

SYSTEM DEMAND - CAPACITY ANALYSIS
ON THE
INBOUND GULF FREEWAY

by

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SYSTEM DEMAND-CAPACITY ANALYSIS ON THE INBOUND GULF FREEWAY

I. INTRODUCTION

BACKGROUND

The work reported herein is a part of Research Project 2-8-61-24, Level of Service. It is a cooperative research project with the cooperating agencies being the Texas Highway Department, the U. S. Bureau of Public Roads and the Texas Transportation Institute.

The Level of Service Project has been divided into three research phases; the Operations Phase, the Design Phase and the Systems Phase. This report represents a portion of the work done under the Systems Phase of the project.

NEED FOR THE STUDY

Development of a Study Technique. 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 congestion on individual freeways. Also, control measures for the purpose of reducing peak-period freeway congestion have been evaluated.

A need, therefore, exists for a means or technique of studying a system composed of a one-directional freeway. Specifically, it must be possible

- a) to locate the critical bottlenecks in the system,
- b) to estimate the capacity flow rate at each critical bottleneck,
- c) to estimate the demand rate at these locations, and
- d) to determine from these analyses by how much and for how long the demand exceeds the capacity at each location.

Traditional 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 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, there are several things of interest. Since freeway congestion sets in at a location when the demand exceeds the capacity, 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.

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 exists for a technique for

- 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.

Inbound Gulf Freeway Study. At the present time, the inbound Gulf Freeway operates under congested conditions from approximately 7 a.m. to 8 a.m. During this time, the entire freeway from Broadway to Dumble Street experiences high-density, low-speed conditions during this one-hour time period. Thus, about four miles of the freeway are congested for about one hour.

Speeds at some locations decrease from 45-50 miles per hour in off-peak periods to about 5-10 miles per hour in the congested period. Travel times through the congested area are two to four times their corresponding off-peak values. Because of the generation and propagation of shock waves during this time, the frequency of rear-end accidents is likely increased.

Since the Gulf Freeway is presently congested, it follows that the demand exceeds the capacity at some locations of the freeway between Broadway and Dumble at some time between 7:00 and 8:00 a.m. In other words, stated simply, at some times during the morning peak period more vehicles attempt to use the inbound Gulf Freeway than it can accommodate.

The excess of demand over capacity must be stored. At present this excess of vehicles is stored on the freeway, producing the increased density on the freeway as well as the low speeds, etc.

In addition to the features of congestion which are most readily noticed by the motorists, congestion decreases the vehicle carrying capability or capacity of the freeway. This can occur in any one of several ways. First, there is considerable evidence to indicate that the development of congestion at a bottleneck can decrease the flow rate at the bottleneck (Ref. 1-4). Secondly, when the queue or shock wave which is generated at the bottleneck backs past upstream exit ramps, the output rate of these ramps is decreased. (See Appendix A). Thirdly, the occurrence of accidents attributable to congestion can drastically reduce the capacity of the freeway, even if they are immediately removed from the roadway. Thus, the congestion which is caused by an excess of traffic demand over capacity can reduce the freeway capacity, thereby contributing further to the problem.

Because the storage on the freeway of the excess of demand over capacity decreases the output capacity of the freeway, the output flow rate of the freeway could be increased by preventing this storage on the freeway. Thus, a control system which could prevent the storage on the freeway of these excess vehicles, could increase the efficiency of the freeway. To do this, the control system would have to keep the demand less than (or equal to) the capacity at each bottleneck.

Before the problem of congestion on the Gulf Freeway can be solved, the extent of the problem must be determined. At each bottleneck, the duration of time for which the demand exceeds the capacity must be known. The amount of excess demand must also be known since this is the number of vehicles which must be prevented from entering the freeway during the critical period.

OBJECTIVES OF THE STUDY

One prime objective of the study was the development and evaluation of a study technique which would permit the operational analysis of a one-directional freeway system during its peak period.

After the technique was developed it was used to analyze the peak period operation of the inbound Gulf Freeway. The specific objectives of these studies were:

1. to identify the critical bottlenecks,
2. to determine the capacity flow rates at each of the bottlenecks,
3. to determine for five-minute time periods the demand rates at each entrance to the inbound freeway,
4. to determine for five-minute time periods the demand rate 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 interpret these data in terms of the type of control system required to prevent congestion,
7. to obtain data suitable for the "before" portions of "before and after" studies to be used for evaluating control experiments, and
8. to use the data to predict the effect of control and/or geometric design changes.

These data were also used to test the hypothesis that the development of congestion at a freeway bottleneck can decrease the flow rate there.

II. STUDY TECHNIQUE USING INPUT-OUTPUT COUNTS ON CLOSED SUBSYSTEMS

DESCRIPTION OF STUDY TECHNIQUE

The study technique using input-output counts on closed subsystems 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 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). Airphoto data can be quite useful in guiding the selection of the boundaries of the system of interest.

When the system of interest is defined it will probably be necessary to divide this system into closed subsystems for the analysis. Manpower requirements normally make this step necessary. 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. The division points between subsystems should be chosen to be a known or suspected bottleneck. 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 such as five minutes and, to eliminate the need to reset the counters, should be recorded in cumulative form. In this way the total number of vehicles entering and leaving the system in the time interval can be determined as can the change in the number of vehicles within the system.

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. 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.

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 every five minutes (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 entering the system should equal the total number 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 the 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 time. This is necessary to assure that at each recording time the number of vehicles in the

system is accurate. For example, if a freeway count is recorded 30 seconds late it could be as much as 50 vehicles in error (assuming a 3-lane section flowing at 100 vpm). This error would also be reflected in the number of vehicles in the system, which might be about 50-500 when correct. Thus a 50-vehicle 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 systems in which the number of vehicles is small.

The accuracy of the counts is extremely critical in studies of this type. A check on this accuracy is available since the total input in the study period should equal the total output in the period.

Also because of the interdependence of count locations it is essential that all of the study personnel show up 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 being 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).

III. APPLICATION TO THE INBOUND GULF FREEWAY

CLOSED SUBSYSTEM STUDIES

Subsystem Selection. A portion of the inbound Gulf Freeway was chosen for study because of the extremely congested operation on this roadway in the morning peak period. The study system extends from Broadway to the CBD distribution system near Dowling -- about 6 1/4 miles. The Broadway location was chosen as a system boundary because congestion does not back to this point so freeway counts there represent demand.

This 6 1/4 mile system was divided into 5 subsystems as shown in Figure 1. Manpower requirements limited the subsystem sizes. The freeway boundaries of the subsystems were chosen to correspond to known or suspected bottlenecks so the freeway counts could be used to estimate the capacities of these bottlenecks.

Input-Output Counts of the Subsystems. In each of the closed subsystems, input-output counts were made during the 6:30-8:30 a.m. time period. This time period includes the entire period of congestion (about 7:00-8:00 a.m.). For each subsystem a week's data (5 weekdays) were collected. However, some of the data proved unusable because of accidents, heavy fog or other "unusual conditions" and on some occasions because of bad counts.

A count was made at each entrance (input) and exit (output) from each subsystem under study (including the freeway input and output). All count data were recorded in cumulative form each five minutes at 6:30, 6:35, 8:20, 8:30, 8:35 a.m. A signal car was used to start and stop the counts.

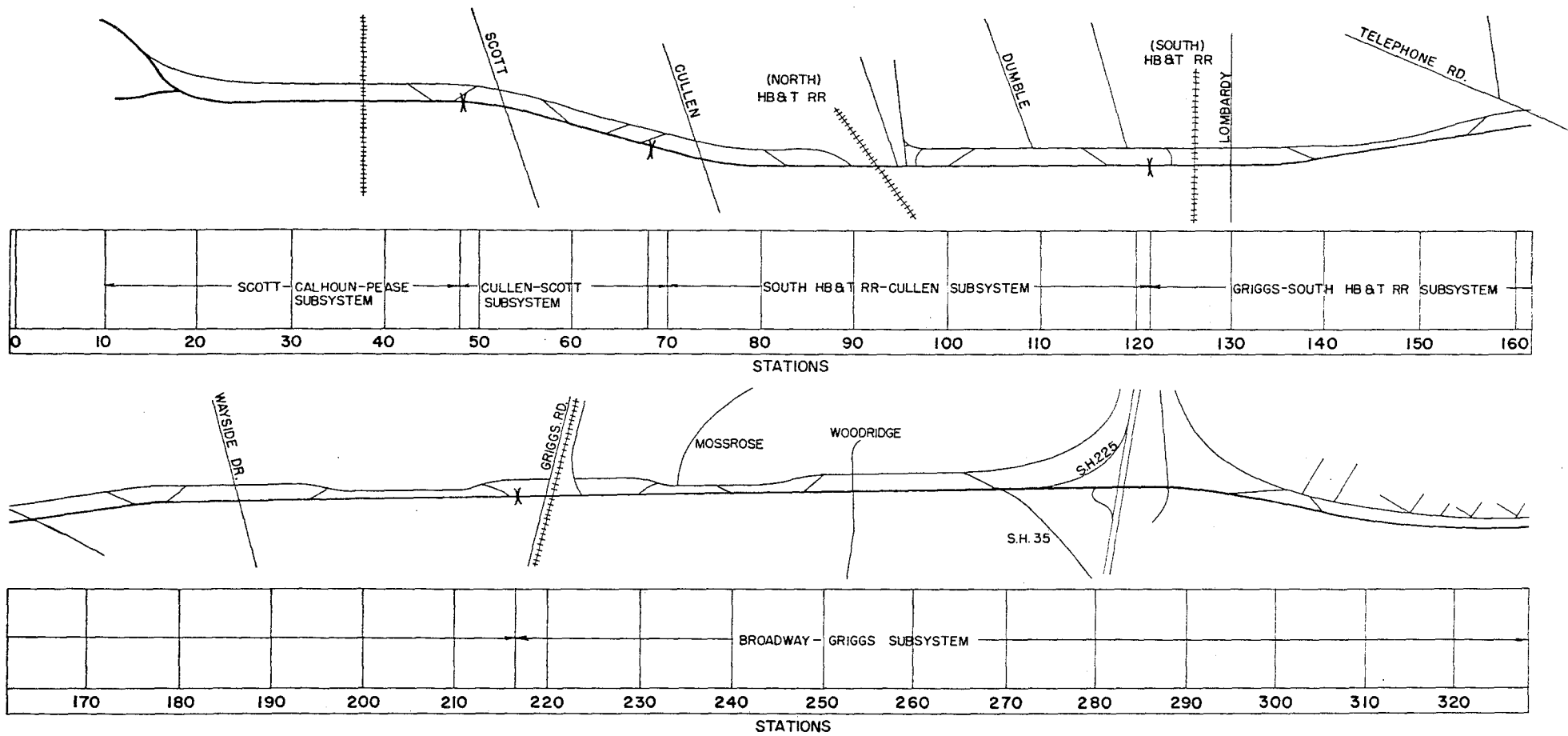


FIGURE I - SYSTEM OF INTEREST AND SUBSYSTEM

CAPACITY STUDIES

In addition to the freeway counts which were part of the closed system studies, other manual counts were made for the purpose of estimating the capacity of the freeway bottlenecks. In these studies the volume count data were recorded every five minutes and, for the purpose of estimating capacities, fifteen minute rates of flow were used. Speed samples were obtained at the count location (one vehicle per lane per minute) during each of these counts.

ORIGIN-DESTINATION STUDIES

An origin-destination study was planned and conducted at each of the entrance ramps on the inbound freeway (from SH 225 to Scott Street) during the morning peak period by another staff member. The details of this study are covered in another report (9) but, since the results were used extensively in the analyses which follow, a brief description of the results of this study is warranted.

For each of the ramps studied, the percent of vehicle exiting at each downstream exit ramp was obtained. Vehicles at each ramp were stopped and given a questionnaire to fill out. The questionnaires were numbered and were distributed sequentially. By recording the number of questionnaires handed out at the end of each five-minute interval, the changes in traffic patterns due to congestion were determined. For the analyses contained in this report these data were divided into three time periods: (a) before 7:30 a.m., (b) 7:30 to 8:00 a.m., and (c) 8:00 to 8:30 a.m.

IV. ANALYSES OF GULF FREEWAY DATA

The data used in these analyses, except where otherwise noted, were free from the effects of accidents, adverse weather, or similar occurrences. Likewise, any questionable count data were discarded.

CLOSED SYSTEM STUDIES

Several analyses were made on the data of each of the subsystem studies. These analyses are discussed below.

Total Input to the Subsystem Versus Time. For each of the subsystems, coordinated counts were made at two locations on the freeway and all of the entrance and exit ramps in between. For each subsystem, the input locations, then, consisted of the upstream freeway location and all of the entrance ramps in the subsystem.

Since all count data were recorded simultaneously each five minutes, the total number of vehicles entering the subsystem in each five-minute period could be determined by adding the individual inputs for each five minutes. This

was done and the resulting total input was plotted by five-minute time periods.

Total Output from the Subsystem Versus Time. In a similar fashion, the total number of vehicles leaving each subsystem in each five-minute period was determined. The resulting total output of each subsystem was plotted by five-minute time periods.

Accumulation in Each Subsystem Versus 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 is a closed system), the difference in the total input and total output for a five-minute 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 was calculated and plotted.

Number of Vehicles in Each Subsystem Versus 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 was known. The difference between these gave the number of vehicles remaining in the system.

The number of vehicles in each system was plotted as a function of time for each of the subsystems. The average number of vehicles in each system was plotted against time for each of the good days of data.

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 could easily be converted into density. For each subsystem, density was also plotted against time.

Total Travel Time in Each Subsystem - 7:00-8:00 a.m. The area under the curve of number of vehicles in a system versus time in any time period is the total travel time accumulated by all vehicles while they are in the system (5-7). This analysis was performed to obtain the total travel time for each subsystem and for the total system for the 7-8 a.m. time period.

Accuracy and Error Distribution. Since the total input during the study period should have equaled the total output for each subsystem, a check on the accuracy of each day's data was available. Table 1 shows these differences observed in each study. A plus indicates that the input was greater than the output.

TABLE I
SUMMARY DATA FOR SUBSYSTEM STUDIES

DATES	SUBSYSTEM	CLOSURE ERRORS				
		Day				
		Monday	Tuesday	Wednesday	Thursday	Friday
Jan. 27-31, 1964	Broadway-Griggs	+25	+ 9*	+ 3*	-43*	+39
March 16-20, 1964	Griggs-So. HB&T RR	-66*	+86*	+26	+73	+56*
March 30 April 3	So. HB&T RR-Cullen	No Data	+89*	- 2*	-18*	-16
April 13-17	Cullen-Scott	-38*	+320	+47	+156	+87*
April 20-24	Scott to Calhoun- Pease	-24*	Holiday No Data	-61	+30*	+55*

* Indicates day of data used in the analyses

As can be seen in Table 1, no day of data was used in the closed system analyses if the difference between total input and total output was greater than 100 vehicles. For all systems the average total input and total output during the study period was about 10,000 vehicles. The input and output, then, checked within 1% in all studies used in the analyses.

The errors were distributed evenly throughout the study period. If, for example, on a given day the total input was 25 vehicles greater than the total output, and if there were 25 five-minute periods (6:30-8:35 a.m.), the output was essentially increased by one vehicle in each five-minute period.

Analyses at Individual Locations. The five-minute counts at the individual input locations (all entrance ramps and the freeway near Broadway) were used to estimate the arrival or demand pattern at these locations. The freeway counts near Broadway are valid estimates of the demand there since (a) there are no bottlenecks farther upstream, and (b) congestion does not back up there from downstream. Only the counts which were unaffected by accidents, adverse weather, etc., were used for this purpose.

Speed-time graphs at the freeway count locations and the density-time graphs for each subsystem were drawn for the purpose of identifying the critical bottlenecks on the inbound freeway. Graphs of flow-speed were also plotted at the freeway count locations to aid in this cause.

ESTIMATED FREEWAY ORIGIN-DESTINATION DATA

Origin-destination data were obtained for the S.H. 225, S.H. 35, Woodridge, Mossrose, Griggs, Wayside, Telephone, Dumble, Cullen and Scott entrance ramps in the questionnaire studies. Of particular interest in the demand estimate analyses is, for each entrance to the freeway system, the percent of vehicles which leave the freeway at each downstream exit. The origin-destination studies yielded this information for the ramps which were included in these studies. However, similar data were not available for the Detroit Street 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 these data for the other two input sources (Detroit entrance and freeway near Broadway).

Figure 2 is a flow map containing the numbers used for some of the estimations. Two very obvious calculations were made first. Of the 5788 vehicles which entered the system on the freeway at Broadway, 414 left on the S.H. 225 exit ramp and 328 left on the S.H. 35 exit ramp (it is almost impossible for vehicles to enter the Detroit entrance ramp on the right and exit at S.H. 35 on the left -- especially during the hours studied). This means that during the study period 7.2% of the vehicles on the freeway at Broadway exit at S.H. 225 and 5.7% of them exit at S.H. 35. (The study period is from 6:30 to 8:30 a.m.)

Of the 450 vehicles exiting at the Woodridge exit ramp, 3 (.25% of 1340) are estimated to have come from the S.H. 225 entrance. This leaves 447 which had to come from the freeway at Broadway and the Detroit entrance. The assumption was made that the origin-destination 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 S.H. 225. Of the 5698 vehicles downstream of the Detroit entrance ramp, 447 or 7.8%, exited at Woodridge. Thus, 7.8% of the vehicles entering at the Detroit entrance and 7.3% of the vehicles on the freeway at Broadway (92.8% of 7.8) exited at Woodridge.

Similar analyses were made to estimate the exiting percents of the other output locations of the Broadway-Griggs subsystem. A similar, somewhat more difficult, procedure was used (combining the data of more than one subsystem) to estimate the percentages of vehicles from the Detroit entrance and Broadway freeway location which leave the freeway at exits downstream of the Broadway-Griggs subsystem.

Table 2 shows for each freeway entrance the percent of vehicles exiting at downstream exits during the peak period. The data for all inputs except the freeway at Broadway and the Detroit entrance were obtained from the questionnaire

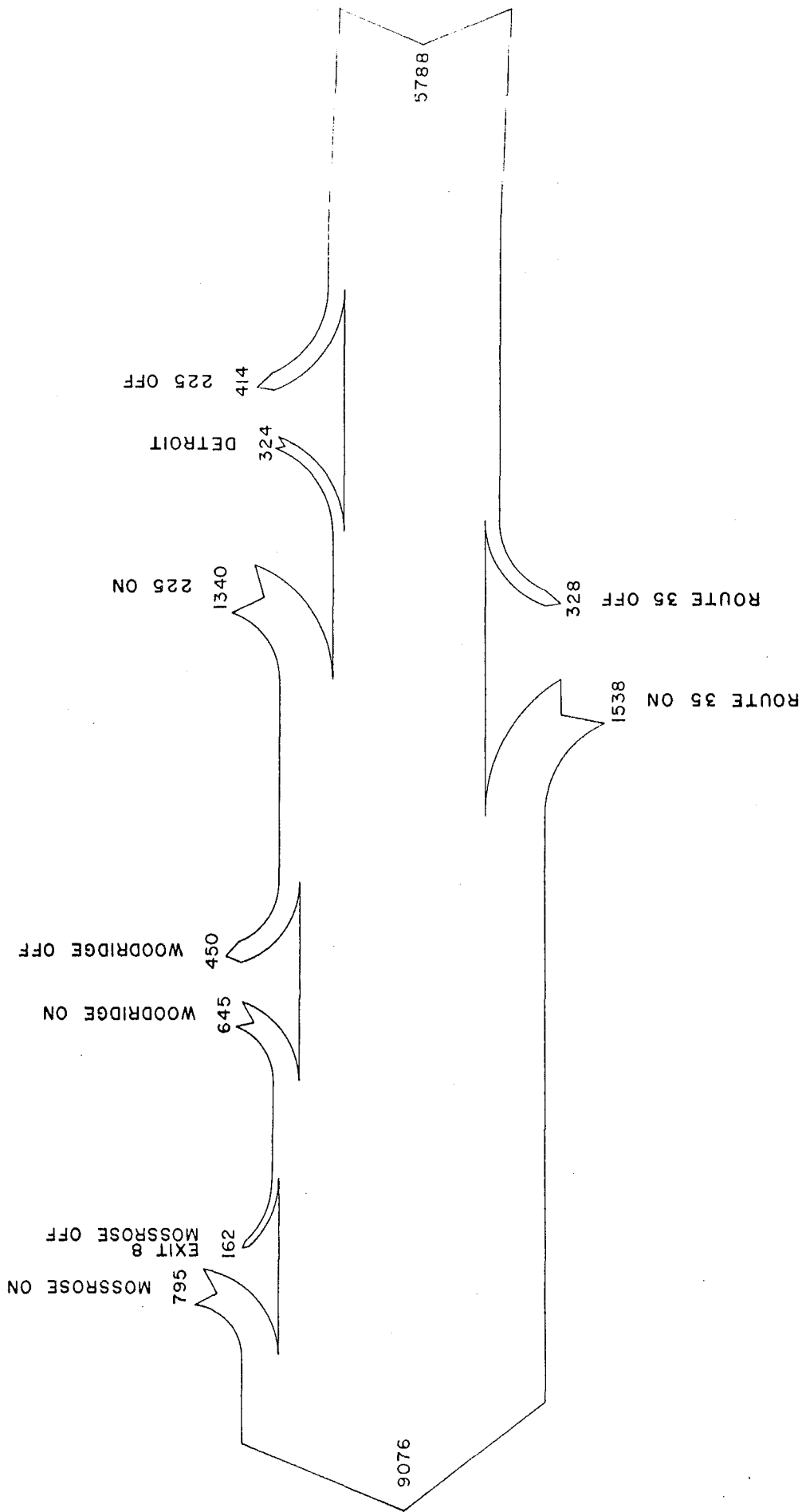


FIGURE 2 STUDY PERIOD FLOW MAP
BROADWAY-GRIGGS SUBSYSTEM

TABLE 2
 ORIGIN-DESTINATION TABLEAU
 PEAK-PERIOD
 Percent Exiting

Entrances	Exits												
	S.H. 225 Off	S.H. 35 Off	Woodridge Off	Exit 8	Wayside Off	Telephone Off	Lombardy Off	Calhoun - Elgin Off	Cullen Off	Scott Off	Sampson Off	Pease Dist.	Calhoun Dist.
Frwy. at Broadway	7.2	5.7	7.3	2.1	11.2	3.8	0.7	9.5	2.6	---	not calculated--	---	---
Detroit Entrance	---	---	7.8	2.4	12.9	4.4	0.8	10.9	3.0	---	not calculated--	---	---
S.H. 225 Entrance	---	---	0.25	0.25	2.5	0.5	1.2	7.9	5.4	2.5	5.4	38.9	35.2
S.H. 35 Entrance	---	---	---	1.5	6.1	2.7	3.6	6.4	3.5	2.8	6.3	37.3	29.8
Woodridge Entrance	---	---	---	0.0	8.6	1.3	3.6	8.3	4.7	2.6	6.0	35.3	29.6
Mossrose Entrance (+ K Illegal)	---	---	---	---	23.1	5.2	5.2	7.1	3.5	1.7	6.3	30.4	17.5
Griggs Entrance	---	---	---	---	---	1.8	2.3	8.3	3.4	2.9	10.3	42.3	28.7
Wayside Entrance	---	---	---	---	---	0.4	1.8	15.1	5.3	1.3	4.9	36.1	35.1
Telephone Entrance	---	---	---	---	---	---	---	13.4	4.2	2.9	4.6	42.5	32.4
Dumble Entrance	---	---	---	---	---	---	---	---	5.6	1.1	5.1	44.7	43.5

studies. These same data were calculated for three time periods within the peak period 6:30 - 7:30, 7:30 - 8:00 and 8:00 - 8:30 a.m. These are shown in Appendix Tables 1-3.

