	25	36
No. 4—Calhoun	-	7	4	8	10	4	1	34	52
No. 3—Cullen	-	2	3	5	5	1	1	17	26
No. 2—Scott	-	2	3	1	1	1	-	8	12
No. 1—Sampson	2	7	7	8	3	2	1	30	46
Pease	8	39	36	32	18	10	3	146	221
US 75—Calhoun	2	19	12	22	22	6	1	84	128
Did not indicate	1	5	3	2	-	2	-	13	20
Frequency of use:									
Seldom	-	-	-	-	-	3	-	3	5
Once/wk	-	1	-	-	-	1	-	2	3
Twice/wk	-	-	2	-	-	-	1	3	5
Three/wk	-	2	-	-	-	-	-	2	3
Four/wk	-	-	1	1	2	1	-	5	8
Five or more/wk	14	96	90	112	112	40	12	476	723
Did not indicate	-	2	-	-	-	-	-	2	3
Other routes:									
Yes	5	37	37	35	58	19	7	189	301
No	9	61	56	76	55	24	6	287	497

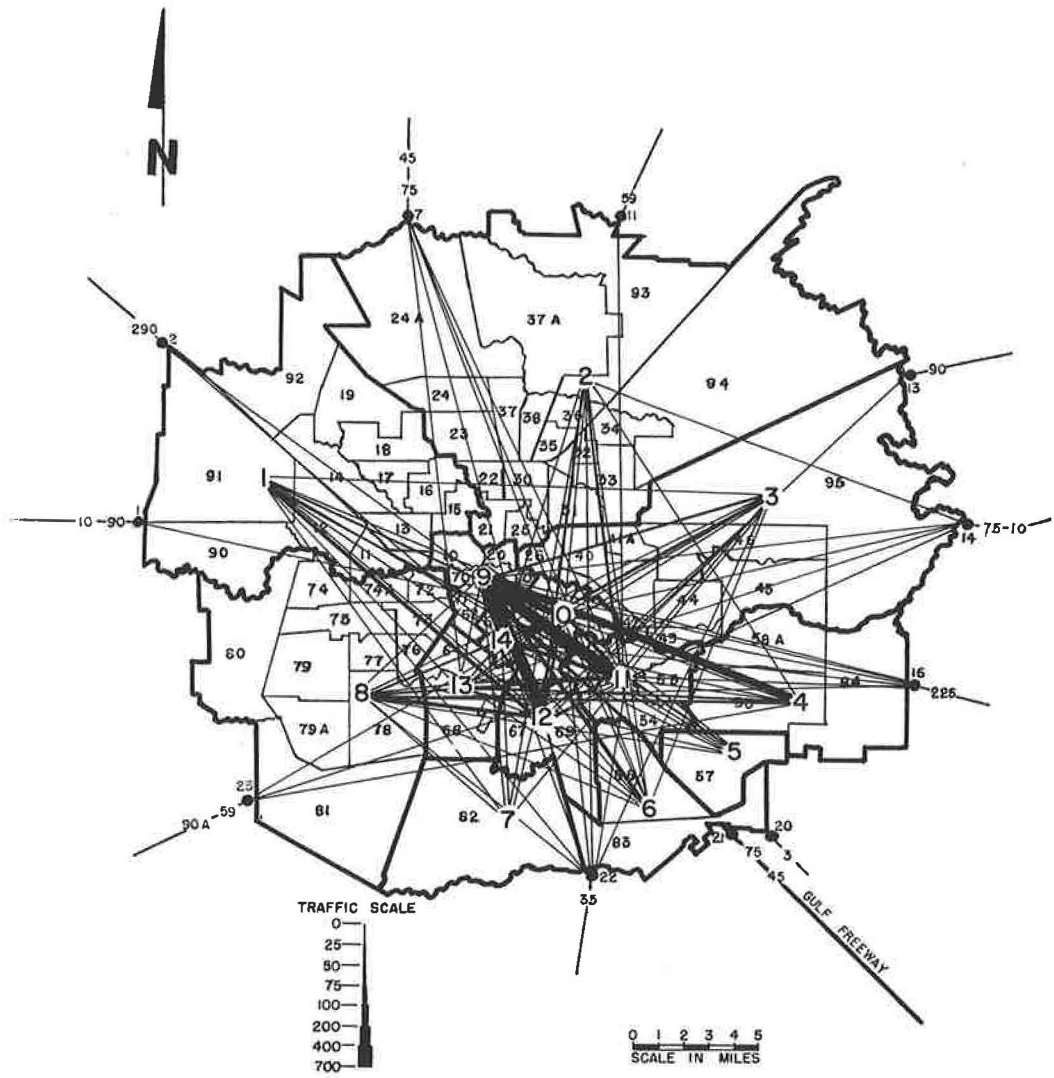

Figure 5. Houston District map, trip desire lines, Gulf Freeway, 6:45-8:30 a.m.

The areas of influence of the individual entrance and exit ramps can be indicated in similar plots (Fig. 6). The origins and destinations of the interchange traffic that used one of the entrance ramps within the study section are linked by desire lines drawn to the freeway ramps used. These desire lines indicate the distribution of the freeway trip lengths from each of the entrance ramps and the possible diversion routes that could be used by some of the interchange traffic.

The areas of influence for individual exit ramps can also be shown in a similar manner.

Application of Data. —Data developed from the O-D studies of freeway interchange traffic have direct applications to the planning and implementation of freeway control. Flow maps of the interchange traffic volumes on the city streets provide the information for determining where the traffic might divert if access to the freeway is changed. Possible alternate routes are easily determined from the traffic assignment map.

The persons to be affected by changes in control could be contacted through the mails or by personal handouts at the ramps to advise them of the control procedure and alternate routes.

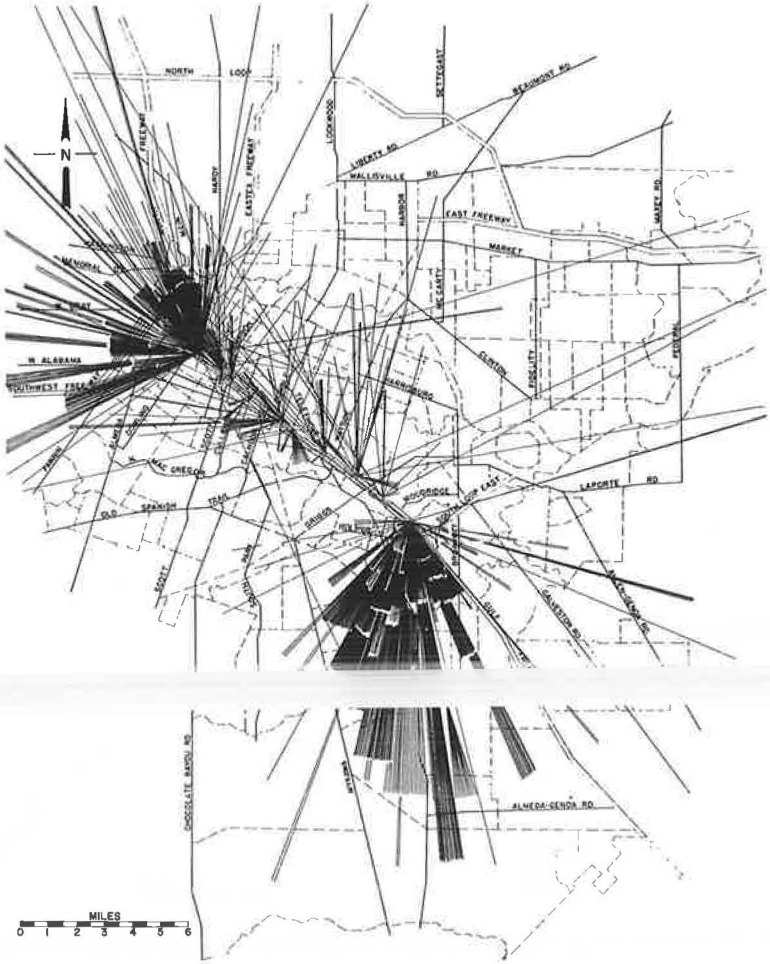

Figure 6. State 35 entrance ramp area of influence, O-D desire lines via freeway link, 6:45-8:30 a.m.