ESTIMATES OF DEMAND AT THE FREEWAY BOTTLENECKS

Volume count data at each input to the freeway were combined with the origin-destination 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 this case the freeway at Broadway and all of the entrance locations between Broadway and the bottleneck. The demand at a bottleneck can also be influenced by the capacity of upstream bottlenecks.

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

$$D_i = \sum_{j=1}^n P_{ij} V_{ij} \quad i=1, \dots, m \quad (\text{Eqn 1})$$

where

V_{ij} is the volume at the j^{th} input during the i^{th} time period and P_{ij} is the decimal 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 S.H. 225 merge location and the freeway subsystem upstream of this location is shown in Figure 3. The number at each input is the decimal fraction of vehicles from that input which pass through the S.H. 225 merging section. Thus, for any time period the demand at the S.H. 225 merging section equals 0.871 x freeway volume at Broadway + 1.00 x volume at the Detroit entrance ramp + 1.00 x volume at the S.H. 225 entrance ramp.

In estimating the demand for a series of bottlenecks on a freeway such as the inbound Gulf Freeway, it is best to first estimate the demand at the farthest upstream bottleneck using the Equation 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

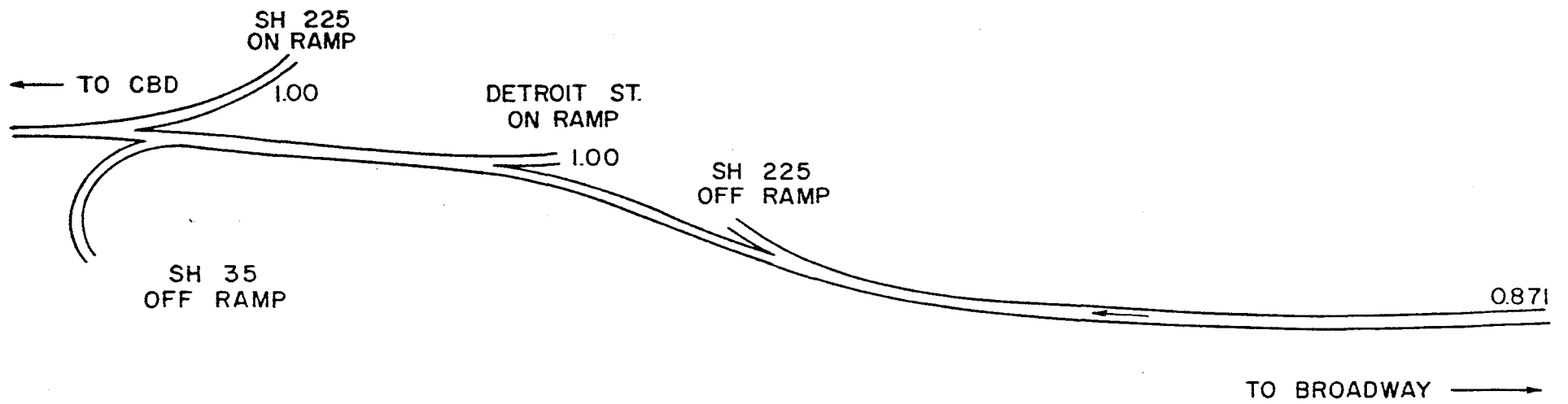


FIGURE 3 FREEWAY SUBSYSTEM UPSTREAM OF SH 225 MERGING SECTION

bottleneck disregarding the bottleneck upstream if it can be obtained using Equation 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 the following six bottlenecks: (1) downstream of the S.H. 35 entrance ramp, (2) at the Griggs Road overpass, (3) downstream of the Griggs Road entrance ramp, (4) downstream of the Wayside Drive entrance ramp, (5) downstream of the Telephone Road entrance ramp and (6) at the south HB&T railroad overpass.

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 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. In the computations performed for this report, only about a 6-7 minute travel time (based on about a 40 mph speed) separates the freeway input at Broadway and the bottleneck at Telephone Road. Therefore, the more sophisticated, more complex approach did not seem warranted.

V. RESULTS OF GULF FREEWAY STUDIES

CLOSED SUBSYSTEM STUDIES

Broadway-Griggs Subsystem. The first subsystem to be studied was the one from Broadway to Griggs Road (See Figure 1). The study ran for one week from January 27-31, 1964, with the averages of the data from Tuesday, Wednesday, and Thursday (January 28-30) used in the analyses. The subsystem location was selected to meet two objectives. The first was that the farthest upstream freeway count location (at Broadway) should be upstream of all congestion so the counts at this freeway input would represent true demand. The Griggs Road boundary of the system was chosen to coincide with a known bottleneck. At this location there is a discontinuity in the frontage road and a high-volume, entrance ramp with poor geometrics is introduced at the foot of the steep upgrade on the overpass structure at Griggs Road. The counts at this location were used as estimates of its capacity.

Figure 4 shows the freeway demand at Broadway plotted by five-minute time periods. As can be seen in this figure, the demand peaks at about 400 vehicles per five minutes from 7:00-7:05 a.m. and decreases to about 200 vehicles per five minutes from 7:30-7:35 a.m. These are surprisingly low peak period freeway demands especially considering the severity of conges-

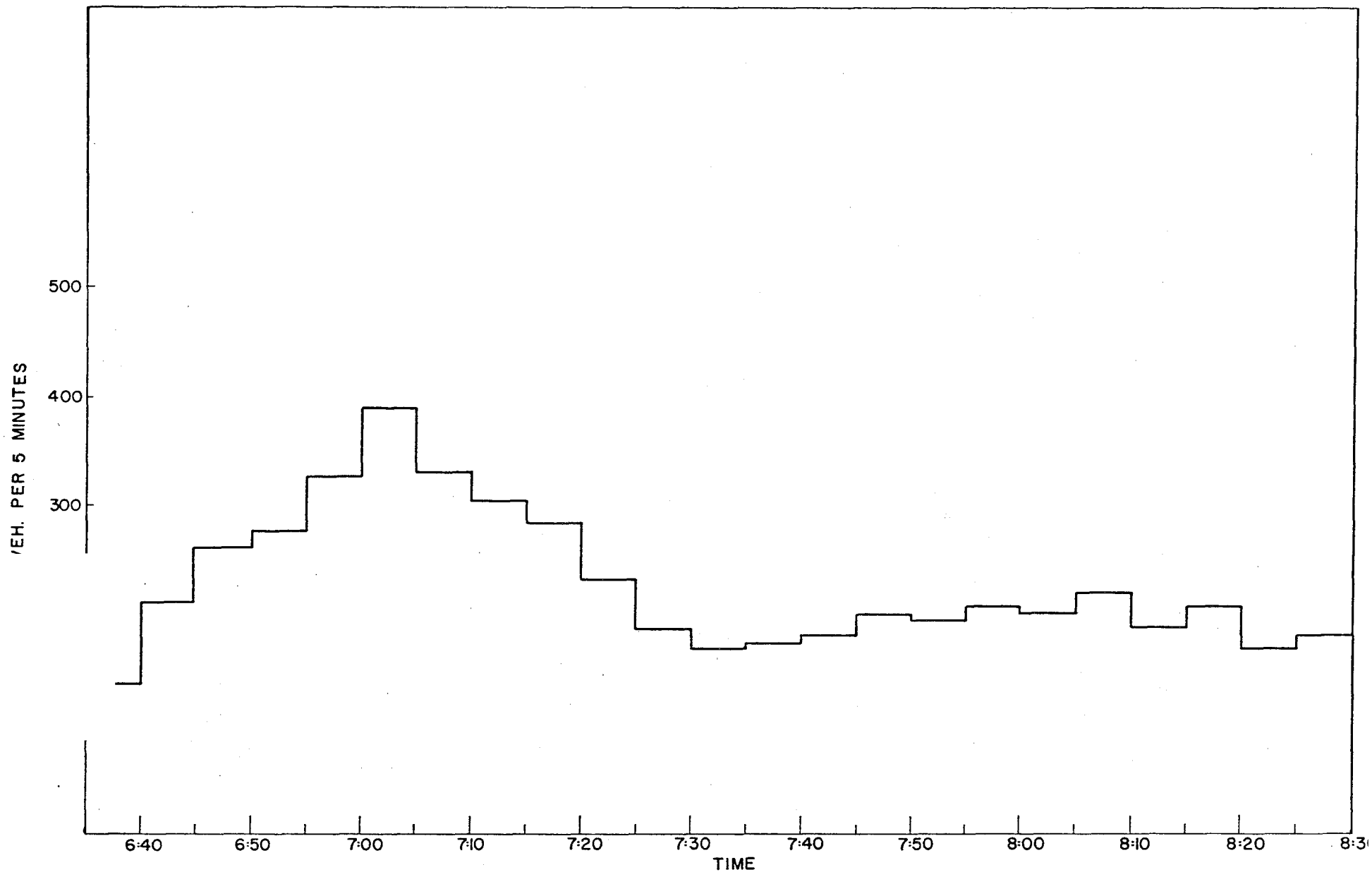


FIGURE 4 FREEWAY DEMAND DOWNSTREAM OF BROADWAY ENTRANCE RAMP

tion which was observed a short distance downstream of this location. Free-flow conditions prevailed at the Broadway count location during the studies.

Figure 5 shows the demand on the S.H. 225 entrance ramp. It peaks at about 90 vehicles per five minutes from 6:45-6:55 a.m. and decreases steadily to about 40 vehicles per five minutes after 7:20 a.m. This decrease in demand at about 6:55 a.m. is probably caused by the development of congestion on the freeway at this time. A driver approaching the freeway on this ramp can see the freeway traffic conditions when he still has time to transfer to the frontage road. After congestion develops on the freeway (about 6:55 or 7:00 a.m.), a motorist can make better time by diverting to the frontage road and entering at the Mossrose entrance ramp. (Because of the discontinuity in the frontage road, a driver who so diverts finds it his best path to enter the freeway there. From 7:00-8:00 a.m. about 25% of the vehicles which enter the freeway at this ramp exit at the next downstream exit ramp, a freeway trip of about 1800 feet -- all of it on an overpass structure.)

A different demand pattern exists at the S.H. 35 entrance ramp -- a high-volume, left-hand entrance ramp. At this ramp a driver must commit himself before he has an opportunity to learn of the freeway traffic conditions and no good alternate routes exist for the traffic from this ramp. Figure 6 shows the demand at this location. It peaks from about 7:05-7:30 a.m. -- at a later time and for a longer duration than the S.H. 225 ramp.

Similar data were obtained for the Woodridge and Mossrose entrance ramps. Figure 7 shows the 7:00-8:00 a.m. volume flow map for this system.

Exit 8 is a slot in the 4-foot wide outer separation and some interesting operations at this location were observed. During the 7:00-8:00 a.m. period about 50 vehicles exit via this ramp. In the same period about 10 vehicles enter the freeway on this ramp to avoid waiting in the queue at the Mossrose entrance ramp (just downstream).

The total number of vehicles entering the subsystem during each five-minute time period was computed (for each time period the sum of the input volume on the freeway at Broadway plus the volumes at the S.H. 225, S.H. 35, Woodridge and Mossrose entrance ramps and the illegal entries on Exit 8) and is plotted in Figure 8. It can be seen in this figure that the total input peaks from 6:55-7:00 a.m. at close to 600 vehicles per five minutes and then decreases steadily until about 7:25 a.m. After 7:25 a.m. the input levels off at about 400 vehicles per five minutes until the peak period ends.

The total number of vehicles leaving the subsystem during each five-minute time period was also plotted and is shown in Figure 9. The output rate of the system seems to drop off sharply from 7:20-7:30 a.m. This will

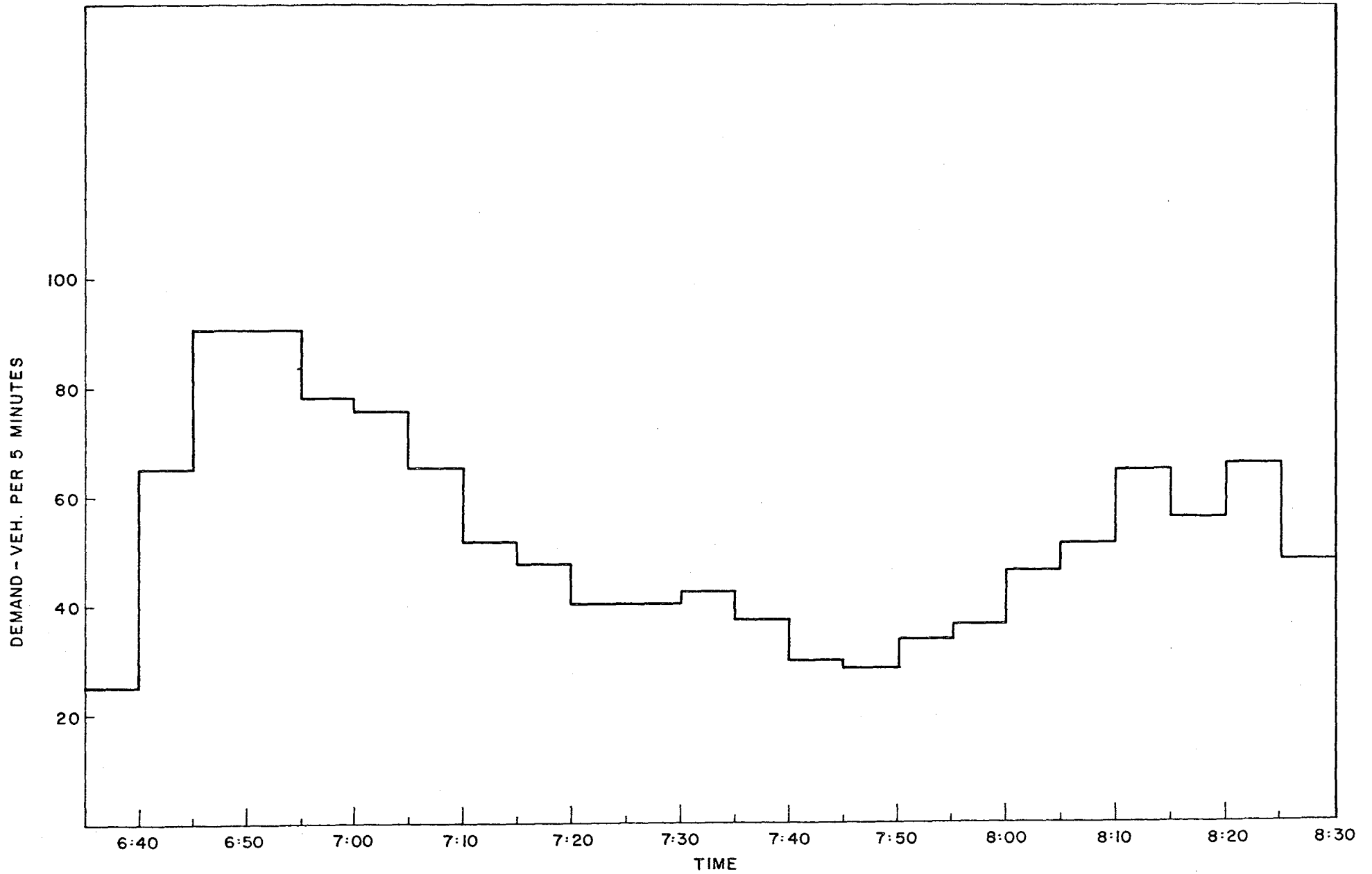


FIGURE 5 DEMAND ON THE SH 225 ENTRANCE RAMP

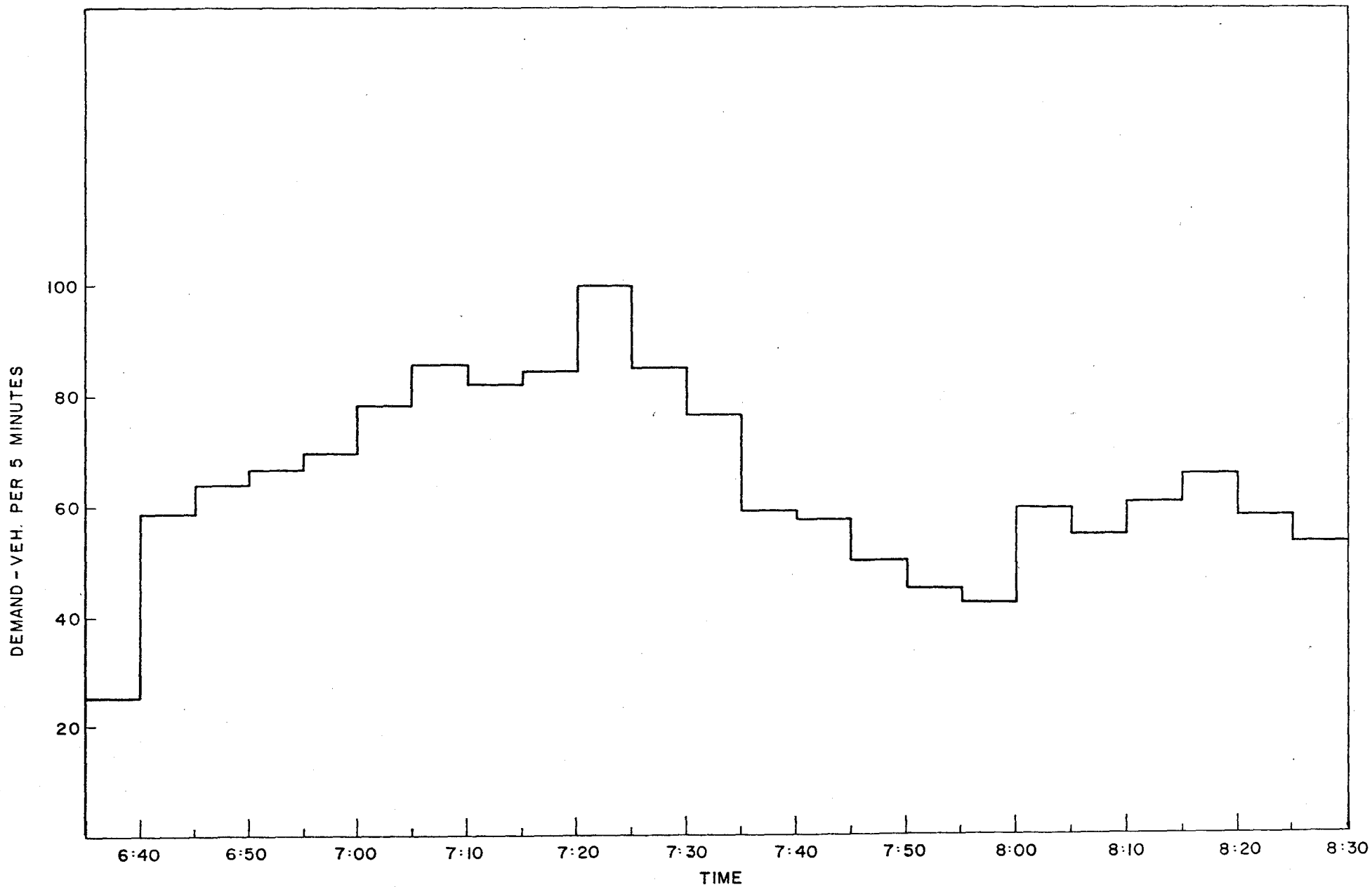


FIGURE 6 DEMAND ON THE SH 35 ENTRANCE RAMP

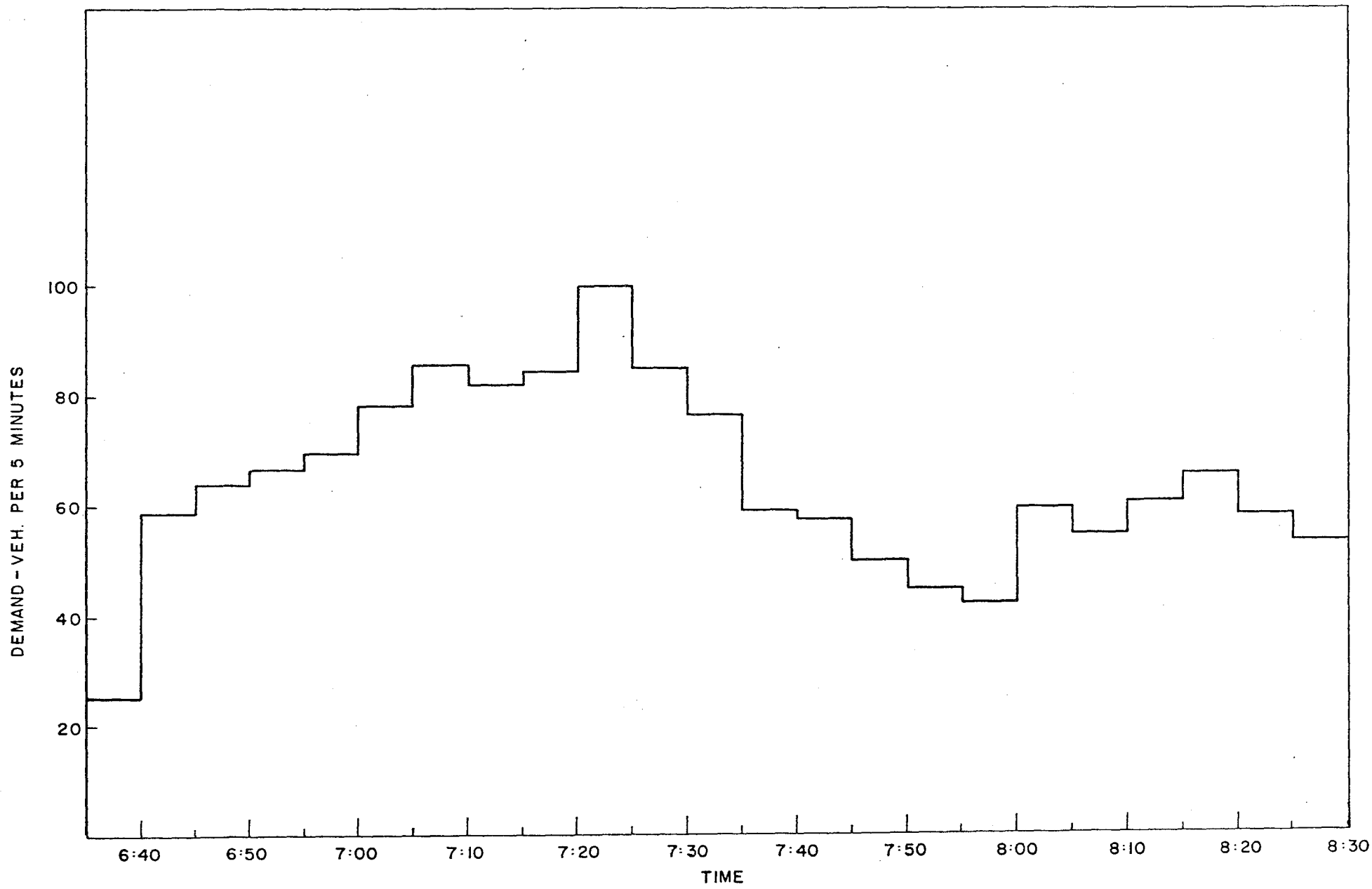
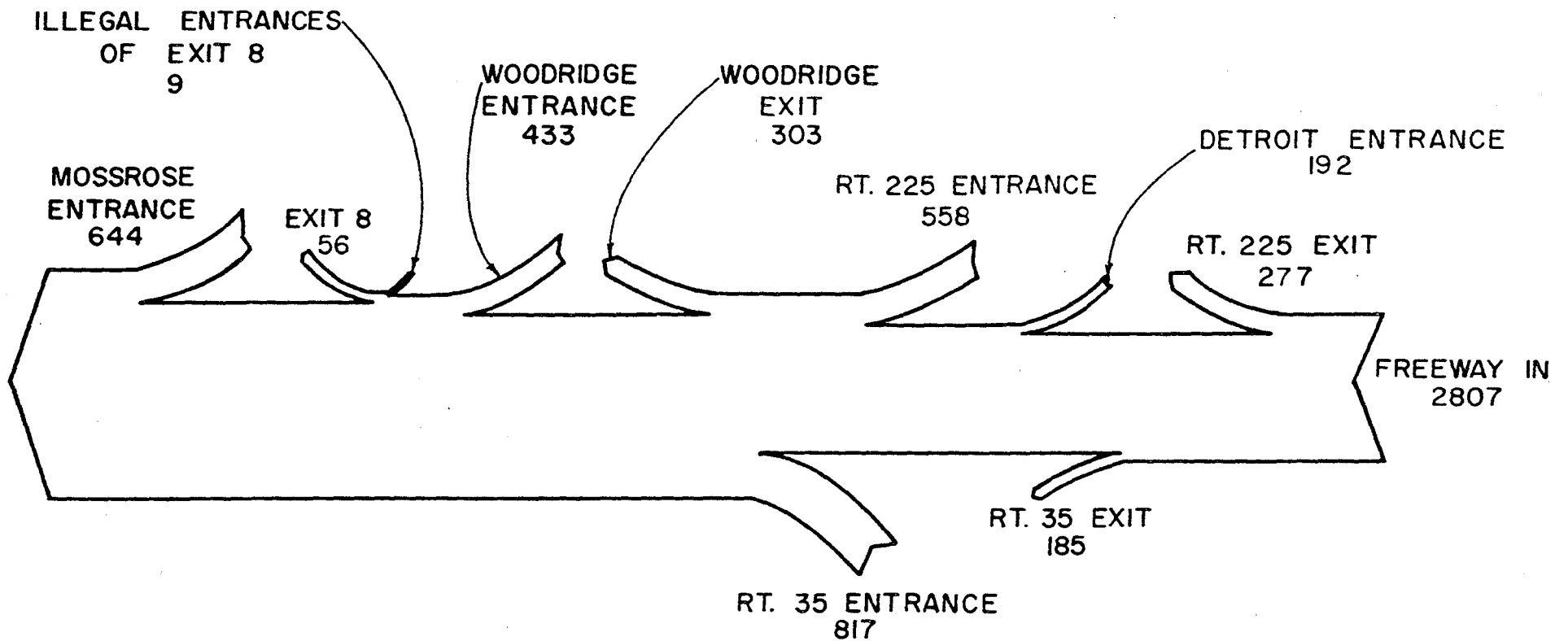


FIGURE 6 DEMAND ON THE SH 35 ENTRANCE RAMP



**FIGURE 7 FLOW MAP
BROADWAY TO GRIGGS
7:00 - 8:00 A.M.**

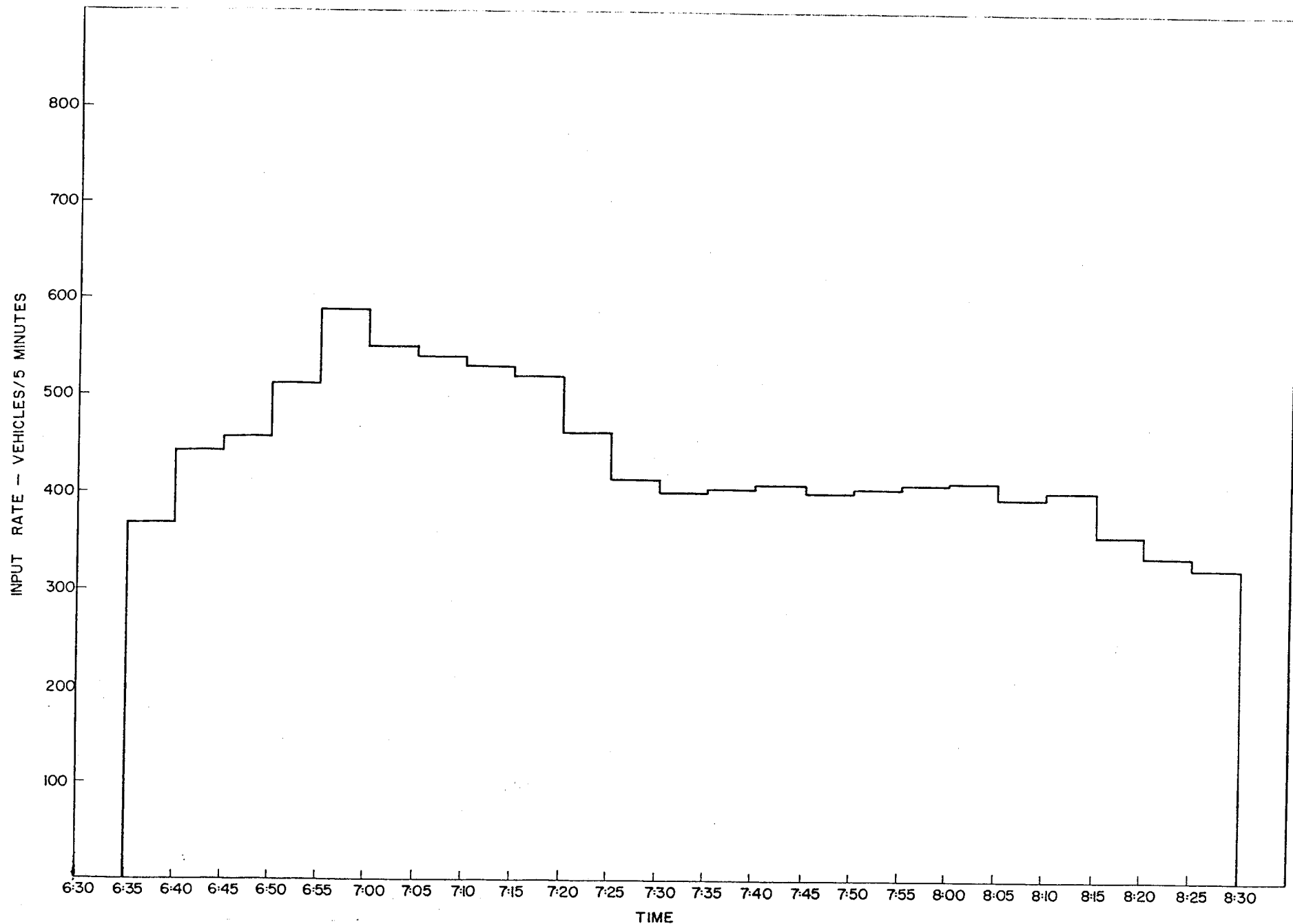
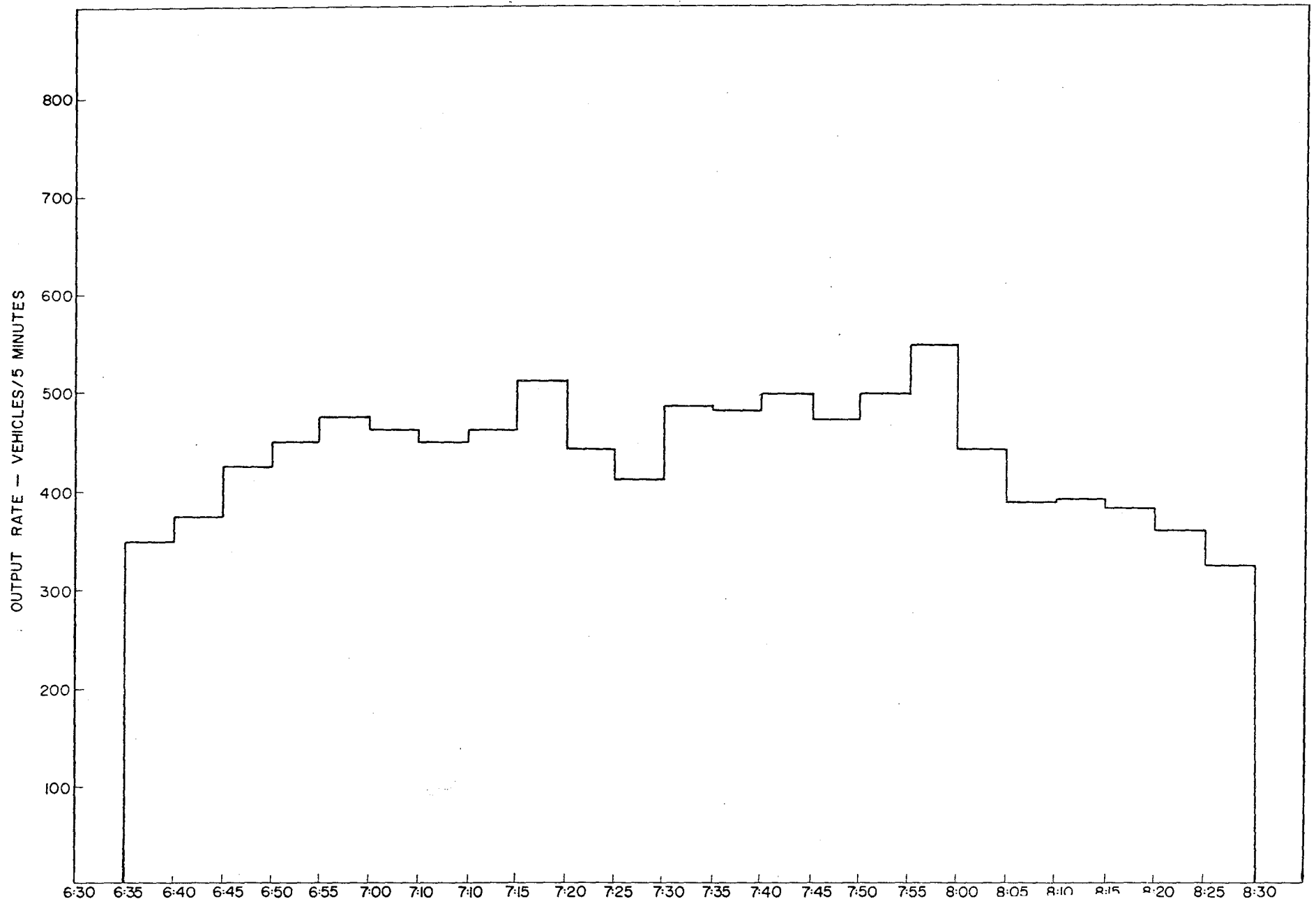


FIGURE 8 INPUT RATE TO BROADWAY - GRIGGS SUBSYSTEM

FIGURE 8 INPUT RATE TO BROADWAY - GRIGGS SUBSYSTEM



be discussed in later sections.

As congestion develops on a freeway, vehicles are accumulated (in the form of increasing density) on the freeway. Since for each time period the number of vehicles entering and leaving the subsystem were known, the rate of accumulation (difference between input and output volume) was also known and is plotted in Figure 10. As can be seen in this figure, the major accumulation in the Broadway-Griggs subsystem takes place from about 6:50-7:15 a.m. From about 7:15-7:30 a.m., steady-state congestion prevails and from about 7:30-8:00 a.m. the system clears.

These same count data were used to obtain the number of vehicles actually in the subsystem. This number is plotted in Figure 11. About 300 vehicles were in the subsystem at 6:50 and again at 7:55 a.m. and about 700-750 vehicles were in from 7:20-7:30 a.m. The 300 vehicles can be considered a "tolerable number" in the subsystem, although this concept can be somewhat misleading (for example, 300 vehicles in the subsystem would not be a tolerable number if they were all in one small part of the subsystem). The number in excess of 300 can be considered to be the "number too many" or excessive number of vehicles in the subsystem.

The total travel time in this system was 579 vehicle hours as obtained from the method using the number of vehicles in the system.

Since Figures 8-11 each represent the average of three days of data, the question of "how consistent are the data?" is a legitimate one. Figures 12 and 13 show the input and output of the subsystem on each of the three days. As can be seen in these figures, the data were exceedingly consistent from one day to another. The accumulation rate and number of vehicles in the system showed corresponding consistency.

Data on the flow and vehicular speed samples were obtained on the down-grade side of the Griggs Road overpass structure on several occasions, including during the Broadway-Griggs subsystem study, the Griggs-South HB&T Railroad overpass subsystem study and during several capacity studies. The flow characteristics of this location are of importance because it is the primary output from the heavily congested Broadway-Griggs subsystem. Figure 14 shows the five-minute flows and speeds obtained during the Griggs-South HB&T Railroad overpass subsystem study. It represents the average of data from the three days (March 16, 17, 20, 1964) which were free from accidents, etc.