TABLE 2

O-D TABLEAU, PEAK-PERIOD

Entrances	Percent Exiting at												
	SH 225	SH 35	Woodridge	Exit 8	Wayside	Telephone	Lombardy	Calhoun-Elgin	Cullen	Scott	Sampson	Pease Dist.	Calhoun Dist.
Freeway at Broadway	7.2	5.7	7.3	2.1	11.2	3.8	0.7	9.5	2.6		Not calculated		
Detroit	-	-	7.8	2.4	12.9	4.4	0.8	10.9	3.0		Not calculated		
SH 225	-	-	0.25	0.25	2.5	0.5	1.2	7.9	5.4	2.5	5.4	38.9	35.2
SH 35	-	-	-	1.5	6.1	2.7	3.6	6.4	3.5	2.8	6.3	37.3	20.8
Woodridge	-	-	-	0.0	8.6	1.3	3.6	8.3	4.7	2.6	6.0	35.3	29.6
Mossrose (+ K Illegal)	-	-	-	-	23.1	5.2	5.2	7.1	3.5	1.7	6.3	30.4	17.5
Griggs	-	-	-	-	-	1.8	2.3	8.3	3.4	2.9	10.3	42.3	28.7
Wayside	-	-	-	-	-	0.4	1.8	15.1	5.3	1.3	4.9	36.1	35.1
Telephone	-	-	-	-	-	-	-	13.4	4.2	2.9	4.6	42.5	32.4
Dumble	-	-	-	-	-	-	-	-	5.6	1.1	5.1	44.7	43.5

The distribution of trip lengths can point out the need for design or control changes that would eliminate the very short trip in favor of the longer trips.

The traffic assignment map indicates the more promising locations for the establishment of advisory or regulatory control to divert traffic to alternate routes.

FREEWAY DEMAND-CAPACITY STUDIES

Freeway Subsystem Input-Output Studies

This study technique has its theoretical basis in the continuity equations of traffic flow which have been discussed in previous reports (5, 6). These equations state that at any instant the rate at which vehicles are entering a closed system equals the rate at which they are leaving the system plus the rate at which they are being accumulated within the system. Alternately stated, the change in the number of vehicles in a closed system in a time period equals the difference between the number of vehicles which enter and the number of vehicles which leave the system during the time period.

When using this study technique in the operational analysis of a congested freeway system, the first step is to determine the boundary points of the system of interest. The upstream boundary should be upstream of all congestion so the counts at this location represent the demand on the freeway. The downstream boundary should be downstream of present congestion and possible future congestion. (If control measures are successful in increasing the flow out of the presently congested system, congestion may develop at some downstream locations.) Air photo data can be quite useful in guiding the selection of the boundaries of the system of interest.

When the system of interest is defined, manpower requirements and availability will probably make it necessary to divide this system into closed subsystems for the analysis. Each closed subsystem consists of a freeway input count, a freeway output count and a count of each of the intermediate entrance and exit ramps. Two men are required at each freeway count location and one man is required at each ramp count location.

The subsystems should be mutually exclusive and collectively exhaustive; that is to say, they do not overlap but together they include the entire system of interest. A known or suspected bottleneck should be chosen as the division points between subsystems. In this way the (freeway) counts there can be used in the estimation of the capacity of these bottlenecks.

Data from all count locations should be recorded simultaneously at regular intervals and, to eliminate the need to reset the counters and to facilitate the analyses, should be recorded in cumulative form. Five-minute time periods proved very satisfactory on the Gulf Freeway studies. In this way the total number of vehicles entering and leaving the system in the time interval, as well as the change in the number of vehicles within the system, can be determined.

The counts are progressively started and stopped by driving a signal car through the subsystem being studied. At the beginning of the study the signal car drives through the subsystem and the upstream freeway counters begin by counting the signal car as soon as it crosses their reference line. Each man counting at an entrance ramp begins by counting the first vehicle on his ramp to enter the freeway after the signal car passes; the exit ramp counters begin with the first vehicle to leave the freeway after the signal car passes. The freeway output counters also begin by counting the signal car as it crosses their reference line.

The driver of the signal car counts and records the net number of vehicles which pass him in the study subsystem (both when starting and stopping the counts). If this is done, the number of vehicles within the closed subsystem is known as soon as the last count is started. The number of vehicles in the subsystem is also known once each 5 min (each time the data are recorded), since the net number of vehicles crossing the cordon line is known. (One can immediately see the similarity between this technique and a parking accumulation study. Indeed, a peak period freeway study is all too often a parking study.) By progressively stopping the counts in the same way, a check on the counts is obtained since the total number of vehicles counted entering the system should equal the total number counted leaving the system.

At freeway count locations, the second man was used to obtain speed samples—one sample per lane per minute. In this way the quality as well as quantity of flow was determined and these data were used to aid in the location of critical bottlenecks.

Limitations of This Type of Study. —When properly conducted, a study of this type yields a wealth of valuable data. There are, however, many things which can void part of these data.

It is essential that the watches of the study personnel be synchronized before the study so that the count data are all recorded at the same times. This is necessary to assure that at each recording time the number of vehicles in the system is accurate. If, for example, a freeway count is recorded 30 sec late, it could be as much as 50 veh in error (assuming a three-lane section flowing at 100 vpm). This error would also be reflected in the number of vehicles in the system, which might be about 50 to 500 when correct. Thus, a 50-veh error could be a large percent error and would be especially serious if it were carried through the entire study period. This can be a more noticeable problem on short subsystems in which the number of vehicles in the subsystem is small.

Similarly, the accuracy of the counts is extremely critical in studies of this type. One inaccurate count can void all of the input-output analyses.

Also, because of the interdependence of count locations, it is essential that all of the study personnel arrive on time for the study. This can become a special problem when the morning peak traffic is studied (due to early hours involved), as in the case reported here. When less than the proper number of men show up, the closed system study has to be postponed (unless substitute personnel are available).

Data Analyses. —Several analyses can be made of the data of each of the subsystem studies.

Total Input to the Subsystem vs Time. —If for each of the subsystems, coordinated counts were made at two locations on the freeway and all of the entrance and exit ramps

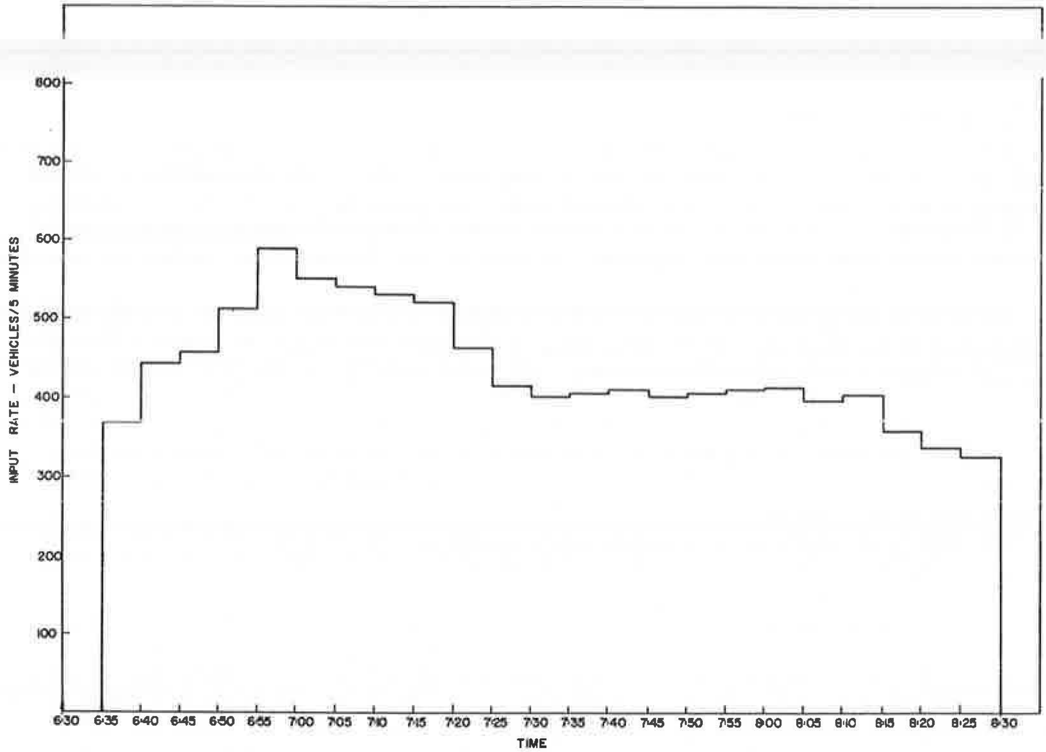

Figure 7. Input rate to Broadway—Griggs subsystem.