As can be seen in Figure 14, the flow at this location increases to a maximum in the 7:00-7:05 a.m. time period and then decreases. The reason for this decrease can be found in the speed data. Shortly after 7:05 a.m. the speeds at Griggs decreased from about 33 mph to about 28 mph and at about 7:20 a.m. decreased further to about 20 mph. Since these data were collected

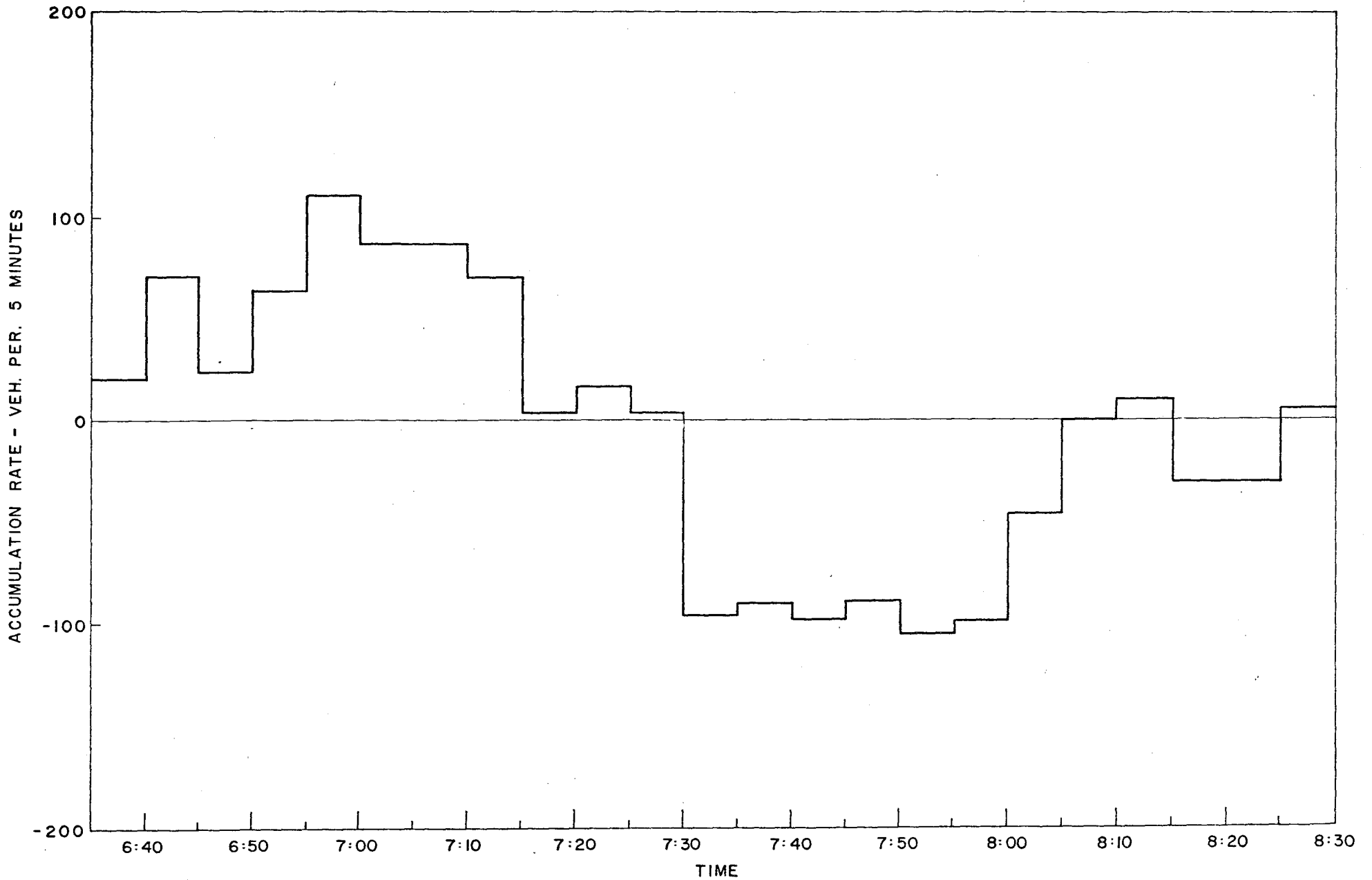


FIGURE 10 RATE OF ACCUMULATION ON FREEWAY FROM BROADWAY TO GRIGGS OVERPASS

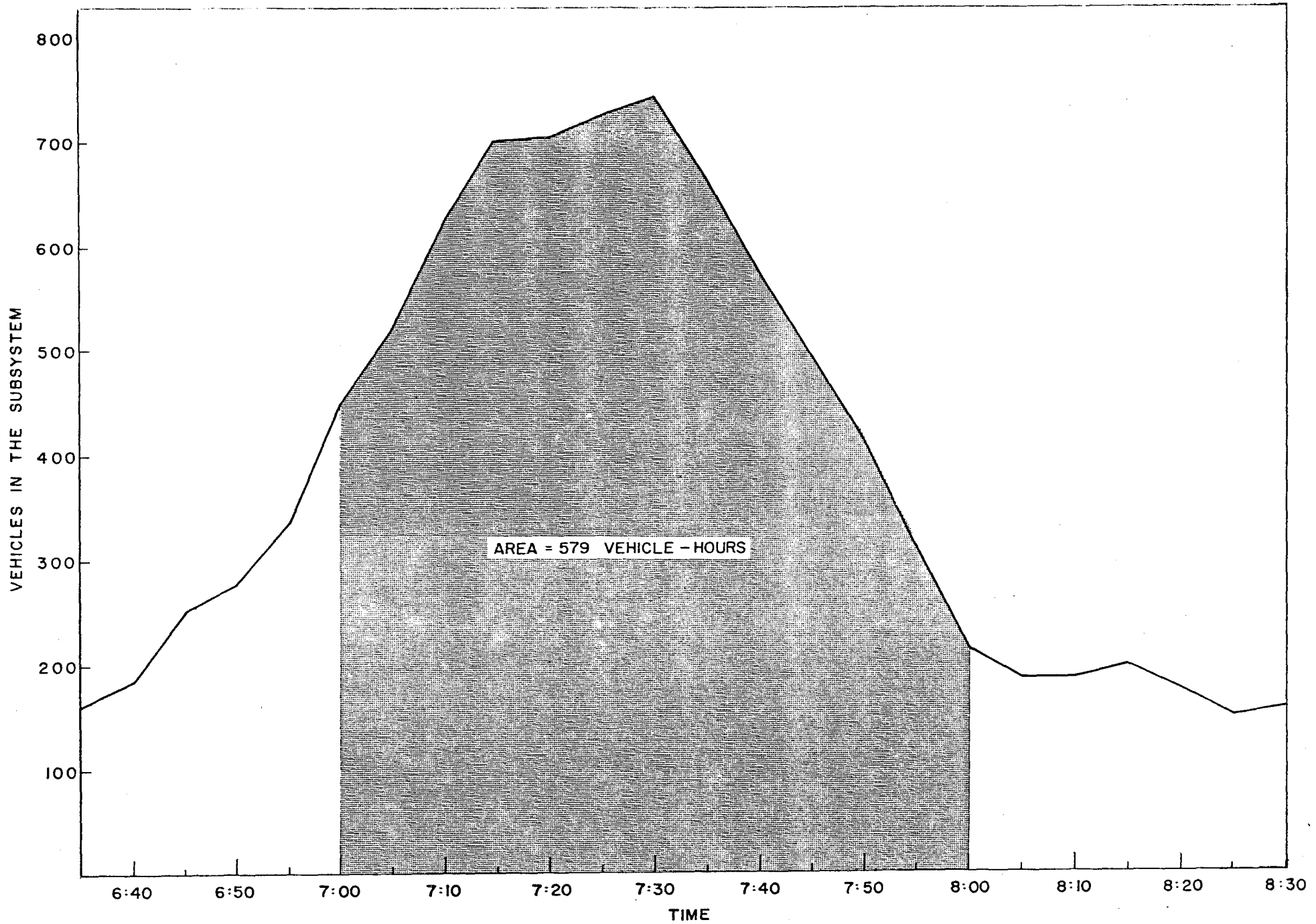


FIGURE II NUMBER OF VEHICLES ON FREEWAY FROM BROADWAY TO GRIGGS OVERPASS

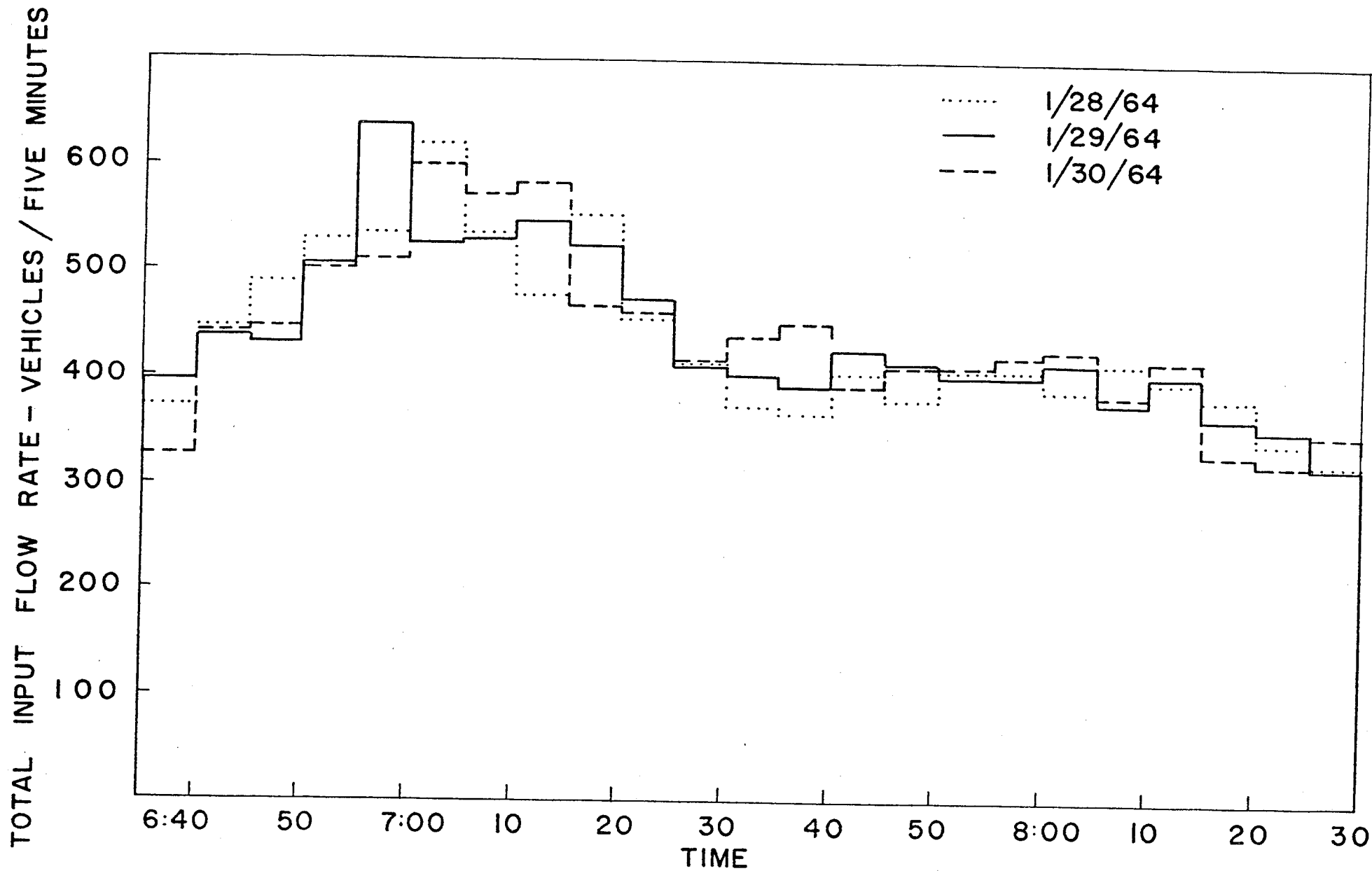


FIGURE 12 INPUT BROADWAY-GRIGGS

TOTAL OUTPUT FLOW RATE - VEHICLES / FIVE MINUTES

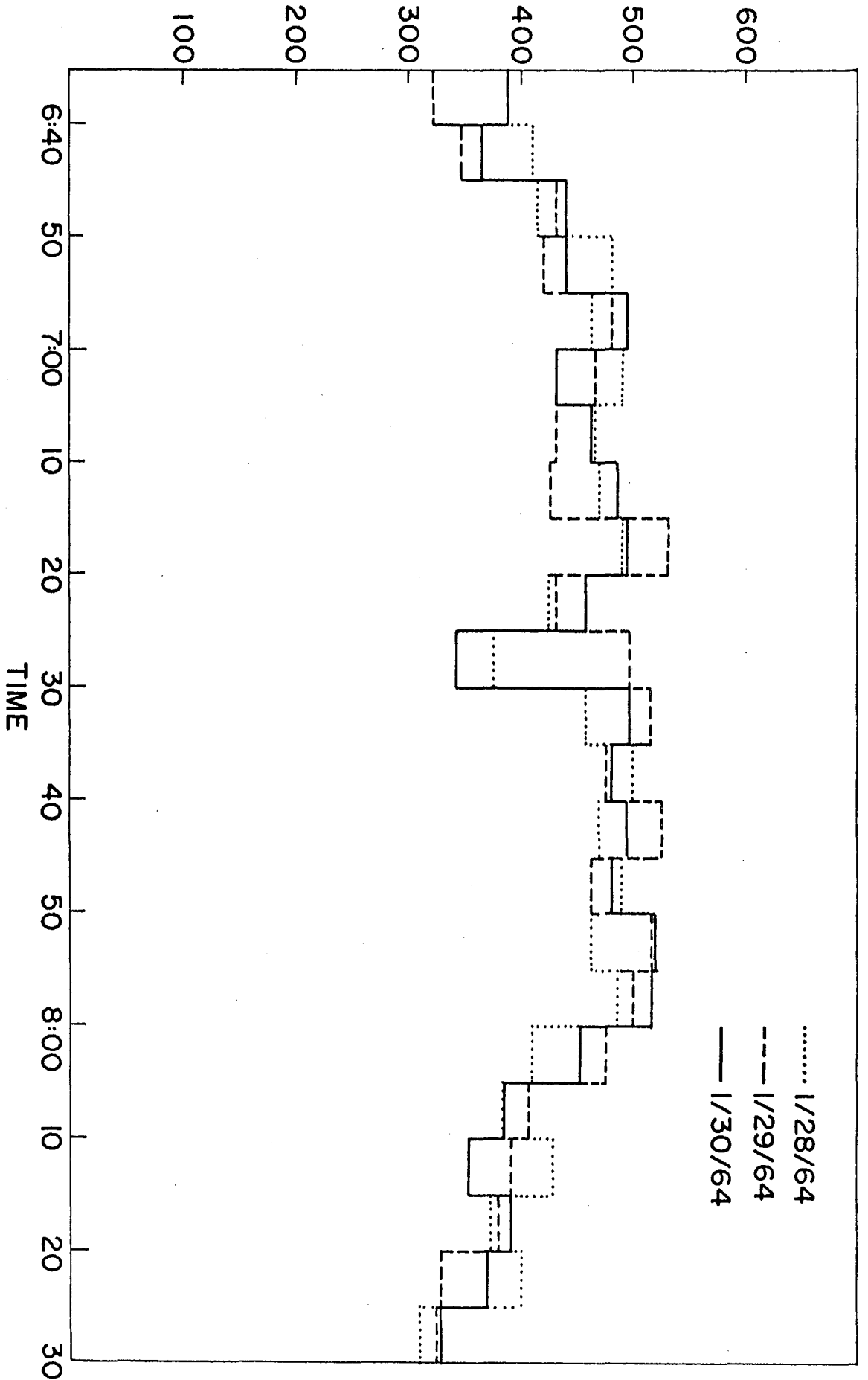


FIGURE 13 OUTPUT BROADWAY - GRIGGS

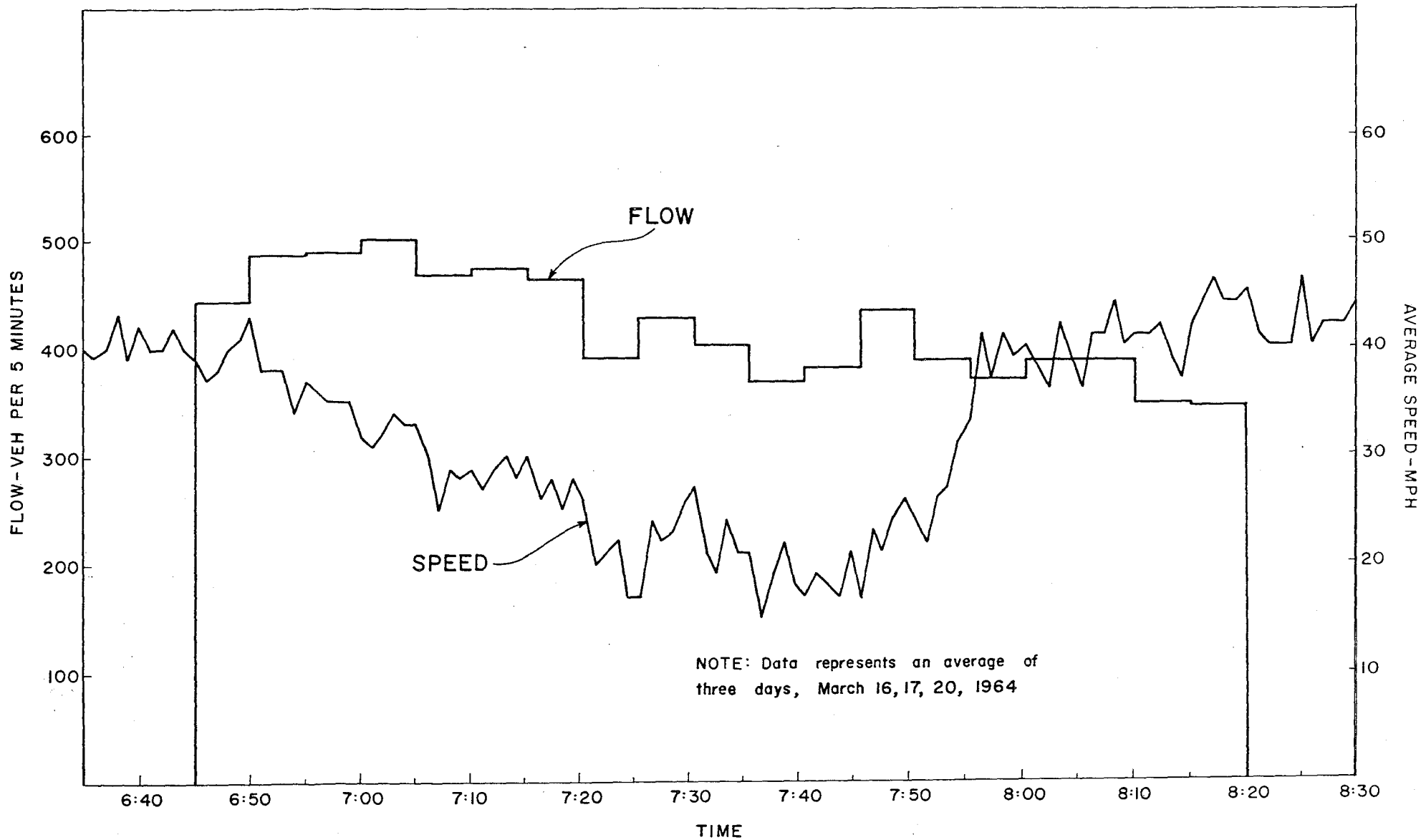


FIGURE 14 FLOW AND SPEED ON FREEWAY AT GRIGGS ROAD

on a downgrade just upstream of a high-volume exit ramp, these low speeds were necessarily caused by a queue of vehicles from a downstream congestion source. (Field observations verified this.) From 7:20-7:55 a.m. this queue from downstream restricted the flow at Griggs to about 400 vehicles per five minutes - considerably less than the estimated capacity flow of 475 vehicles per five minutes there. Thus, the effect of downstream congestion on the output rate of the Broadway-Griggs subsystem can be seen to be substantial and much of the storage of vehicles (congestion) in this subsystem is due to this queue from downstream.

Griggs-South HB&T Railroad Subsystem. The second subsystem to be studied extended from Griggs Road to the south HB&T Railroad overpass (between Telephone Road and Dumble Street in Figure 1). The study ran one week from March 16-20, 1964, and the data from Monday, Tuesday and Friday (March 16, 17 and 20) were used in the analyses. The Griggs Road freeway count station was at the same location as the corresponding station in the earlier study, thus assuring no loss of coverage between subsystems. The downstream location was selected for two reasons. The first is that it was known to be a bottleneck and the counts there could be used to estimate its capacity. The second is that this location was known from earlier studies to be downstream of the severely congested area. Thus, the output rate of a congested subsystem could be investigated.

Figure 15 shows the rate at which vehicles entered this subsystem (again from all entrance ramps and the freeway at Griggs Road). The input rate is maintained at high levels (555-595 veh/5-min.) from 6:50 until 7:20 a.m. when it decreases, largely due to the decrease in flow on the freeway at Griggs Road.

Figure 16 shows the output rate of the subsystem. The output rate reaches a peak shortly after 7:00 a.m. and then decreases until about 7:40 a.m.

Figure 17 is a plot of the rate of accumulation of vehicles in this subsystem. Vehicles are accumulated in this system until about 7:30 a.m. and are cleared from 7:30 until 8:00 a.m. -- much like the Broadway-Griggs subsystem. The rate of accumulation is smaller in this subsystem, however (probably due mainly to its shorter length).

The number of vehicles in the Griggs-south HB&T Railroad subsystem is shown in Figure 18. This number increases from about 270 at 7:00 a.m. and then decreases to about 270 at 8:00 a.m. Since 7:00-8:00 a.m. is the period of congestion, the "tolerable number" in this subsystem is 270 and the "excessive number" in the subsystem is about 150.

The total travel time in the Griggs-south HB&T Railroad subsystem (as obtained from the number of vehicles in the subsystem) was 367 vehicle hours

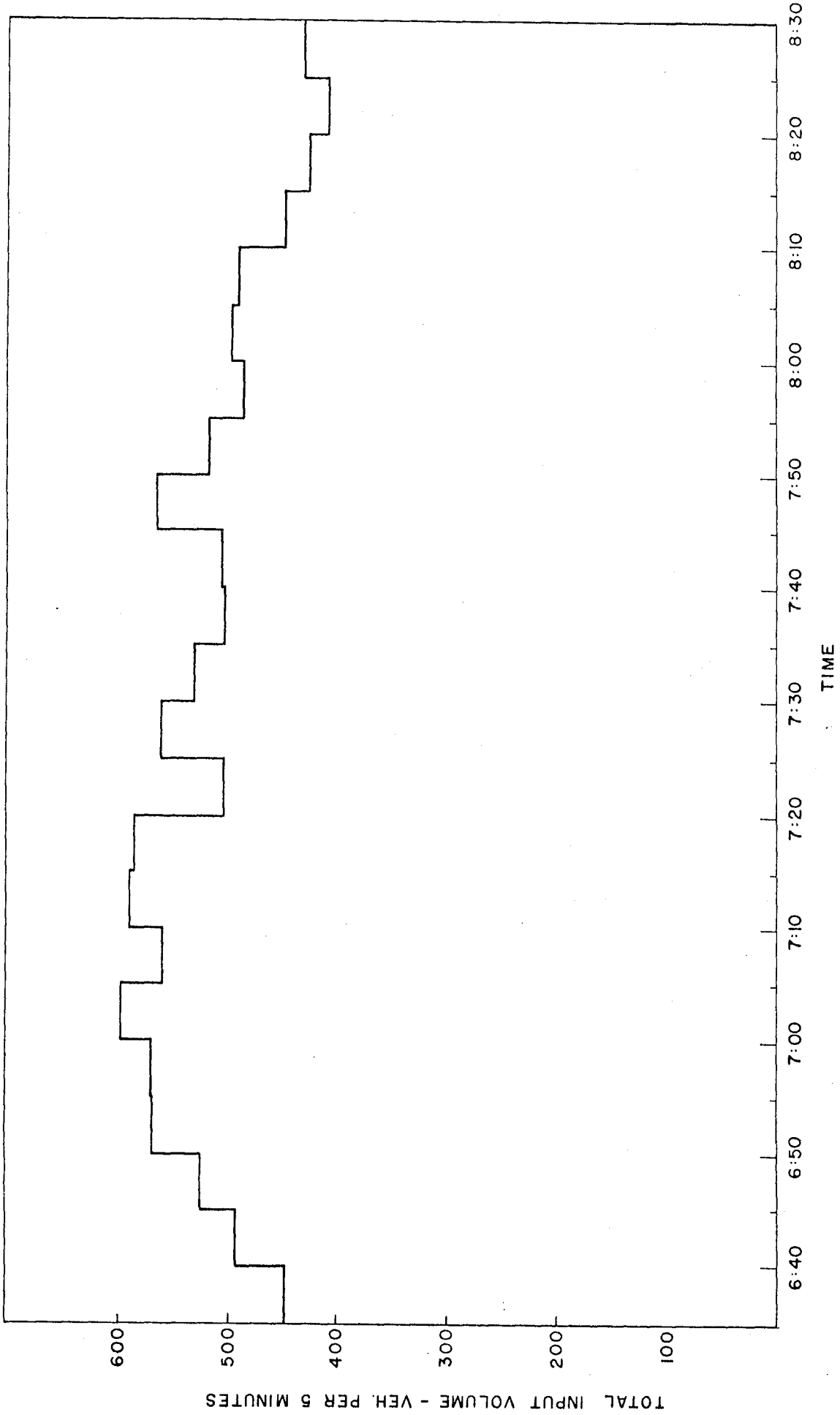


FIGURE 15 INPUT VOLUME - GRIGGS - SOUTH HB & T RR SUBSYSTEM

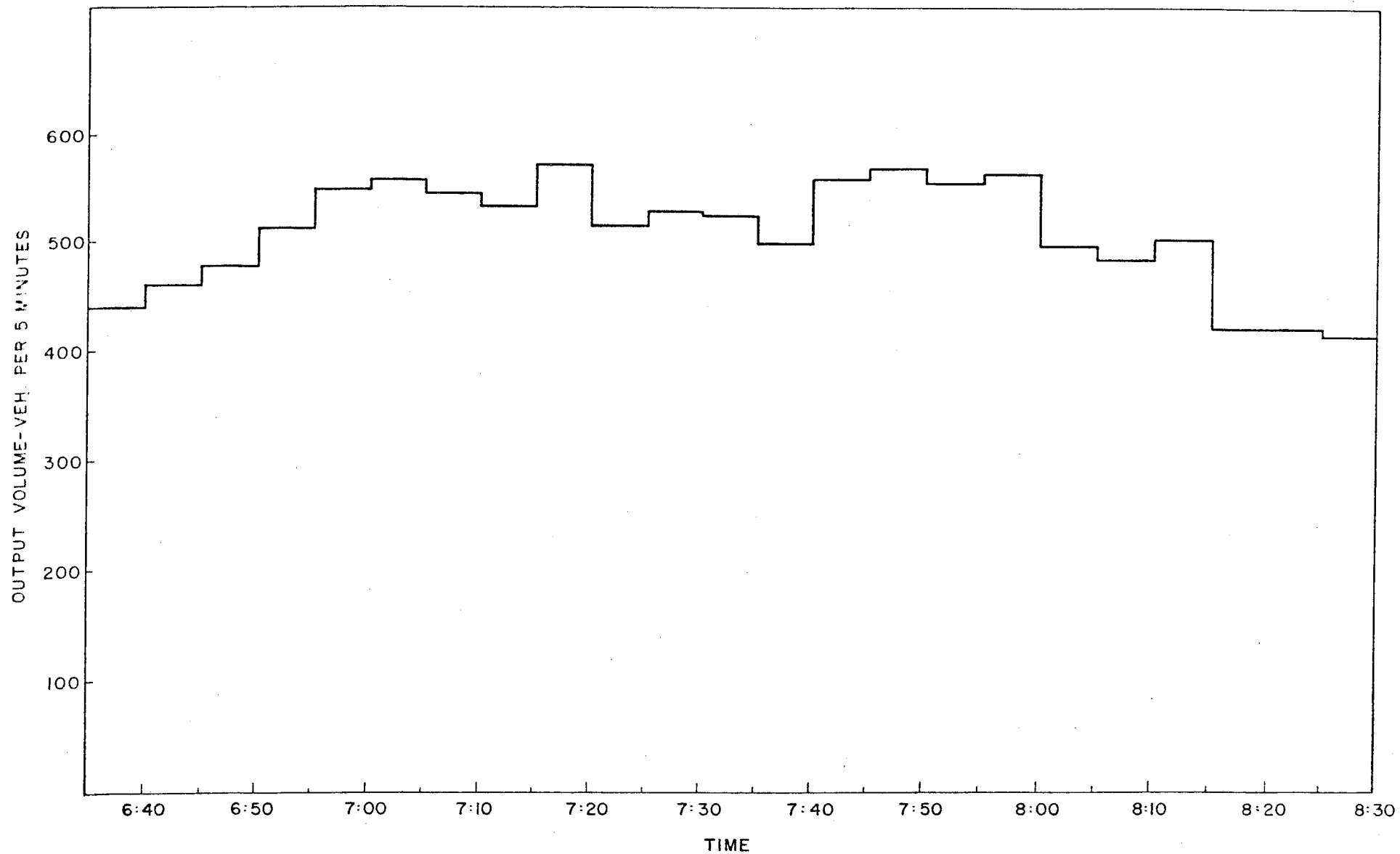


FIGURE 16 OUTPUT VOLUME-GRIGGS - SOUTH HB & T RR SYSTEM

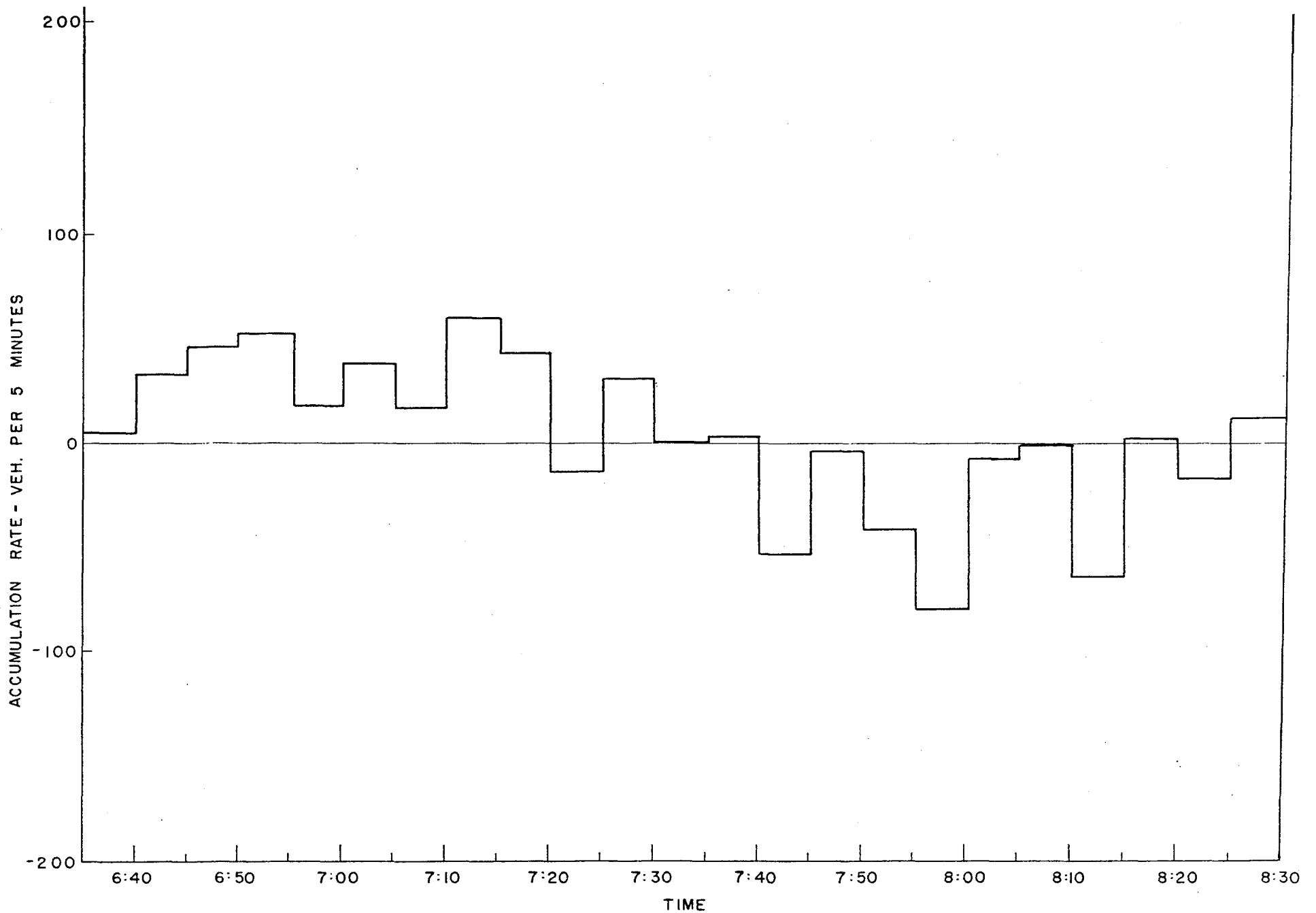


FIGURE 17 RATE OF ACCUMULATION ON FREEWAY FROM GRIGGS TO SOUTH HB & T RAILROAD

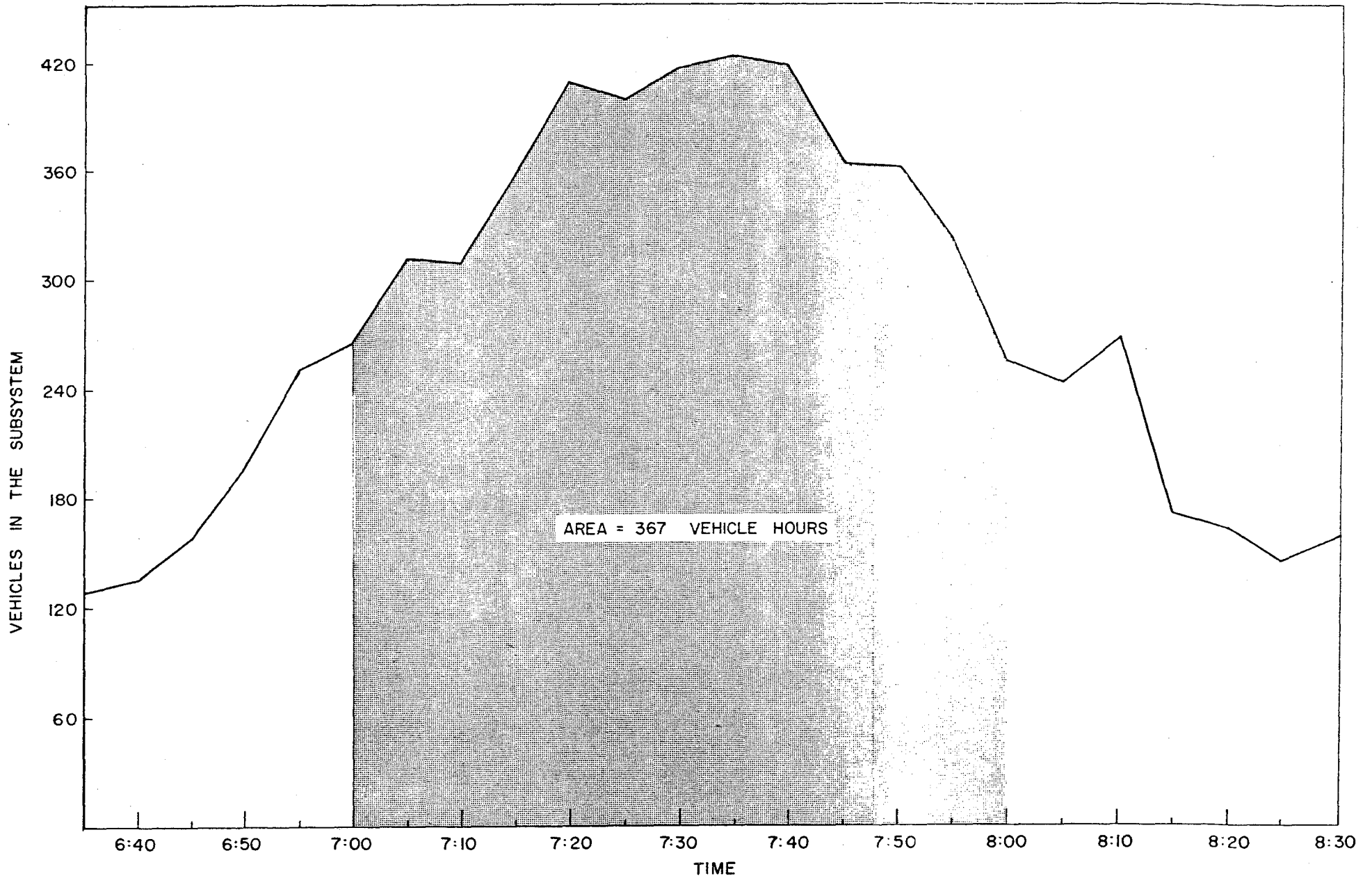


FIGURE 18 NUMBER OF VEHICLES ON FREEWAY FROM GRIGGS TO SOUTH HB & T RAILROAD

for the 7:00-8:00 a.m. time period.

Three Subsystems from South HB&T Railroad to Calhoun-Pease Distribution System. Because of manpower limitations, it was necessary to divide the freeway from the South HB&T Railroad to the Calhoun-Pease distribution system into three subsystems. The first extended from the South HB&T Railroad overpass to Cullen Street, the second from Cullen Street to Scott Street, and the third from Scott Street to the Calhoun-Pease distribution system.

The input, output, etc. data for these subsystems are not presented here since these subsystems were found to be essentially free from congestion.

The total travel time for the 7:00-8:00 a.m. time period (again obtained from technique using the number of vehicles in the system) for each of the three subsystems is 153, 85, and 61 vehicle hours, respectively. From 7-8 a.m., then, a total of 1245 vehicle hours of travel time are spent each weekday by motorists on the inbound Gulf Freeway between Broadway and the Calhoun-Pease distribution system.

Frontage Road Subsystems. The freeway traffic conditions affect the operation of the frontage roads and vice versa. Also, when freeway controls (ramp closure, ramp metering, or other) are initiated, both the freeway traffic conditions and frontage road traffic conditions will be changed. Hence, in order to obtain a true "before" study picture, it is necessary to include the frontage roads in the study area.

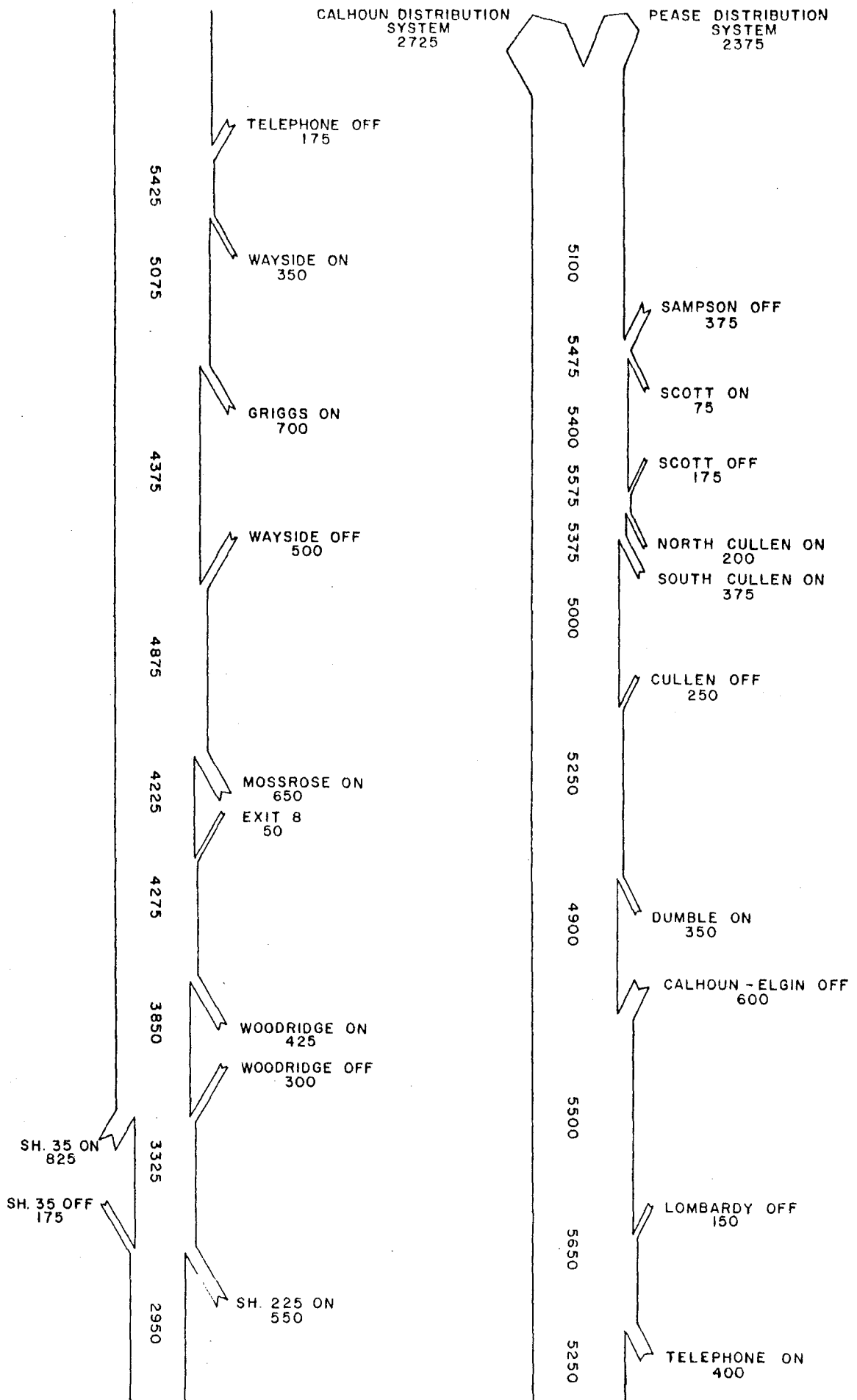
The inbound frontage road was also divided into subsystems and these same analyses were made. Because of the similar nature of these data and because this phase of the work has not been completed, these data are not included in this report.

PEAK-HOUR TRAFFIC FLOW MAP

Figure 19 is the traffic flow map of the inbound Gulf Freeway for the 7:00-8:00 a.m. peak period. It was quite surprising to find that the Reveille Interchange area (interchange of S.H. 225 and S.H. 35 with the freeway) had such low (3,000-4,000) peak hour volumes since previous studies (8), as well as the present studies, indicated that in this area the speeds were lowest and density was the highest during the congested period.

Two high-volume areas are present on the inbound freeway. The first is the Wayside-Telephone area in which the serious freeway congestion originates. The second is at Cullen Street where the freeway is essentially congestion-free.

FIGURE 19— VOLUME FLOW MAP - INBOUND GULF FREEWAY



DENSITY VERSUS TIME IN EACH SUBSYSTEM.

Since, for each of the five freeway subsystems, the number of vehicles within the subsystem was known each five minutes, the density in each subsystem could be easily obtained since the length of each subsystem was known. The density plot for each subsystem is shown in Figure 20.

Until 6:50 a.m., the densities of all five subsystems are essentially the same. The density in the Broadway-Griggs subsystem is considerably greater than the density of the other systems during much of the congested period. Only the two subsystems from Broadway to Griggs and from Griggs to the South HB&T Railroad exceed the optimum density of 180 vehicles per mile for three lanes (with the exception of one time in the Cullen-Scott subsystem).

It can be seen, however, that the Broadway-Griggs subsystem clears out before the Griggs-south HB&T subsystem, indicating that the queue (congestion) dissipates from upstream to downstream.

EFFECT OF CONGESTION ON FREEWAY OUTPUT RATES

In the situation in which the peak period is free from the effect of accidents, disabled vehicles, and other capacity-reducing events, congestion at a freeway bottleneck is hypothesized to decrease the freeway output in two ways. The first is that the flow at the bottleneck itself is decreased due to the congestion. The second is that the output rate of exit ramps upstream of the bottleneck can be reduced.

There are those who argue that a freeway bottleneck will maintain its maximum flow rate under congested upstream conditions, in fact, that these conditions are necessary in order to assure a constant demand on the bottleneck. This situation will be discussed in some detail. The second condition is fairly self-evident and is discussed in Appendix A. It is merely necessary to consider that the congestion originating at a bottleneck causes queuing which can delay vehicles which are going to exit upstream of the bottleneck. In other words, some vehicles on the freeway experience delay due to the congestion which they had no part in causing and to which they did not contribute.