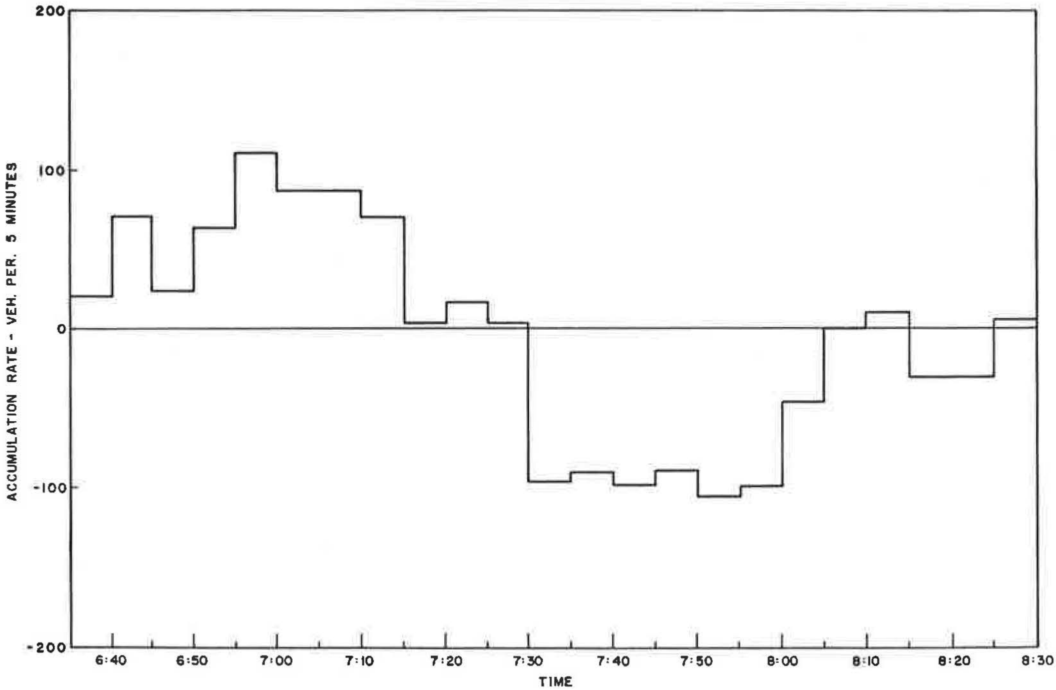

Figure 8. Rate of accumulation on freeway from Broadway to Griggs overpass.

in between, for each subsystem, then, the input locations consisted of the upstream freeway location and all of the entrance ramps in the subsystem.

Since all count data were recorded simultaneously each 5-min, the total number of vehicles entering the subsystem in each 5-min period could be determined by adding the individual inputs for each 5 min. When this is done, the resulting total input can be plotted by 5-min time periods. Figure 7 shows an example of this plot obtained for one subsystem on the Gulf Freeway studies.

Total Output from the Subsystem vs Time.—In a similar fashion, the total number of vehicles leaving each subsystem in each 5-min period can be determined. The resulting total output of each subsystem can be plotted by 5-min time periods.

Accumulation in Each Subsystem vs Time.—In a closed system, for any time period the difference between the number entering the system and the number leaving the system is the change in the number in the system. In each of the freeway subsystems (each a closed system), the difference in the total input and total output for a 5-min period is the number of vehicles accumulated or stored in the system during the time period.

The difference between the total input and total output for each system can be calculated and plotted. Figure 8 shows an example of this type of plot obtained for the same subsystem on the Gulf Freeway studies. From this figure it can be seen that the greatest rate of accumulation takes place in this subsystem from 6:50 to 7:15 a.m., that steady-state congestion prevails from about 7:15 to 7:30 a.m., and that the subsystem clears from 7:30 to 8:05 a.m. This indicates that the demand exceeds the capacity in this subsystem primarily between 6:50 and 7:15 a.m., and the entire period of congestion lasts from 6:50-8:05 a.m.

Number of Vehicles in Each Subsystem vs Time.—For each subsystem, at the time the data were recorded, the total number of vehicles which had entered the system and the total number which had left the system from the beginning of the time period are known. The difference between these gave the number of vehicles remaining in the system.

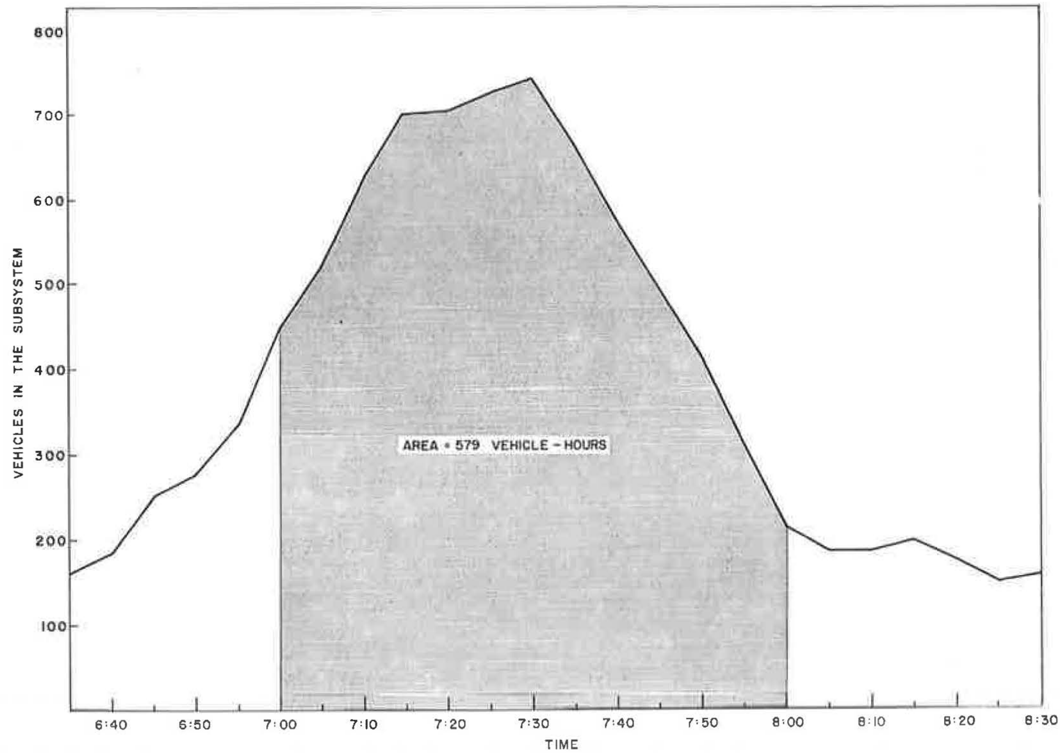

Figure 9. Number of vehicles on freeway from Broadway to Griggs overpass.

The number of vehicles in each subsystem can be plotted as a function of time. Figure 9 shows an example of a plot of the number of vehicles in one freeway subsystem on the inbound Gulf Freeway.

Since the density in a subsystem equals the number of vehicles in the subsystem divided by the subsystem's length, the number of vehicles in each subsystem can easily be converted into density which can be plotted against time.

Total Travel Time in Each Subsystem During the Peak Hour. —The area under the curve of the number of vehicles in a system vs time in any time period is the total travel time accumulated by all vehicles while they are in the system (5, 7). This analysis can be performed to obtain the total travel time for each subsystem for the peak hour or any other time period. The total travel time of 579 veh-hr on one of the inbound Gulf Freeway subsystems can be seen in Figure 9.

The total travel time in a freeway subsystem can be calculated within 1 to 2 hr after the end of a study by one man with a desk calculator. This speed of analysis makes this technique quite useful in before-and-after studies to determine the effect of a control measure since it is desirable to know this effect immediately.

Accuracy and Error Distribution. —Since the total input count during the study period should equal the total output count for each subsystem, a check on the accuracy of each day's data is available.

The errors are distributed evenly throughout the study period. If, for example, on a given day the total input count was 25 veh greater than the total output count and there are 25 5-min time periods (6:30 to 8:35 a.m., for example), the output can essentially be increased by one vehicle in each 5-min time period. In the Gulf Freeway studies no data were used in the analyses if the discrepancy between input and output counts was greater than 1 percent.

Capacity Counts. —In addition to the freeway counts which are a necessary part of the closed subsystem studies, additional freeway counts can be made for the purpose

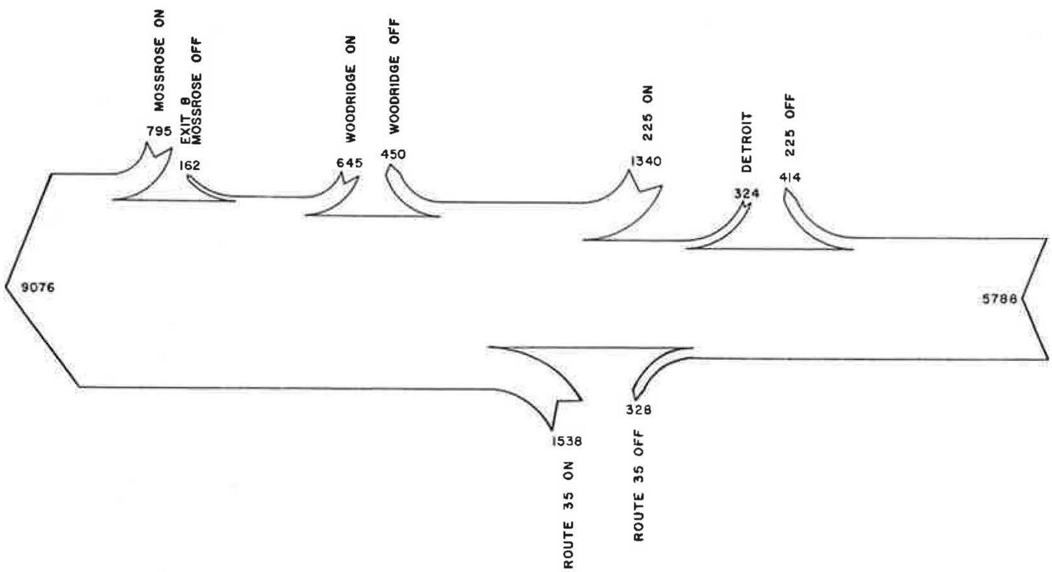

Figure 10. Study period flow map, Broadway-Griggs subsystem.

of refining estimates of the capacity flow rate at each critical bottleneck. In these studies, the volume count data were recorded each 5 min, and 15-min volumes were used for the purpose of estimating capacities.

Speed samples were obtained at the count locations (a sample of one vehicle per lane each minute using stopwatches to time sampled vehicles through a trap) during each of these counts. The speed data were useful in indicating when the flow at a location was reduced due to a backup of congestion from downstream.

Application of Data

Estimated O-D Data for Freeway.—The O-D surveys at the entrance ramps to a freeway can be made with little trouble. Similar surveys for the freeway at the upstream input source, in all but a few exceptions, are not feasible. Hence, it is necessary to estimate the peak period O-D data for this freeway input. The necessary information at this location is the distribution of traffic at this location to the downstream exits, i.e., the percent of vehicles at the upstream freeway input which exit at the downstream ramps. An example of some of the computations used to determine these O-D percentages for the freeway input for the Gulf Freeway studies is used to present the technique.

The O-D studies yielded information on the percent of vehicles which leave the freeway at each downstream exit for each entrance ramp included in these studies. However, similar data were not available for the Detroit St. entrance ramp and the freeway near Broadway (both at the upstream end of the system of interest). It was possible to combine the existing O-D data with the closed system counts to estimate this data for the other two input sources (Detroit entrance and freeway near Broadway).

Figure 10 is a flow map containing the numbers used for some of the estimations. Two very obvious calculations were made first. Of the 5,788 veh which entered the system on the freeway at Broadway, 414 left on the SH 225 exit ramp and 328 left on the SH 35 exit ramp. (It is almost impossible for vehicles to enter the Detroit entrance ramp on the right and exit at SH 35 on the left—especially during the hours studied.) This means that during the study period, 7.2 percent of the vehicles on the freeway at Broadway exit at SH 225 and 5.7 percent of them exit at SH 35.

Of the 450 veh exiting at the Woodridge exit ramp, 3 (0.25 percent of 1,340) are estimated to have come from the SH 225 entrance. This leaves 447 which had to come

from the freeway at Broadway and the Detroit entrance. The assumption was made that the O-D characteristics of the vehicles entering at the Detroit ramp are the same as those of the vehicles which are on the freeway just upstream of the Detroit entrance ramp, i.e., those vehicles on the freeway at Broadway which do not exit at SH 225. Of the 5,698 veh downstream of the Detroit entrance ramp, 447, or 7.8 percent, exited at Woodridge. Thus, 7.8 percent of the vehicles entering at the Detroit entrance and 7.3 percent of the vehicles on the freeway at Broadway (92.8 percent of 7.8) exited at Woodridge.

Similar analyses were made to estimate the exiting percentages at the other output locations of the Broadway-Griggs subsystem. A similar, somewhat more difficult procedure (combining the data of more than one subsystem) was used to estimate the percentages of vehicles from the Detroit entrance and freeway at Broadway which exit downstream of the Broadway-Griggs subsystem. The estimated O-D data for the freeway at Broadway and for the Detroit St. entrance ramp are included in Table 2.

Estimates of Demand at Freeway Bottlenecks (10).—Volume count data at each input to the freeway can be combined with the O-D data and freeway capacity estimates to obtain the demand rate at each of the known or suspected freeway bottlenecks. The demand at a given bottleneck can come from all of the upstream freeway inputs. In the case of the in-bound Gulf Freeway, all upstream inputs include the freeway at Broadway and all of the entrance locations between Broadway and the bottleneck. The demand at a bottleneck can be influenced by the capacity of upstream bottlenecks.

Some vehicles from each of the upstream inputs may go through the bottleneck and some may exit upstream of the bottleneck. Thus, only some portion of each upstream input volume represents demand at the bottleneck. If there are no bottlenecks upstream of the one under consideration and if for each input the percentage of vehicles which pass through it is known, an estimate of the demand in the i^{th} time period is:

$$D_i = \sum_{j=1}^{n} P_{ij}V_{ij}, \quad i=1,\ldots\ldots m \tag{1}$$

fraction of vehicles from the j^{th} input which are destined for the bottleneck, again during the i^{th} time period.

On the inbound Gulf Freeway the farthest upstream (suspected) bottleneck was at the SH 225 merge location and the freeway subsystem upstream of this location is shown in Figure 11. The number at each input is the decimal fraction of vehicles from that input which pass through the SH 225 merging section. Thus, for any time period, the demand at the SH 225 merging section equals 0.871 × freeway volume at Broadway + 1.00 × volume at the Detroit entrance ramp + 1.00 × volume at the SH 225 entrance ramp.