Since the congestion in the Griggs-south HB&T Railroad subsystem originates in that subsystem and is not affected by downstream traffic conditions, a study of the output characteristics of this subsystem affords an opportunity to investigate the effects of congestion.

Figure 21 shows the output-time characteristics as well as the density-time function for the Griggs-south HB&T Railroad subsystem for Friday, March 20, 1964. The lowest output curve (solid line) represents the five-minute flows on the freeway

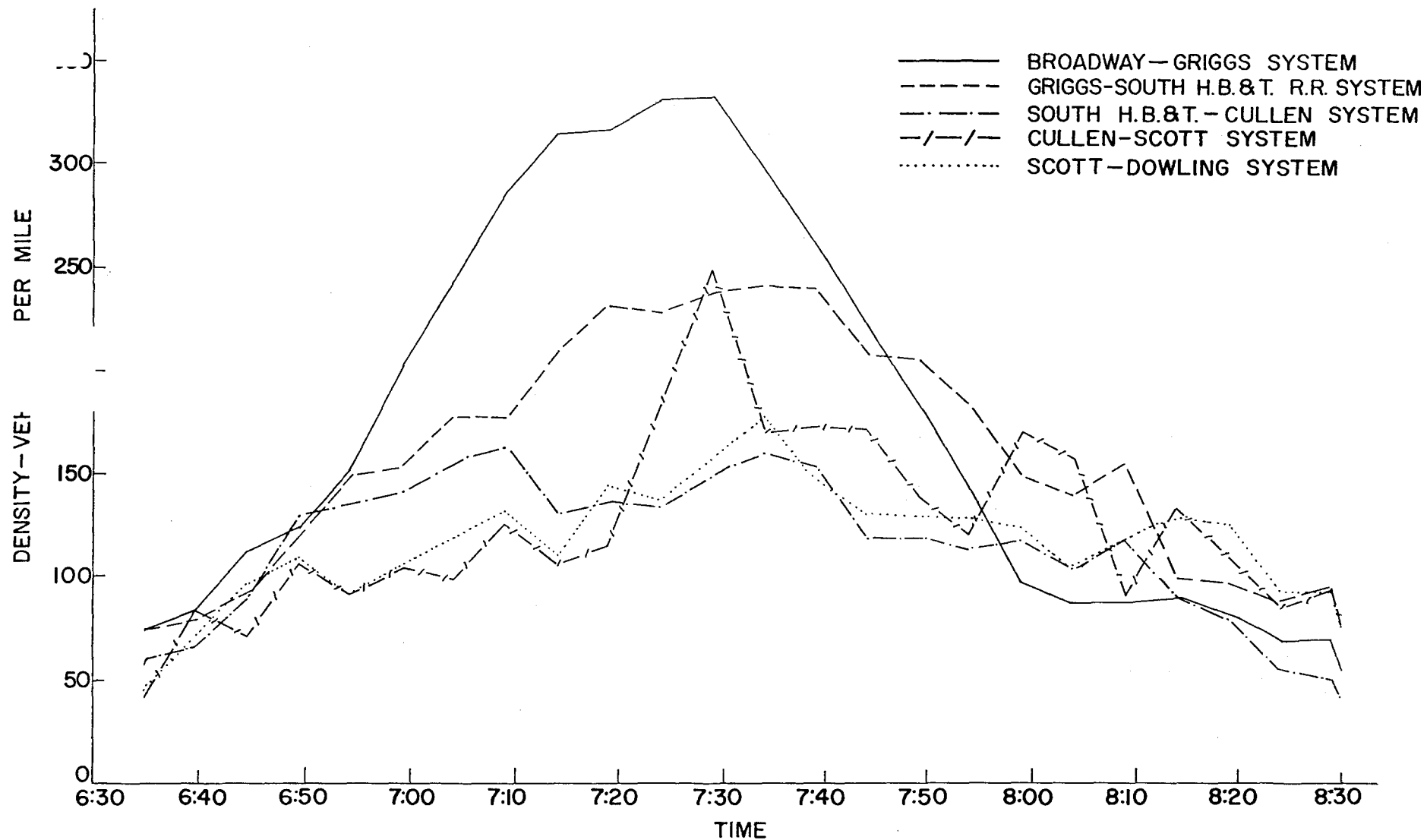


FIGURE 20 DENSITY VERSUS TIME — ALL SUBSYSTEMS

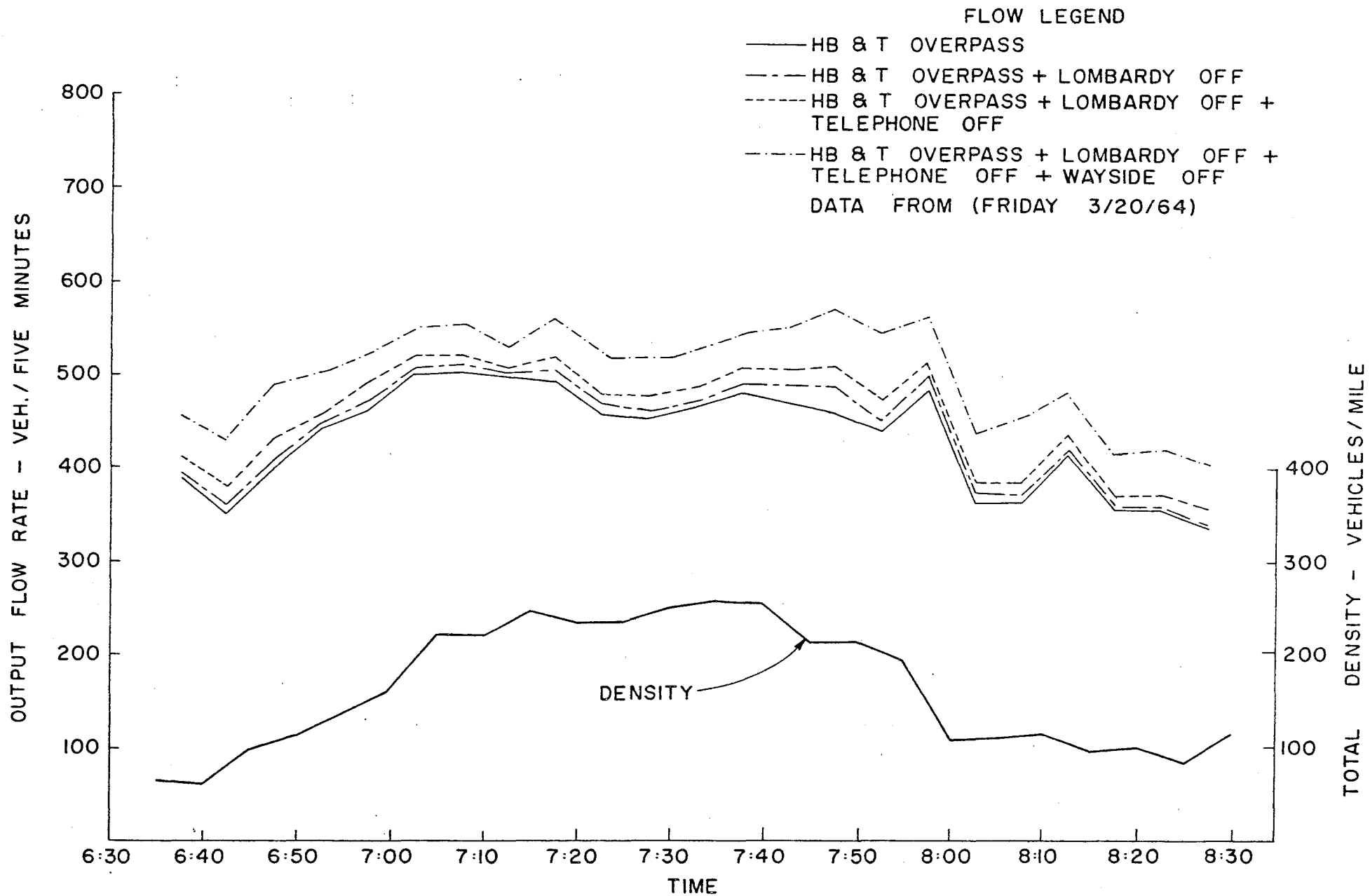


FIGURE 21 OUTPUT FLOW RATES AND TOTAL DENSITY - GRIGGS - SOUTH HB & T RR SUBSYSTEM

on the downgrade of the south HB&T Railroad overpass (each five-minute flow is plotted as a point rather than a bar to avoid having the curves cross). The second curve (dashed line) is this same flow plus the exiting flow at the Lombardy exit ramp. The next curve (dashed and dotted line) is the sum of these two flows plus the flow exiting at Telephone Road. The upper curve (dotted line) represents the total system output flow each five minutes and equals the sum of the output flows on the freeway at the South HB&T Railroad, Lombardy off-ramp, Telephone off-ramp and the Wayside Drive off-ramp.

The density shown in this figure is the total subsystem density obtained by the counts on March 20.

Figure 22 shows the average speed at the south HB&T freeway count location. At this location from 7:00-8:00 a.m. the speeds were predominantly between 30 and 35 mph. One exception is the short period between 7:11 and 7:12 a.m. when the average speed decreased to 25 mph. These data indicate that downstream traffic conditions had little effect on the flow at this count location.

Since there is severe congestion in the Griggs-south HB&T Railroad subsystem and it is not caused by downstream conditions, the critical bottleneck (or bottlenecks) must lie within this subsystem. Therefore, one of the lower three output curves in Figure 21 necessarily represents the flow away from the critical bottleneck(s). The freeway output flow rate reaches a maximum from 7:00-7:20 a.m. when an average flow of 495 vehicles per five minutes was found and then is lower from 7:20-7:55 a.m. when the freeway output averaged 458 vehicles per five minutes -- a 7.5% decrease in flow. The corresponding decreases in the flow curves for the freeway output plus the Lombardy off-ramp output and for the freeway output plus the Lombardy off-ramp output plus the Telephone off-ramp output are 8.1% and 5.1% respectively.

The density in this subsystem is quite high from 7:05 to 7:55 a.m. as seen in Figure 21. Thus, these decreases in flow were not caused by a lack of demand.

From this it can be concluded that the flow rate at the critical bottleneck did decrease due to the congestion there. It cannot be stated that a certain level of density caused or accompanied the decrease in flow since the high density was maintained during some periods of high flow and all periods of low flow (during the congested period). Thus it appears that time as well as density plays a part in the decrease in flow. It was somewhat surprising that the first appearance of high density in the subsystem did not cause the bottleneck flow to decrease immediately. This seems to contradict some earlier ideas and interpretations of volume-speed, etc., curves. Since it has been essentially assumed that one-to-one relationships exist between speed and flow, density and flow, and speed and density, it was believed that when the critical density was reached, the flow rate would immediately decrease. It appears that time is also a critical parameter.

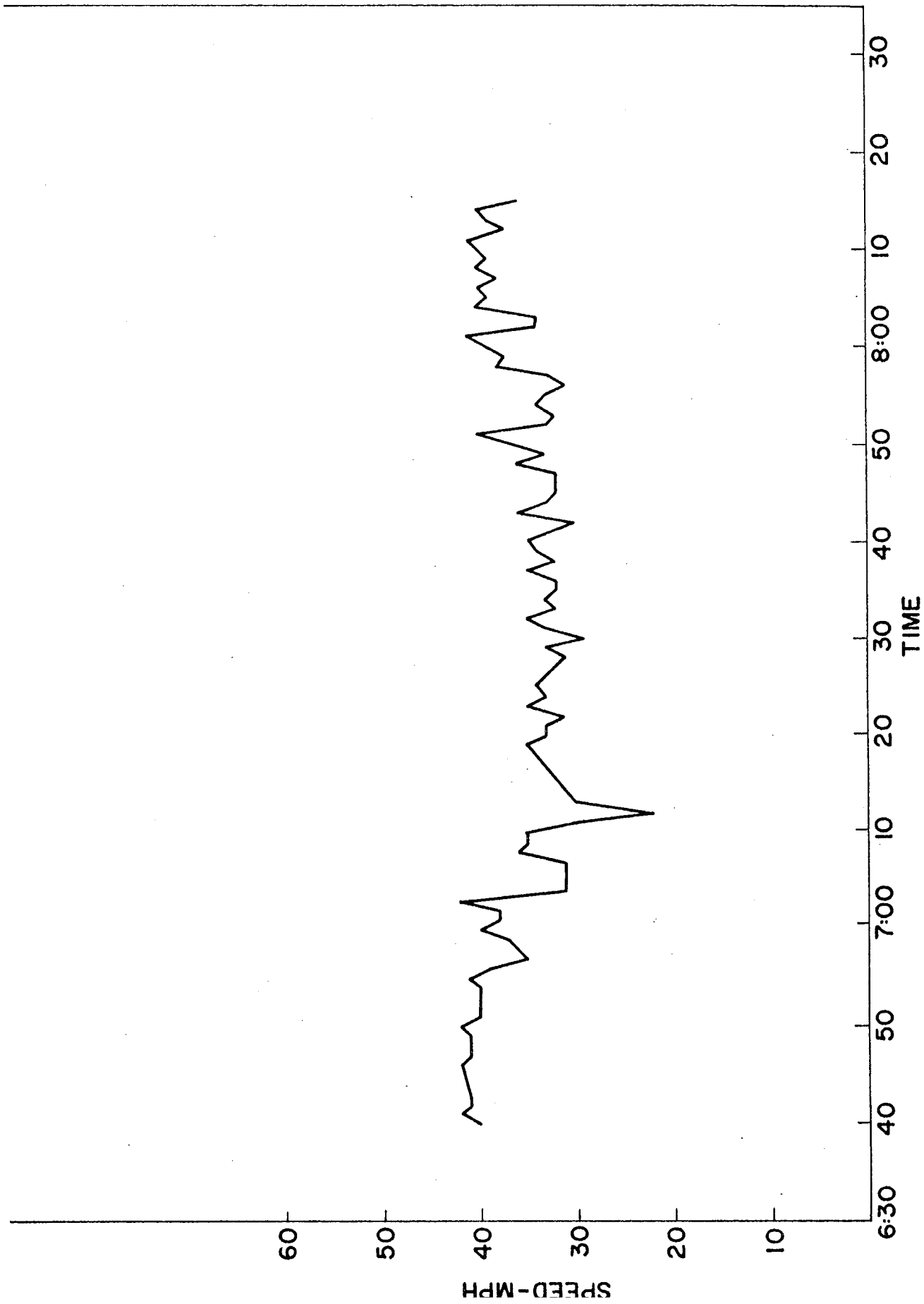


FIGURE 22 AVERAGE SPEED AT SOUTH HB&T RAILROAD

The data from one day (Friday, March 20, 1964) have been presented in detail with the assumption that they are relatively typical. Because of the important nature of this subject (especially to those engaged in freeway control work) two additional days (Monday and Tuesday, March 16-17, 1964) of data are included as Appendix Figures C1-C4.

Flow-Subsystem Density Curves. Figure 23 shows the combined output flow rate of the freeway at the south HB&T Railroad overpass, the Lombardy off-ramp and the Telephone off-ramp plotted against the density in the Griggs-south HB&T RR subsystem. The data for March 16, 17 and 20, 1964, have been plotted. The density plotted is that at the beginning of the time period in which the flow was measured. The hypothesis was that up to a certain density, the output rate would increase with increasing density but after some critical subsystem density was exceeded, the subsystem output rates would be decreased. Figure 23 shows this to be generally true but that the decrease of output flow with increasing density is not drastic and it is difficult to pinpoint the "critical density". The output rate essentially increased until a density of about 160 vehicles/mile was reached and that for densities between 160 and 220 vehicles/mile, the output remained constant. Densities greater than 220 vehicles/mile seem to decrease this combined output flow rate.

When the Wayside exit flow is considered with these three output flows, Figure 24 is obtained. The density for maximum output in this case is a range of about 170-210 vehicles/mile. Densities larger than about 210 vehicles per mile cause the subsystem output rate to be decreased.

From these two figures, it can be seen that as the density of a subsystem is increased above some range of critical densities, the output flow rate of the subsystem can be decreased. This decrease in output flow rate cannot be attributed to downstream congestion (as was seen from the speeds at the freeway output) nor to lack of demand (as is seen in the density graphs).

As Figure 14 showed, the congestion in the Griggs-south HB&T RR subsystem can decrease the flow rate on the freeway at Griggs Road and can hence decrease the output rate of the Broadway-Griggs subsystem. Figure 25 shows the 5-minute flows on the freeway at Griggs Road plotted against the density of the Griggs-south HB&T RR subsystem at the beginning of each period. The increased density from Griggs Road to the south HB&T RR overpass does not decrease the flow at Griggs until a level of about 160-190 vehicles per mile is reached. When the density exceeds this range of values, the freeway flow at Griggs Road is decreased.

Effect of an Accident. That an accident can reduce the freeway flow rates is an established fact. Figure 26 shows the flow and speed data on the freeway at the south HB&T Railroad overpass location obtained during a capacity study there. From 6:55-7:10 a.m., the speeds at this location were between 35 and 40 mph, indicating no queueing effects from downstream bottlenecks, and the flows were

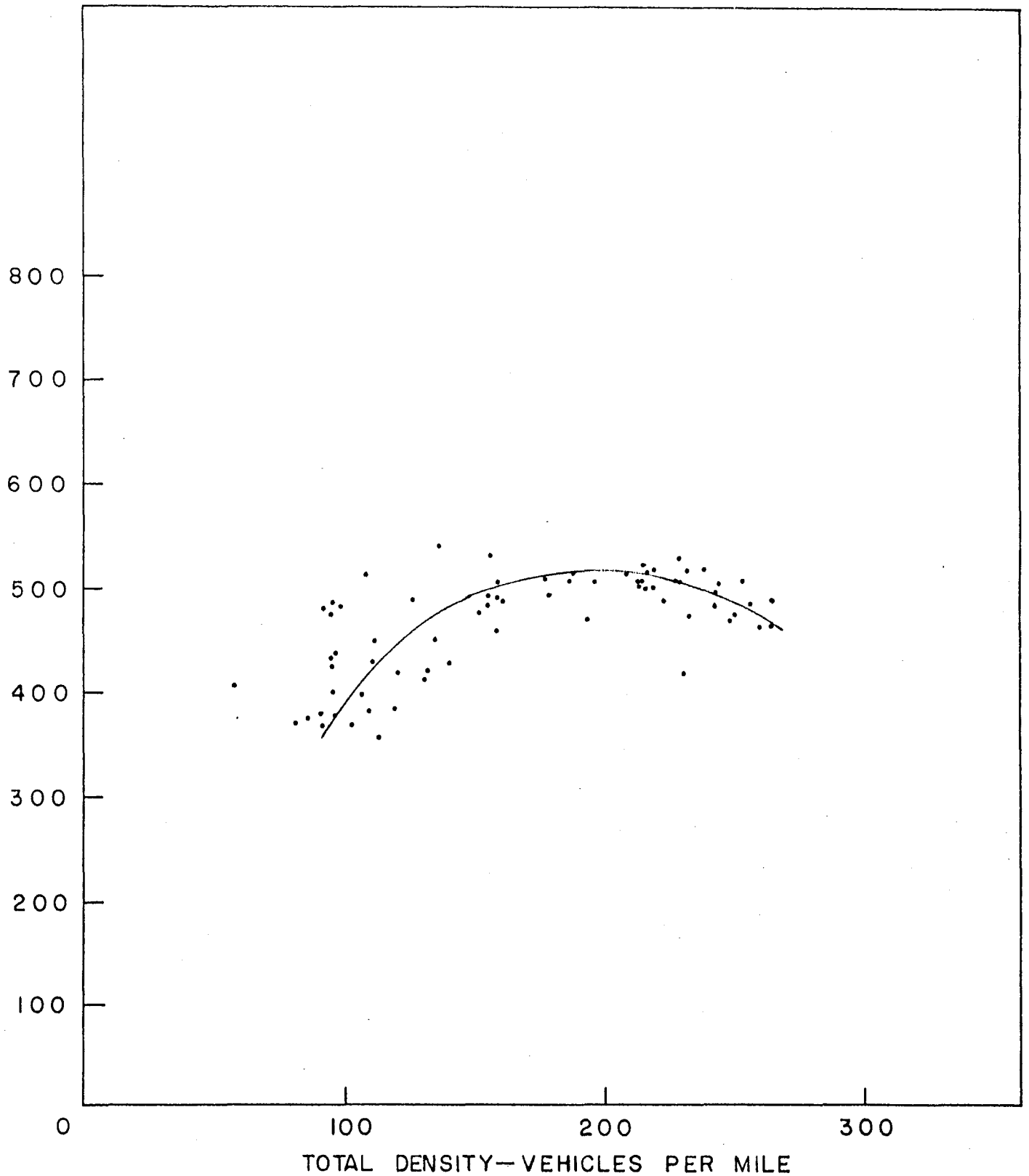


FIGURE 23 OUTPUT FLOW ON FREEWAY AT SOUTH HB&T RAILROAD PLUS LOMBARDY AND TELEPHONE EXIT RAMPS VERSUS DENSITY IN THE GRIGGS—SOUTH HB&T RAILROAD SUBSYSTEM