In estimating the demand for a series of bottlenecks on one direction of a freeway, it is best to first estimate the demand at the farthest upstream bottleneck using Eq. 1. It is then assumed that at this bottleneck the flow equals demand or capacity depending on (a) if demand is less than capacity and (b) if there is a storage of vehicles upstream of the bottleneck (caused when demand exceeds the capacity). The demand at the next downstream bottleneck, disregarding the bottleneck upstream of it, can be obtained using Eq. 1. This must then be altered to take account of the storage of vehicles at the upstream bottleneck. The demand at this downstream bottleneck can then be compared to its capacity. The procedure can be repeated to obtain estimates of the demands at successive downstream bottlenecks.

Five-minute demands were computed in this way at six bottlenecks on the inbound Gulf Freeway. Figure 12 shows the demand estimate at the Griggs Rd. overpass bottleneck.

In these computations no attempt was made to take into account the temporal separations of the various locations. In other words the demand at a bottleneck was estimated during a certain time period using the upstream inputs during the same time

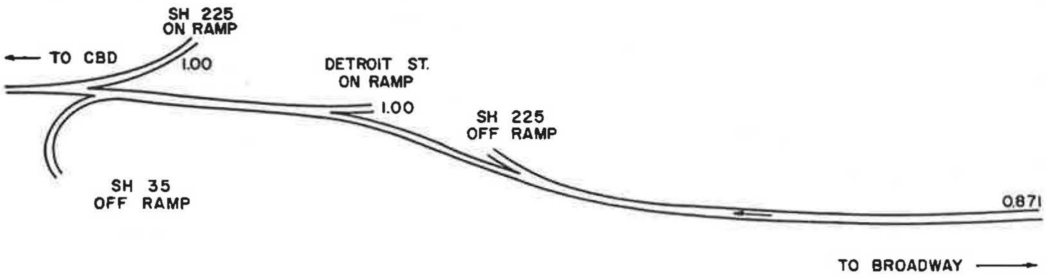

Figure 11. Freeway subsystem upstream of SH 225 merging section.

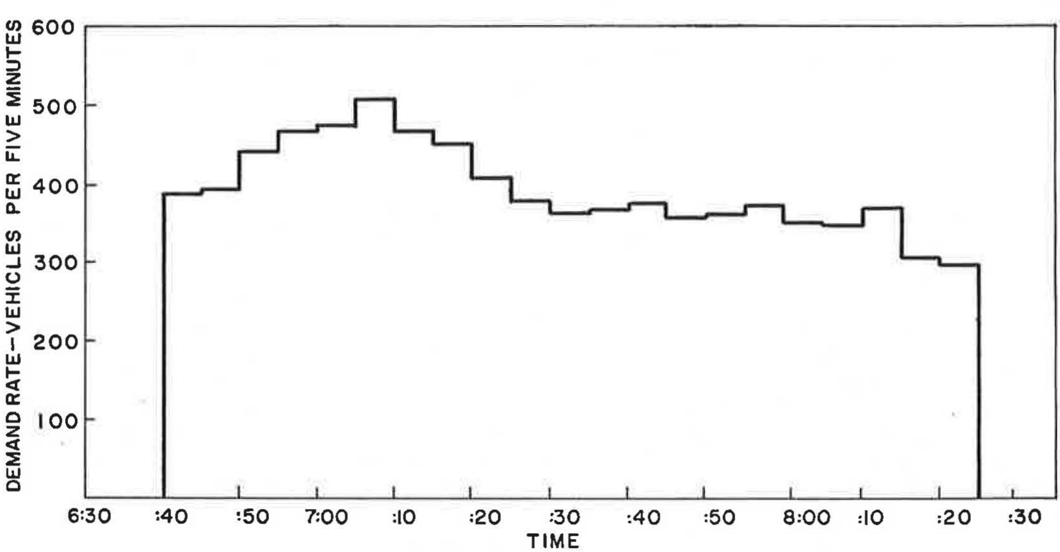

Figure 12. Demand at Griggs overpass.

period, thereby disregarding the travel times between the inputs and the bottleneck. A more sophisticated demand analysis on a longer system could take this into account.

Estimates of Capacity at Freeway Bottlenecks. —The estimates of the capacity flow rates at the freeway bottlenecks were straight forward (based on manual counts at the bottlenecks) and little explanation is needed. The count data were recorded by 5-min time periods and the highest 15-min flow for each day of data was used as the basis for the estimated capacity values. Many days of data were collected to estimate the capacity values accurately.

Interpretation of Demand-Capacity Data

Before congestion develops on a freeway, the demand is less than the capacity at each bottleneck on the freeway. As the peak period progresses, the demand will increase to an amount greater than the capacity at one or more bottlenecks and congestion will develop. The excess of demand over capacity is stored on the freeway in the form of a queue of high density. As the queue backs past upstream exit ramps, vehicles which are going to exit without passing through the bottleneck are trapped in the queue and are thereby delayed. Thus, the queue reflects not only the amount of

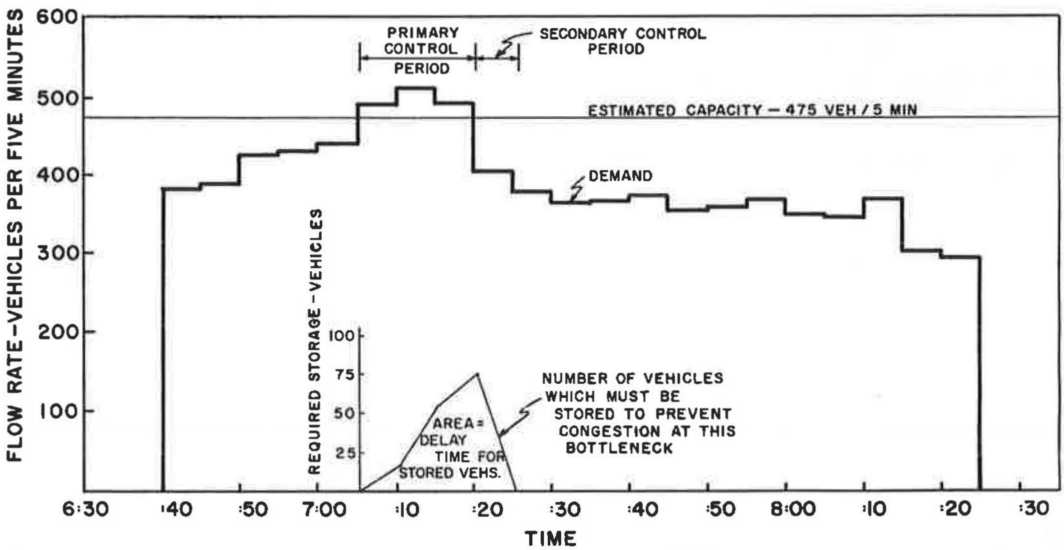

Figure 13. Demand and capacity at hypothetical freeway bottleneck.

excess demand but also some of the exiting vehicles. If the queue extends for several miles, as is frequently the case, the number of exiting vehicles trapped in the queue may be quite large.

If a control system is to prevent congestion, it must prevent the demand from exceeding the capacity at each bottleneck in the system. At any bottleneck the excess of demand over capacity would have to be stored (on the ramp, frontage road, or street) or diverted during the primary control period, which is the time during which the [illegible] below the capacity, some of the stored vehicles can be released onto the freeway at a rate which again will keep the total demand at the bottleneck less than or equal to the capacity. The portion of the control period during which stored vehicles are released could be called the secondary control period.

The storage of the excess of demand over capacity as described in the previous paragraph somewhat implies an entrance ramp metering scheme. If a short-time ramp closure scheme were envisioned, the ramp would have to be closed only during the primary control period since no vehicles would be stored (i.e., all would be diverted). This would alter the demand at other ramps, however.

Since the demand-capacity study technique outlined in this report can be used to estimate the demand rate as a function of time and also the capacity flow rate at each bottleneck, it yields data which are amenable to interpretations regarding peak period control. From the demand and capacity estimates, it is possible to estimate for each bottleneck the length of time which the demand exceeds the capacity (primary control period), the amount of excess demand in each time period, the number of vehicles which would be stored at the end of each time period and the length of time required to clear the stored vehicles (secondary control period).

Figure 13 shows the demand and capacity at a hypothetical bottleneck. From 7:05 to 7:20 a.m. the demand exceeds the capacity so this is the primary control period. The number of vehicles which must be stored rises during the primary control period, reaching a maximum at the transition from the primary to the secondary control periods. The figure shows that a maximum of about 75 vehicles must be stored or diverted at this bottleneck and the maximum storage occurs at 7:20 a.m.

The secondary control period which is required to clear all of the stored vehicles in this example lasts from 7:20 to about 7:26 a.m. After 7:26 a.m., the demand is less than capacity and all stored vehicles have been cleared so the system can maintain

congestion-free operation without strict controls. Hence, the total control period lasts from 7:05 to 7:26 a.m.

The delay accruing to all vehicles while they are stored is equal to the area under the curve of the number of stored vehicles vs time as shown in Figure 13.

FRONTAGE ROAD INTERSECTION STUDIES

The primary function of the frontage road is to provide access to the freeway, but of increasing importance is the ability to provide additional capacity for the peak period movement of freeway traffic to avoid overloading the freeway. The flexibility afforded by this extra capacity can be useful under normal operation of the freeway but can be even more beneficial in cases of severe reduction of capacity on the freeway, as in the case of accidents. The at-grade intersections at the cross streets limit the capacity of the frontage road. It is of importance, then, to have the highest capacity possible at these intersections.

In most instances the intersections are part of a signalized diamond interchange so that the problem of increasing capacity is that of providing the maximum green time on the critical approach. Some design modifications can also be made to improve the flow.

Three studies that can be made for each approach to the intersection are capacity-demand determination, turning movement counts, and geometric design analysis.

Study Techniques

Capacity-Demand Studies. —Observations are made to determine the average starting delay and headway for each movement from the approach, and the capacity per cycle is calculated. These values are then checked from observed counts of the maximum number of vehicles that enter the intersection during one cycle.

The demand for each approach is determined by the input-output count procedure described earlier in this chapter. The boundary points of the system are the stop

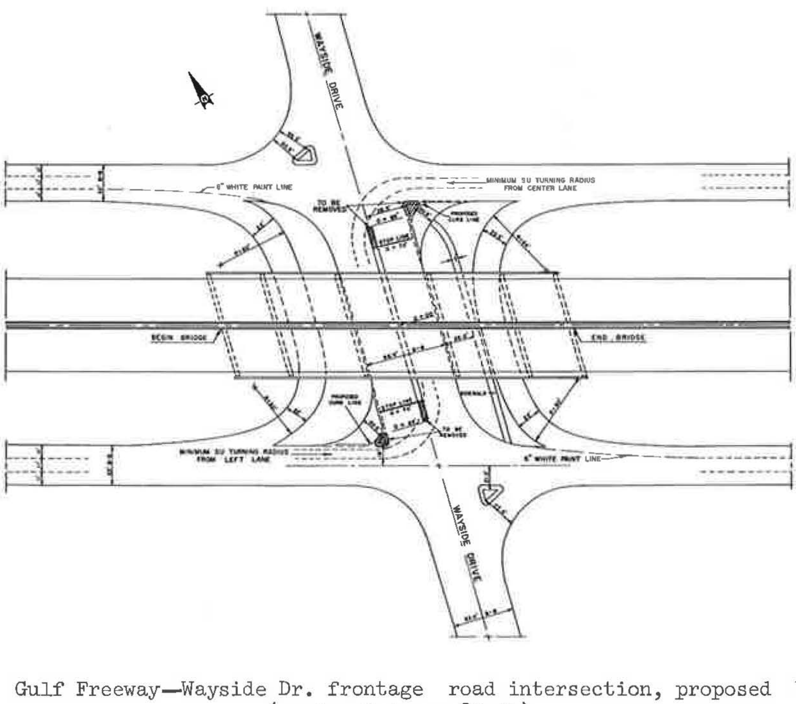

Figure 14. Gulf Freeway—Wayside Dr. frontage road intersection, proposed U-turn bays (scale: 1 in. = 80 ft).

line at the intersection and the end of the queue waiting on the approach. The system is closed by making counts at all driveways or streets that intersect the system between the boundary limits.

Two men on each approach are sufficient if there are few side counts to be made. The counts are started simultaneously by a voice or hand signal. The observer at the output of the system notes the number of vehicles in the system at the start. Data at all count locations are recorded simultaneously at regular intervals. To eliminate the need to reset the counters, the counts are recorded in cumulative form. The counts are stopped simultaneously by a voice or hand signal and the observer at the output station notes the number of vehicles remaining in the system.

It is essential that the counts at all locations be recorded at the same time. Since the time intervals for recording data are usually very short, a 10- or 15-sec difference can have a significant effect on the results. Also, the fact that the output of the system is concentrated in the shorter time intervals of the green phases of the signal cycle stresses the need for coordinated time checks.

It is advisable to select a time interval that is not an even multiple of the cycle length. For example, if a cycle length of 60 sec is being used, a time interval other than x minutes should be used, where x is a whole number. If the recording interval coincides with the cycle length, the readings will be made at the same position relative to the end of the green phase. To obtain comparable data on other approaches, or on the same approach but on different days, the same relative position would have to be used. By using a time interval other than a multiple of the cycle length, average data for the approach are obtained.

Turning Movement Counts.—The distribution of traffic by lanes and by turning movements is very important in the establishment of lane-use controls and the design of signal timing. The demand for each traffic movement is determined from vehicle counts recorded at the end of the green phase for the approach. The lane distribution is obtained from queue counts in the separate lanes recorded at the beginning of the green phase for the approach. At diamond interchanges, the left-turning vehicles from the frontage road to the cross street are observed at the second intersection to determine the number of U-turn movements.

from plan views to determine if the capacities of the approaches can be increased. The diamond interchange in Figure 14 can be improved if:

1. Minimum turning radii are provided for the type of vehicles using the intersection and the type of control being employed. These two factors may change from time to time without including the necessary design modifications.
2. Additional lanes can be added to the approaches to accommodate the traffic demand.
3. U-turn bays or turning roadways can be added if sufficient demand for these turning movements is evident. The pattern of turning movements on any approach can change quickly as land use in the area changes.

Data Analyses

Capacity-Demand Studies.—Several analyses can be made on the data taken from each approach.

Total Input to the Approach vs Time.—The input volumes to the system represent the traffic demand on that intersection approach. These volumes can be plotted vs time and compared to a horizontal line representing the capacity of the approach as shown in Figure 15.

Number of Vehicles in the System vs Time.—At each time the data are recorded, the total number of vehicles which had entered the system and the total number which had left the system from the beginning of the time period are known. The difference between these gives the number of vehicles remaining in the system, i.e., waiting for the traffic light.

Since the length of the system is variable and equal to the distance from the stop line to the end of the queue, the number of vehicles in the system is the number of

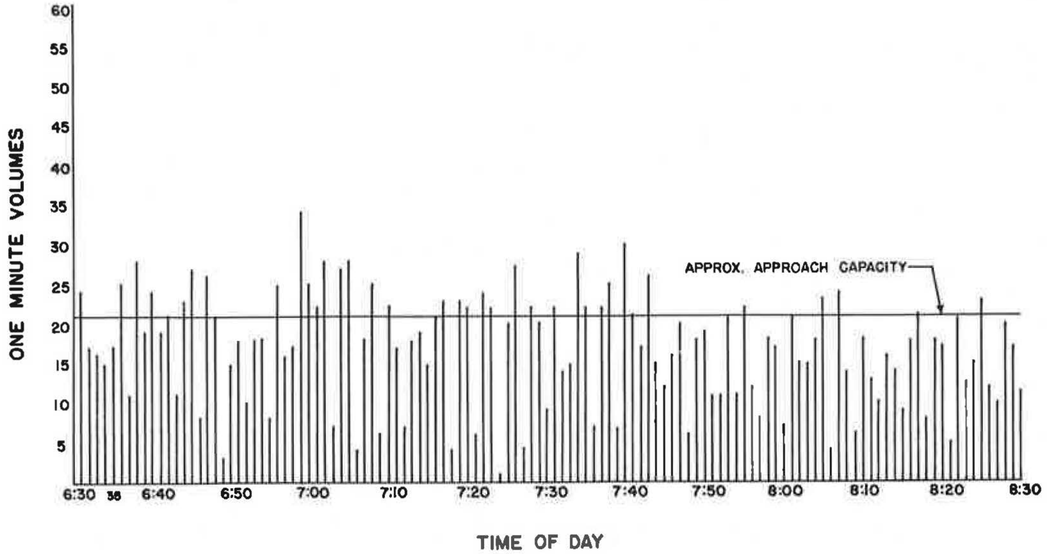

Figure 15. Wayside southbound approach, 1-min volumes, peak hour volume = 1,057.