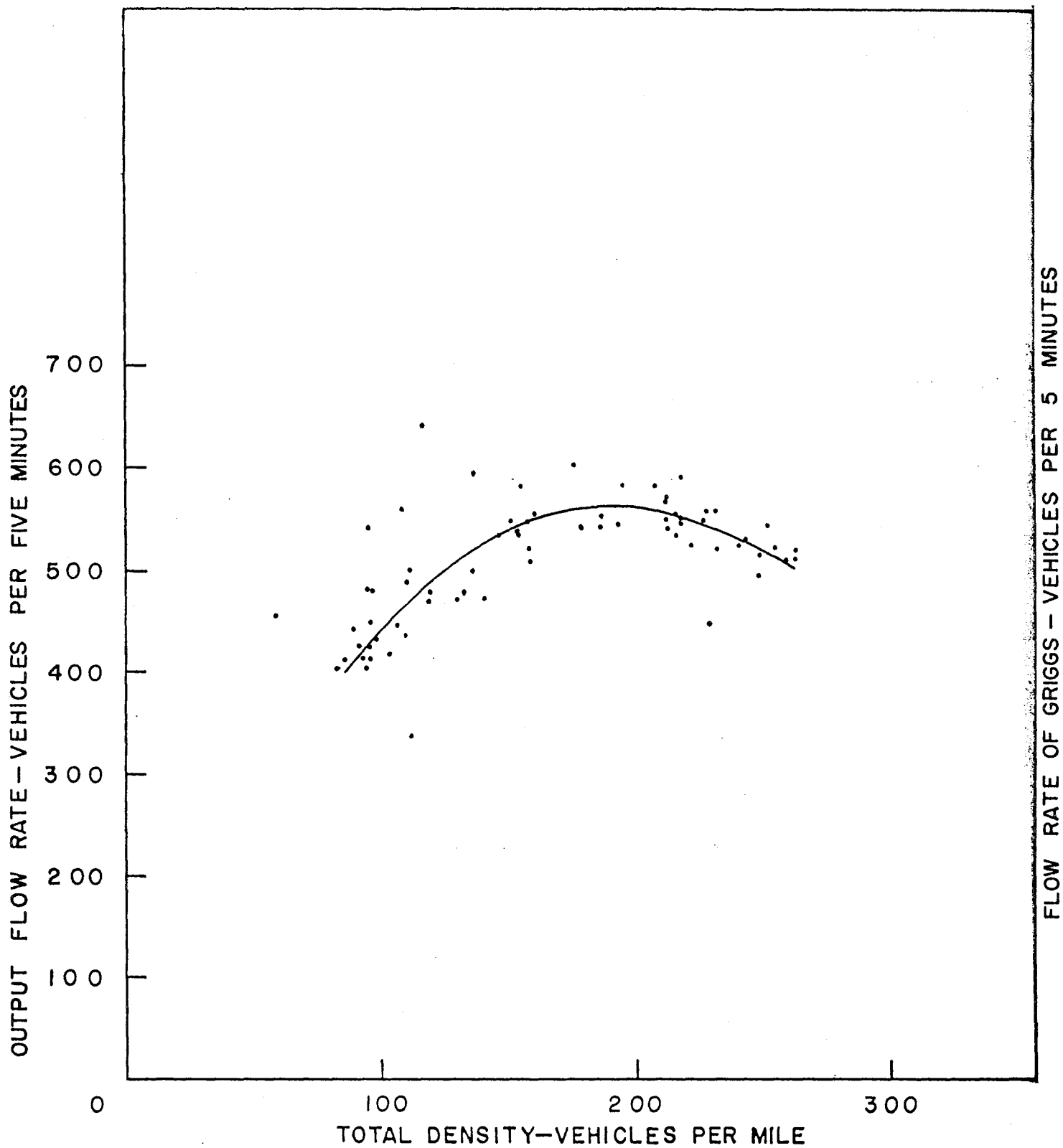
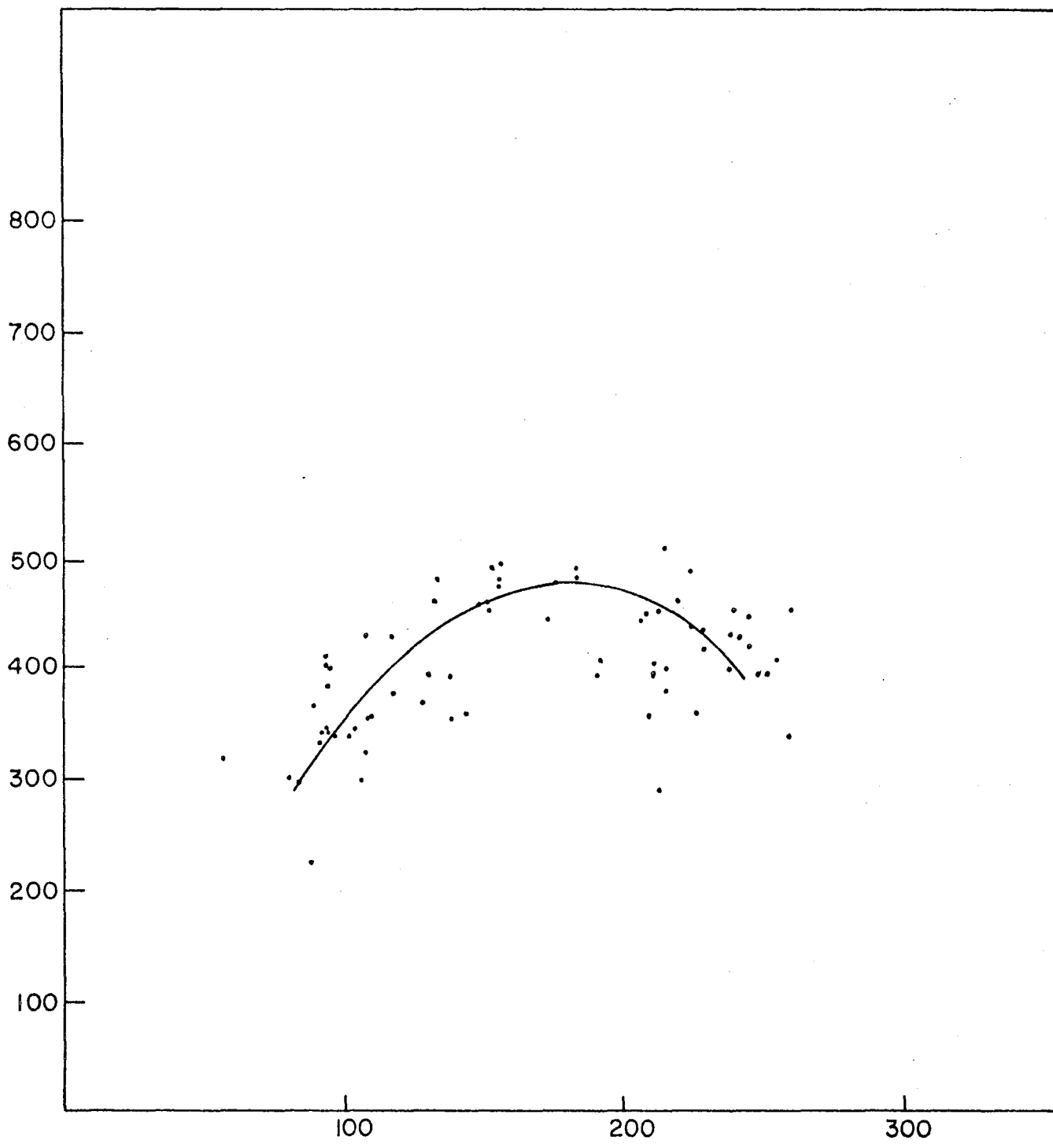


FIGURE 24 TOTAL OUTPUT FLOW VERSUS DENSITY-GRIGGS-SOUTH HB & T RAILROAD SUBSYSTEM



TOTAL DENSITY — VEHICLES PER MILES

FIGURE 25 FREEWAY FLOW AT GRIGGS ROAD VERSUS DENSITY IN GRIGGS - SOUTH HB & T RAILROAD SUB - SYSTEM

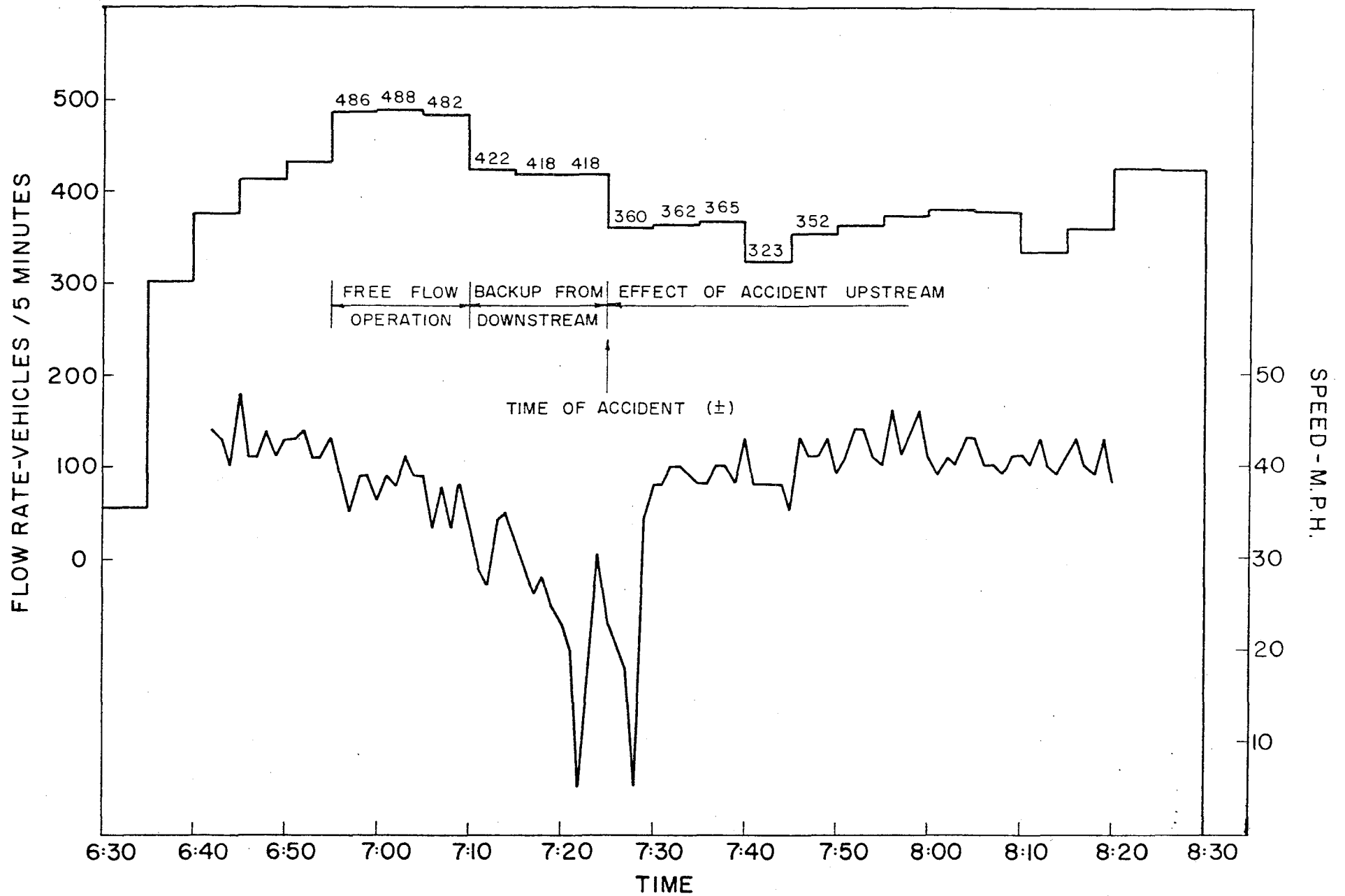


FIGURE 26 EFFECT OF AN UPSTREAM ACCIDENT ON THE FLOW RATES AND SPEEDS ON THE FREEWAY AT SOUTH HB & T RR OVERPASS

about 480 vehicles/5 minutes. At about 7:10 a queue from downstream reached the count location and reduced the flow there to about 420 vehicles/5 minutes for the 7:10-7:25 a.m. time period.

Between 7:25 and 7:30 a.m. the flow at the count location decreased sharply to about 360 vehicles/5 minutes, and the speeds increased to between 35 and 40 mph. The count personnel hypothesized that an accident had occurred upstream of the count location since the queue from downstream appeared to have caused heavy congestion at this location and since normal flows seemed heavier and slower there. The low-flow, high-speed operation prevailed during the remainder of the peak period. The helicopter traffic reports of a local radio station verified the fact that an accident had indeed occurred upstream of the count location.

It was interesting to note that following the upstream accident the next three flows were 360, 362, and 365 vehicles/5 minutes. The consistency of these data suggest that in a freeway control system such counts could be used to determine the capacity flow rate at the location of an accident or similar occurrence, providing, of course, that electronic detectors were located properly. In fact, it seems probable that detection downstream of the accident would have yielded a quicker indication of the accident than would upstream detection, at least in this particular situation. Since the accident location was already congested at the time the accident occurred, a detection station upstream of it would probably have indicated an increased density or lane occupancy or lower speeds due to the accident but it would probably be difficult to definitely assess it as an accident or other temporary capacity reduction. However, when a location normally operating under congestion suddenly clears up, the probability of an upstream capacity reduction is great (especially if it is known that the upstream conditions are congested).

SPEED-FLOW CURVES

Speed-flow curves at several freeway locations can be useful in locating bottlenecks. While they do not lend themselves to relating traffic behavior at several points as well as chronological plots of flow and speed at each location, several speed-flow curves are presented here for completeness.

Figure 27 shows the summary speed-flow curves for 6 locations on inbound Gulf Freeway. The locations are at (1) Broadway, (2) Griggs Road (downgrade of overpass), (3) upstream of Wayside on ramp, (4) upstream of Telephone on ramp, (5) south HB&T RR (downgrade of overpass) and (6) upstream of Cullen entrance ramps. These curves were fitted by eye and the data and fitted curve for each location are shown in Appendix Figures D1-D6.

While the curves shown in Figure 27 do represent averages they can provide useful interpretations. For example, the curve for the Broadway location does not have a low-speed portion and the flows there do not exceed 400 vehicles per 5 minutes. The curves for Griggs, Wayside, and Telephone all have the low-speed portions indicating that each of these locations is a bottleneck or is upstream of a bottleneck. The curves for the south HB&T RR and Cullen locations do not extend into the low-speed range, indicating that these locations are downstream

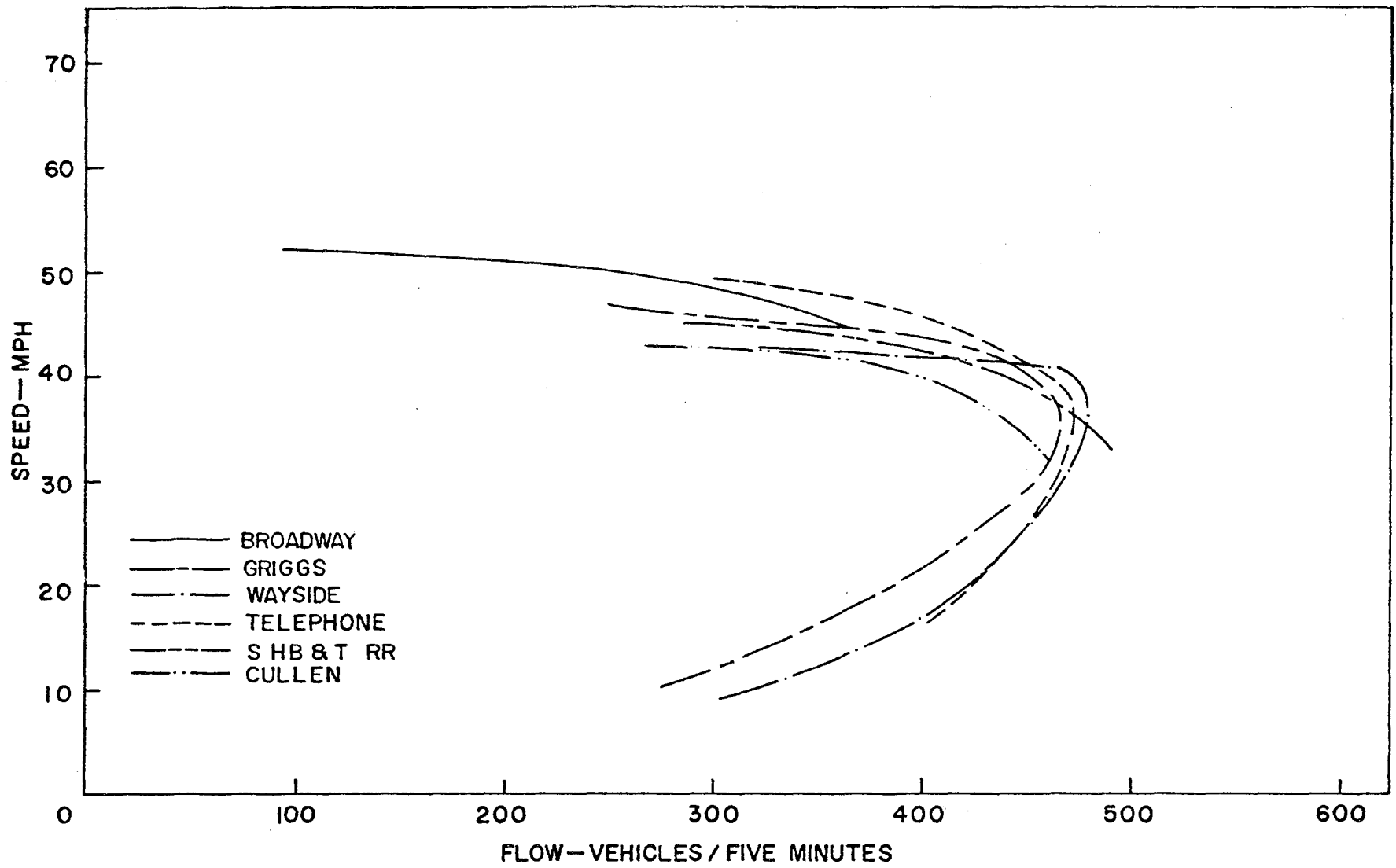


FIGURE 27 - SUMMARY SPEED-FLOW CURVES
GULF FREEWAY DATA

of the congested area. From these curves it can be seen that the entire area of congestion lies between the south HB&T RR overpass and Broadway.

Examination of Appendix Figures D1-D9, the original data points and fitted speed-flow curves, reveal that in each case there was a large variation in the data about the fitted curve. Thus for a given flow there is a range of speeds rather than a single speed value.

ESTIMATES OF DEMAND AT FREEWAY BOTTLENECKS

Using the data from the counts on the freeway at Broadway and on the entrance ramps combined with the origin-destination data, the 5-minute demand rates were estimated for the 6:40 - 8:25 a.m. time period at each of six bottlenecks. Graphs of the demand at four of these locations are shown in Figures 28-31.

The first bottleneck for which the demand is presented (Figure 28) is the merging bottleneck at the left-hand entrance at S.H. 35. The demand rate has a sharp peak, rising to a maximum of about 490 vehicles/5 minutes from 7:05 - 7:10 a.m. and dropping sharply from that time to the 7:35 - 7:40 period when the demand rate is about 280 vehicles per 5 minutes.

The demand at the Griggs Road overpass, where the freeway is taken over Griggs Road on a structure, is shown in Figure 29. This demand increases to a maximum of about 505 vehicles/5 minutes from 7:05 - 7:10 a.m. and after 7:20 a.m. drops off sharply to about 350-400 vehicles/5 minutes for the rest of the peak period.

Figure 30 shows the demand downstream of the Wayside entrance ramp, the second of two consecutive entrance ramps. The demand rate at this location increases to about 490-525 vehicles/5 minutes from 6:55-7:20 a.m. and then decreases sharply to about 400 vehicles/5 minutes until about 8:15 a.m.

The demand downstream of the Telephone Road entrance ramp (just upstream of the overpass at the south HB&T Railroad) is shown in Figure 31. The period of peak demand at this location is 6:55 - 7:30 a.m.

Accuracy of Demand Estimates. The demand rate at most freeway locations cannot be directly counted. When congestion is building up, part of the demand is being stored upstream of the location and when congestion dissipates the flow at a point can be higher than the demand (since some of the flow represents demand at an earlier time). Hence, during the peak period only counts over a long time period, which begins before congestion sets in and ends after congestion clears, represent true demand.