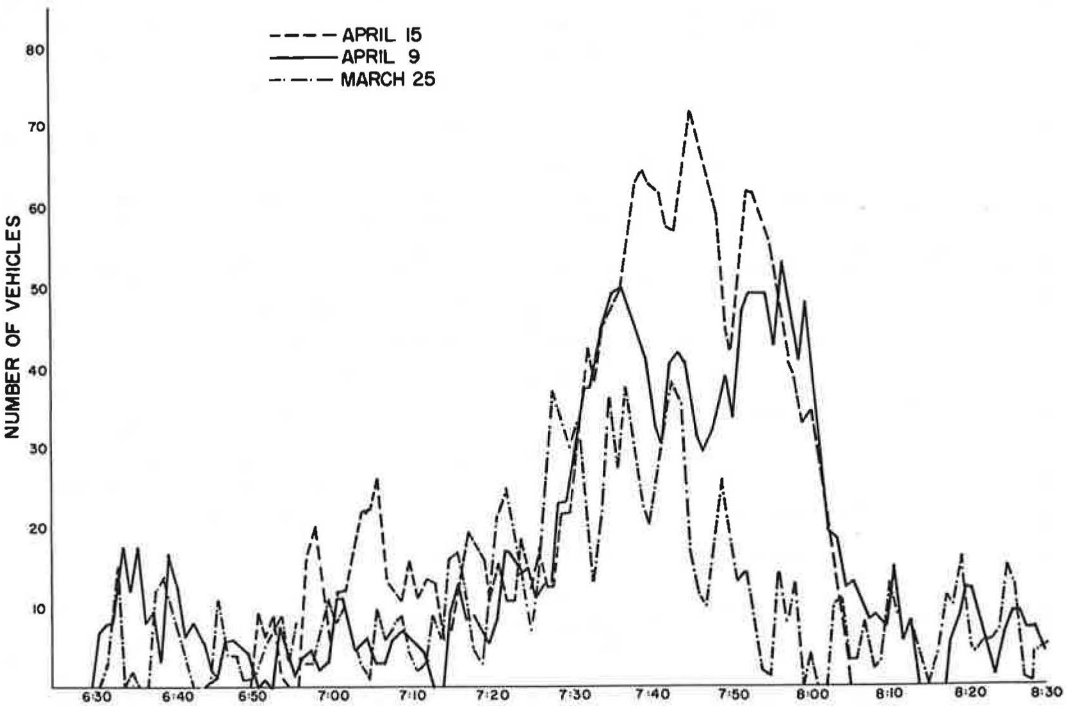

Figure 16. Wayside frontage road westbound, queue lengths, average vehicle delay between 7 and 8 a.m., 25.7 veh-hr.

vehicles in the queue delayed by the traffic signal. The number of vehicles in the system can be plotted as a function of time (Fig. 16). The area under the curve of the number of vehicles in the system vs time in any time period is the total travel time accumulated by all vehicles while they are in the system. In Figure 16 the average total travel is 25.7 veh-hr during the 1-hr period from 7:00 to 8:00 a.m.

Turning Movement Studies.—These studies include two types.

Output Movements from System vs Time.—The total traffic demand on an intersection approach is represented by the total input volume to the system over the peak period. This demand is divided into the several traffic movements which are based on the vehicle counts at the output of the system and can be plotted against time and compared to the capacity for each movement.

Total U-turn Movements.—The number of U-turn movements made during some time period indicates the demand for the U-turn bay and the resulting increase in capacity of the left-turn movement from the frontage road if separate turning roadways are provided.

Application of Data

Capacity-Demand Studies.—The curves for the number of vehicles in the system can be useful in the reapportionment of green time at an intersection. A comparison of the curves for each of the four approaches will indicate if the total travel time can be reduced by shifting green time from one approach to another.

Total travel time parameters can be used to evaluate the effects of changes in design and control such as (a) freeway control procedures that require rerouting the traffic onto the frontage roads and major arterials, (b) changes in signal timing or lane-use control on the intersection approaches, or (c) modifications in the geometric design of the approach, such as adding turning lanes and increasing turning radii.

Turning Movement Studies.—The U-turn movements can be important in the operation of a diamond interchange. The capacity of the total interchange can be reduced by one for every U-turn vehicle because of the effect on the cross street traffic. The usual diamond interchange signal phasing uses two phase overlaps (Fig. 17). For these phase

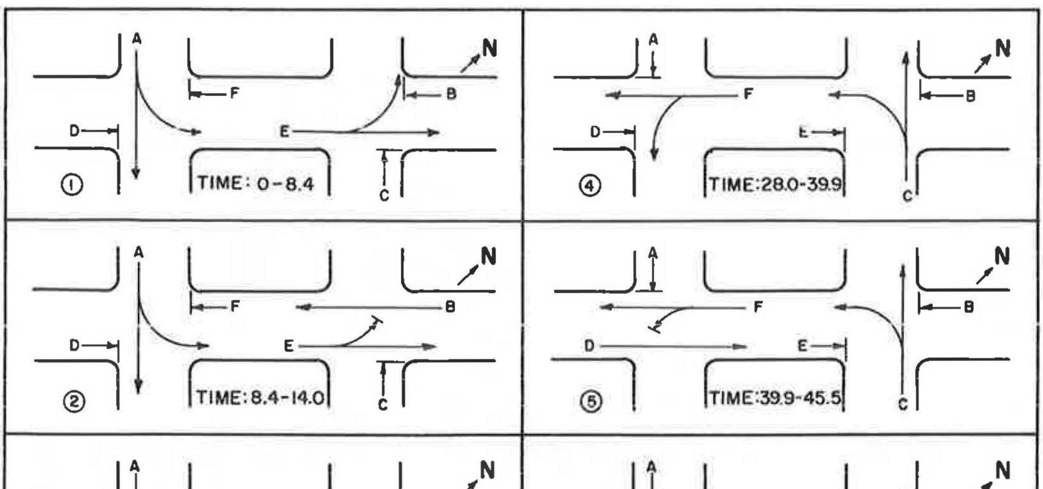

Figure 17. Phasing of traffic movements, 5.6-sec overlap existing signal timing.

overlaps to be effective, the area between the two intersections should be clear of stopped vehicles, but this timing design does not clear those vehicles that make U-turns. Therefore, they are stopped at the second intersection and reduce the capacity of the cross street.

The overall delay caused by the intersection is also increased by the time the U-turn vehicles must wait at the second intersection.

Evaluation of Geometric Design. —The analysis of the geometric design of the intersections can determine if the capacity of an approach can be improved by design modifications. The application of these results will depend on the studies of the traffic demand requirements.

AERIAL PHOTOGRAPHY

The input-output studies provide a great deal of very valuable data for a particular subsystem being studied. To obtain a true picture of the conditions of traffic on the freeway, the system should include the entire length of freeway. However, a simultaneous study of several miles of freeway would require a very large field crew if input and output counts were made at each access point.

Another method of data collection, aerial photography, can be used to obtain some data which can also be obtained by the input-output studies and the air photo technique requires a field crew of only three men. The length of the study area is limited only by the frequency of coverage required.

The application of aerial photography to traffic studies is not new, but only in the last 5 yr have there been any extensive studies of traffic operations by this method. With the expansion of study areas into systems that cover several miles, the costs of conducting aerial surveys is now comparable to those of conducting ground studies for obtaining certain types of data.

Study Technique

Time-lapse photography where individual pictures are taken at short intervals of time should be used in a study of this type. The information to be taken from the film determines the technical requirements of the photograph. One of the most natural applications of aerial photography in the study of freeway operation is in the determination of the number of vehicles within a system (similar to the data obtained in the closed system input-output studies). Therefore, only vehicle counts will be made and each picture can cover as large an area as will permit identification of the individual vehicles. Also, since no time-dependent measurements, such as vehicle speeds or gaps, are taken from the film, a minimum overlap from picture to picture is acceptable and the interval between pictures does not have to be constant.

A procedure was adapted for use in the study of the Gulf Freeway, a distance of 6 mi. The flight crew consisted of three men—a pilot, photographer, and an assistant. The plane was a fixed-wing Cessna 170. The flight plan was to make as many runs of the study area as possible during the 2-hr peak period. The plane flew in a counter-clockwise pattern from one end of the freeway to the other at an altitude of 1,500 ft, approximately 300 to 500 ft to the side of the freeway. Photographs were taken through the window of the plane in both directions with a hand-held 35-mm camera equipped with a 50-mm lens. A minimum overlap was used. During each run the assistant recorded the time of the first and last pictures for the run, reloaded a spare camera, set up an identification board which was photographed at the beginning of each run, tagged the exposed film, and made appropriate notes of the flights.

Data Analysis

The times of day for the start and finish of each filming run were recorded. The time interval between pictures within a run was assumed to be constant so that the time of day for each picture could be estimated. Since several pictures on a run were required to cover each subsystem, the time of day for the picture taken at the center of each subsystem was used to reference the number of vehicles in the system.

The number of vehicles in each of the subsystems was determined by first selecting matched points on adjacent pictures so that there was no overlap of the roadway. The matched points at the beginning and end of the freeway subsystems were those used in the input-output studies. The number of vehicles observed between the matched points on each slide were counted and summed for all slides included in each subsystem. The total represents the number of vehicles in the system at the time of day the center picture was taken. It is assumed that the number of vehicles in the subsystem does not change during the time interval required to fly its length.

The number of vehicles in the subsystem can be plotted against time from this data and the total travel time can be computed. Traffic volumes cannot be determined from the aerial photographs but supplementary ground counts at a few locations can supply this information. The data can be analyzed using any freeway subsystems of interest. The same photographs can be used to make similar studies on the frontage roads as well as to study the queues on freeway entrance ramps or signalized intersections near the freeway. This technique also provides a good parameter, total travel time, for measuring the effect of change in before-and-after studies.

Aerial photographs provide data for other studies such as the lane distribution of traffic, the effect of accidents on traffic operations, the length of time required to clear accidents from the moving lanes, the effect of trucks on the traffic stream, and shoulder usage.

USE OF STUDY TECHNIQUES ON GULF FREEWAY SURVEILLANCE PROJECT

The Texas Transportation Institute, in cooperation with the Texas Highway Department and the U.S. Bureau of Public Roads, is conducting a peak period freeway surveillance study on the Gulf Freeway in Houston. The studies of the type described in this report reached full momentum about Jan. 15, 1964. Until September 1964, most of these studies were confined to the inbound Gulf Freeway in the morning peak period. Studies of the outbound freeway traffic are planned for the near future.

O-D questionnaires were distributed to motorists on each inbound entrance ramp

on the data from these studies, including, for each entrance ramp, the distribution of traffic among the downstream exits (4).

The inbound Gulf Freeway was divided into five closed subsystems and input-output studies were run on each. One week of data was collected for each subsystem. From these studies it was possible to identify three major bottlenecks, to establish flow patterns at each entrance ramp and the upstream freeway input, and to estimate the total travel time accruing to all vehicles in each subsystem during the peak period.

The freeway counts from the closed subsystem studies and supplementary capacity counts were used to estimate the capacity of each of the major bottlenecks. The entrance ramp and freeway input count data, combined with the O-D data and bottleneck capacity estimates, were used to estimate the demand at each of the three freeway bottlenecks (8).

Critical intersections in the freeway area of influence, especially those of the frontage roads and the crossing arterials, were studied and some signal retiming was accomplished (9).

A ramp control plan was developed based on the demand and capacity estimates at the three major bottlenecks. The philosophy of the controls was to keep the demand less than or equal to capacity at the two downstream bottlenecks. (A critical frontage road intersection temporarily precluded a more comprehensive and restrictive control plan which would probably have diverted a large volume of traffic through the critical signal but which would have further improved freeway operations.) In August, four ramps were closed for 20, 25, 40 and 40 min) during their primary control periods and one was metered for 40 min at a rate based on the demand and capacity estimates. The control was highly successful and produced a marked improvement in the freeway operation and had little or no adverse effect on the alternate routes. The details of this study are contained in another report.

Air photo studies were made to provide a before-and-after comparison for this study.

CONCLUSIONS

1. The O-D technique for obtaining travel patterns of the freeway interchange traffic provides very reliable results. Only in locations where the stoppage of traffic is hazardous should the method of questionnaire distribution be changed.
2. The design of the questionnaire can be improved. The definition of the trip for which the questions are asked should be included in the explanation to avoid confusions of morning and afternoon trips.
3. The high percent return indicated an acceptance by the public of this type of survey and their interest in a cure to the problem of peak period freeway congestion.
4. The information received from this type of survey has been most valuable in several phases of research on the development of control techniques for improving freeway operations.
5. The study technique using input-output counts on closed freeway subsystems is an excellent method of quantifying the problem of freeway congestion.
6. The input-output data are also quite useful in before-and-after comparisons since total system travel time is one by-product.
7. Demand at freeway bottlenecks can be estimated by combining count data at each freeway input with the O-D data and bottleneck capacity data.
8. By comparing the demand rate to the capacity flow rate at a critical bottleneck, it is possible to estimate the duration and severity of control that would be required to prevent congestion, as well as the number of vehicles that would have to be stored (queued) or diverted from the freeway at the control location.
9. Aerial photography is a good method for determining the number of vehicles using a given facility at a given time. The technique using a 35-mm camera was found to be sufficient for this determination.
10. The design evaluation of existing frontage road intersections can, in many cases, prove fruitful by leading to improvements in design or control which can increase the capacity of the intersection.

REFERENCES

1. Route 3 "Lights On" Traffic Survey. Port of New York Authority, Planning Div., 1960.
2. Brenner, R., Telford, E. T., and Frischer, D. A Quantitative Evaluation of Traffic in a Complex Freeway Network. Highway Research Board Bull. 291, pp. 163-206, 1961.
3. Characteristics of Traffic Entering the Westbound Congress Expressway Within the Plot Detection System Study Section. Chicago Area Expressway Surveillance Proj. Rept. 5, 1962.
4. McCasland, W. R. Traffic Characteristics of the Westbound Freeway Interchange Traffic of the Gulf Freeway. Texas Transp. Inst. Res. Proj. 24-7, 1964.
5. Wattleworth, J. A. Peak-Period Control of a Freeway System—Some Theoretical Considerations. Doctoral Diss., Northwestern Univ., 1963; Chicago Area Expressway Surveillance Proj., Rept. 9.
6. Wattleworth, J. A., and Berry, D. S. Peak-Period Control of a Freeway System—Some Theoretical Investigations. Highway Research Record No. 89, pp. 1-25, 1965.
7. Rothrock, C. A., and Keefer, L. E. Measurement of Urban Traffic Congestion. Highway Research Board Bull. 156, pp. 1-13, 1957.
8. Wattleworth, J. A. System Demand-Capacity Analysis on the Inbound Gulf Freeway. Texas Transp. Inst. Res. Rept. 24-8, 1964.
9. McCasland, W. R. Capacity-Demand Analysis of the Wayside Interchange on the Gulf Freeway. Texas Transp. Inst. Res. Rept. 24-9, 1964.
10. Wattleworth, J. A. The Estimation of Demand at Freeway Bottlenecks. Traffic Eng., Nov. 1964.