Since some of the origin-destination data had to be synthesized, a check

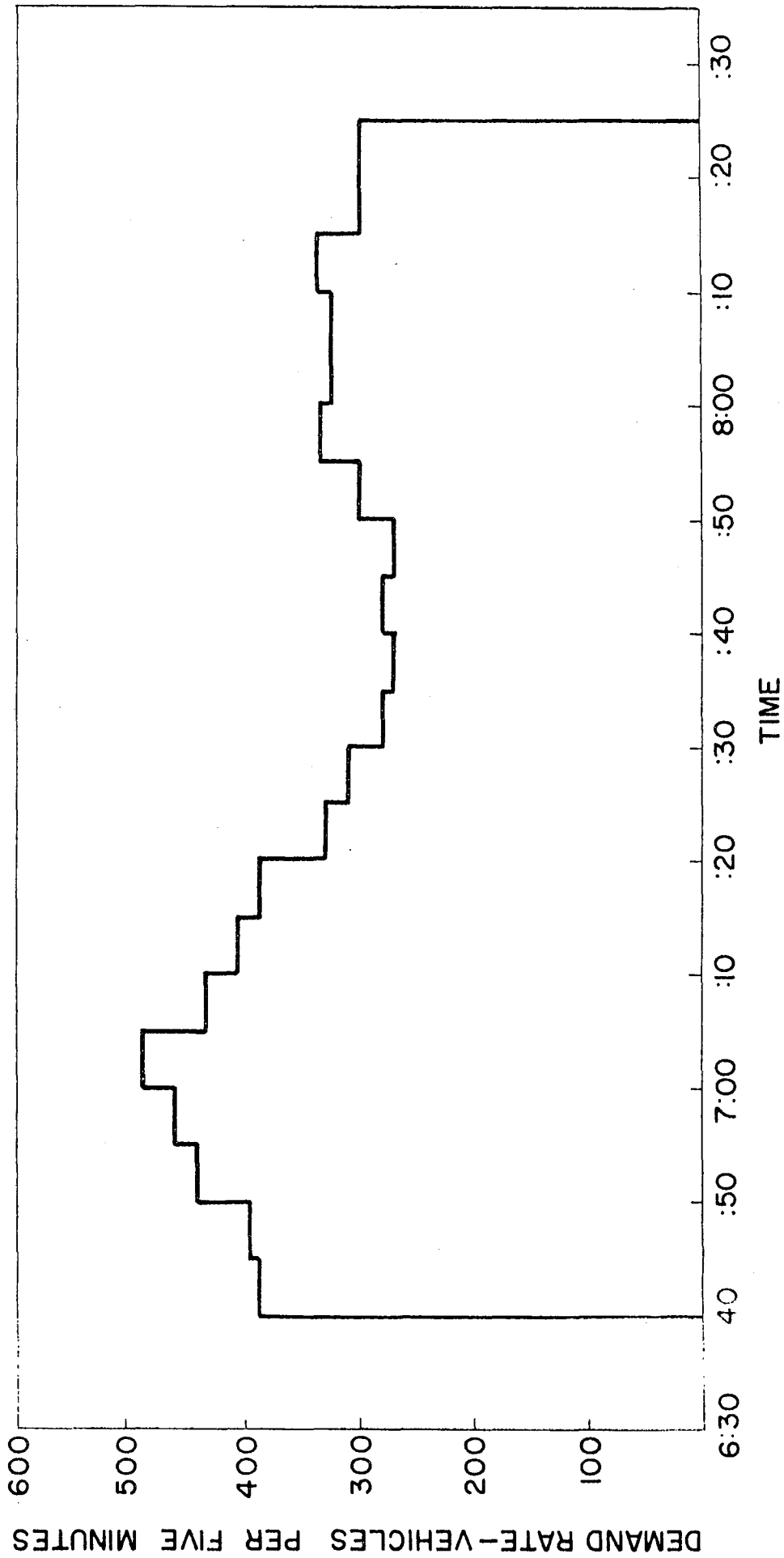


FIGURE 28 DEMAND DOWNSTREAM OF SH 35 ENTRANCE RAMP

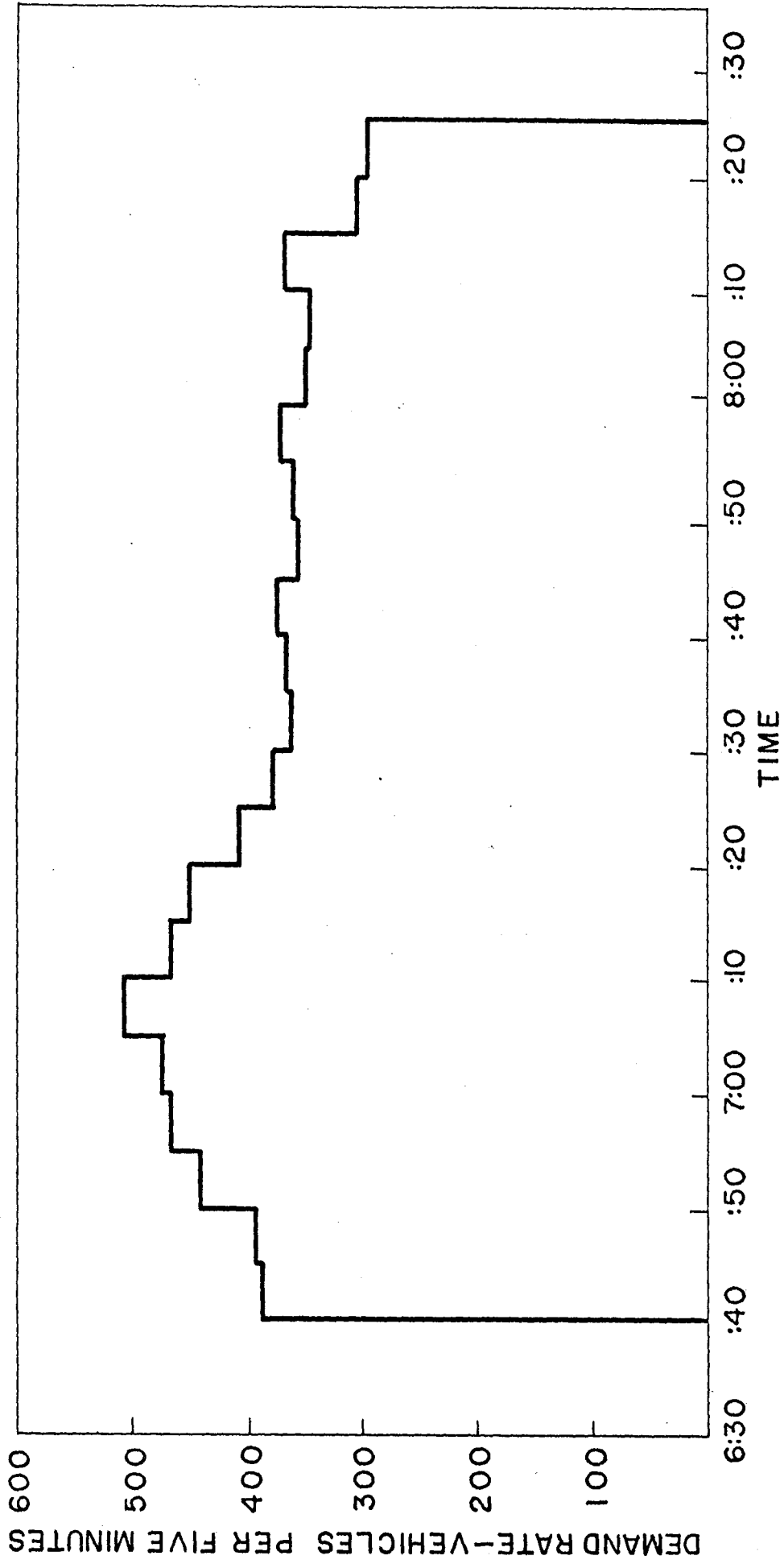


FIGURE 29 DEMAND AT THE GRIGGS OVERPASS

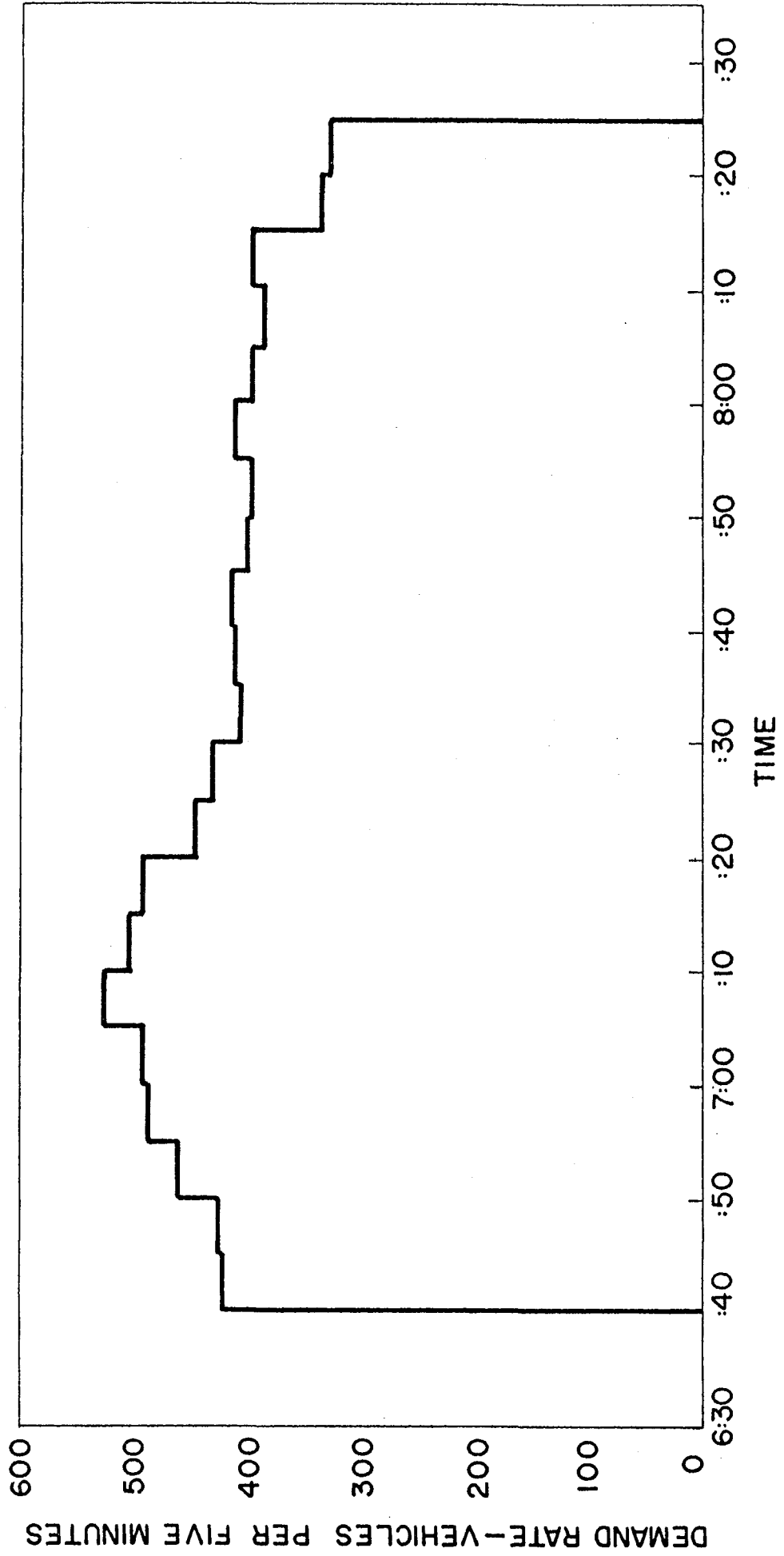


FIGURE 30 DEMAND DOWNSTREAM OF THE WAYSIDE ENTRANCE RAMP

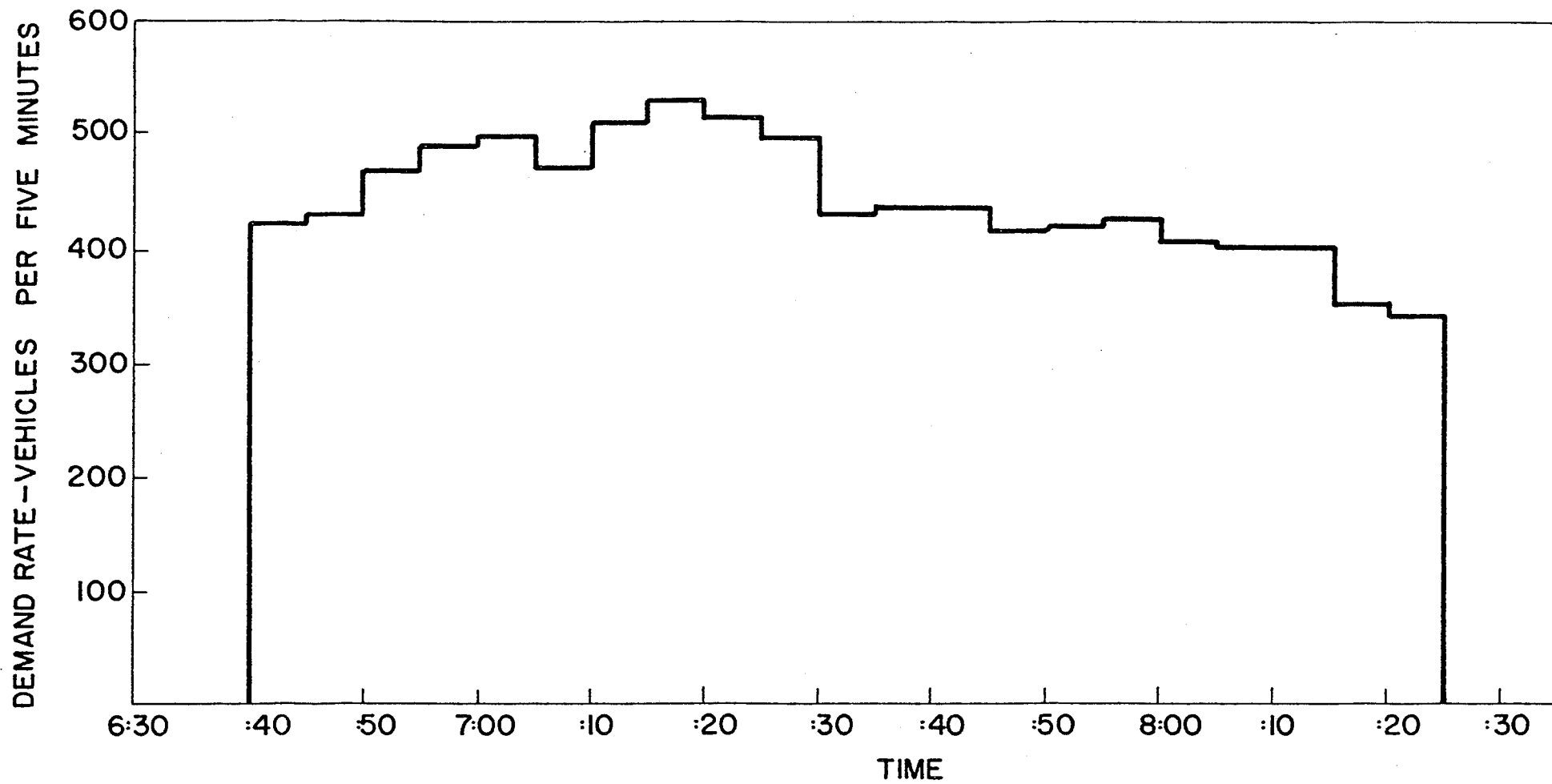


FIGURE 31 DEMAND DOWNSTREAM OF TELEPHONE ENTRANCE RAMP

was made on the demand at three locations. The time period from 7 - 8 a.m. was chosen because it encompasses the congested period. Table III contains a summary of this data. All of the errors were less than 1.0% for the hour period, indicating that the demand estimates are fairly accurate (at least for long periods).

TABLE 3
ACCURACY OF DEMAND ESTIMATES

<u>Location</u>	<u>Estimated</u>	<u>7 - 8 a.m. Demand</u>		
		<u>Actual*</u>	<u>Difference</u>	<u>Percent</u>
Griggs Overpass	4912	4875	- 37	- 0.8%
Upstream of Griggs Entrance Ramp	4365	4375	+ 10	+ 0.2%
Downstream of Telephone Entrance Ramp	5594	5650	+ 56	+ 1.0%

* See Flow Map - Figure 19

VI. CONTROL INTERPRETATIONS

The study technique using input-output counts for closed freeway sub-systems yields data for which control interpretations are quite natural. Since congestion occurs at a location on a freeway when the demand rate at the location exceeds the capacity there, a control system which could keep the flow at each bottleneck less than or equal to its capacity could prevent the development of congestion. An important question is by how much and for how long the demand exceeds the capacity at each bottleneck, i.e., how severe must the controls be to prevent congestion? Another important question is how much excess demand would have to be denied access to the freeway (stored on the ramps, frontage roads or streets or diverted) in order to prevent congestion.

Since the demand rates and capacity flow rates have been estimated for each of the four most critical bottlenecks on the inbound Gulf Freeway, it is not difficult to estimate by how much the demand exceeds the capacity at each of these locations by five-minute time periods.

The capacity estimates used in this analysis are as follows: S.H. 35 merge capacity 460 vehicles/5 minutes, Griggs overpass capacity 475 vehicles/5 minutes, downstream of the Wayside entrance ramp 485 vehicles/5 minutes, and downstream of Telephone entrance ramp 480 vehicles per 5 minutes.

Table 4 shows the amount by which the demand exceeds the capacity at each of these four most critical bottlenecks on the inbound Gulf Freeway in each five minute time period. For example, in the 7:05 - 10 a.m. time period at the Griggs Road overpass the demand exceeds the capacity by about 31 vehicles while the Wayside entrance ramp merging bottleneck is over capacity by about 42 vehicles. Since neither of the other bottlenecks is over capacity, there is a total of 73 vehicles of excess demand on the inbound Gulf Freeway in the 7:05 - 7:10 time period. The total amount of excess demand for the entire peak period is about 300 vehicles (293 in Table 4).

TABLE 4

AMOUNT OF EXCESS DEMAND AT THE FOUR CRITICAL BOTTLENECKS ON THE INBOUND GULF FREEWAY

Time Period	Bottleneck Location				Total
	S.H. 35 Merge	Griggs Overpass	Downstream of Wayside on Ramp	Downstream of Telephone on Ramp	
6:55-7:00 a.m.	1		1	10	12
7:00-7:05 a.m.	29		6	19	54
7:05-7:10 a.m.		31	42	0	73
7:10-7:15 a.m.			18	30	48
7:15-7:20 a.m.			6	48	54
7:20-7:25 a.m.				36	36
7:25-7:30 a.m.				16	16
Total for all periods					293 vehicles

Also of interest in a freeway control system is the number of vehicles that must be stored at each bottleneck (assuming that the control can be operated in such a manner as to store only the number of vehicles of excess demand)

in order to prevent the demand from exceeding the capacity, i.e., to prevent the development of congestion. During time periods in which the demand at a bottleneck exceeds its capacity, the control system would have to store vehicles (presumably on the entrance ramp, frontage road or nearby street). When the demand fell below the capacity the number of stored vehicles could be reduced; in each time period the reduction in the number of stored vehicles would equal the amount by which the demand was less than the capacity (assuming this number is less than the total number stored there).

Table 5 shows the number of vehicles required to be stored to prevent congestion on the inbound Gulf Freeway. For the S.H. 35 merge bottleneck, the required storage is 1 vehicle at 7:00 a.m. since the demand exceeded the capacity by 1 vehicle in the 6:55 - 7:00 a.m. in time period (see Table 4). In the 7:00 - 7:05 a.m. period, the demand exceeded the capacity by 29 vehicles (see Table 4) so at 7:05 a.m. 30 vehicles would have to be stored there in order to prevent the development of congestion. The demand from 7:05 - 7:10 a.m. was less than the capacity by 26 vehicles (demand equals 436 vehicles/5 minutes, capacity equals 460 vehicles/5 minutes) so the number of stored vehicles could be reduced by 26 in this time period, leaving 4 stored at 7:10 a.m. These four would be cleared before 7:15 a.m.

The maximum storage or maximum queue that would be formed (assuming that the length of queue did not alter the demand pattern) at each bottleneck (actually the queue would be formed at the entrance ramp just upstream of the bottleneck) can be seen in Table 5. Thus a maximum queue of about 30 vehicles would be expected at the S.H. 35 entrance ramp, about 31 at the Mossrose entrance ramp (just upstream of the Griggs overpass), about 73 at the Wayside entrance ramp, and about 150 at the Telephone entrance ramp.

This storage can be considered the excess number of vehicles at each bottleneck. The sum of the storage at all bottlenecks is the excess number of vehicles on the entire facility. From the last column in Table 5 it can be seen that this excess number on the inbound Gulf Freeway is about 171 vehicles and this occurs at about 7:20 a.m. This number is quite small when considering that, as a consequence of this maximum of 171 vehicles of over-capacity, about four miles of the freeway operates under congested conditions for about one hour during a normal inbound peak period.

Earlier studies (8) have shown that the highest density and lowest speeds during the inbound peak period on the Gulf Freeway occur in the area of the Reveille interchange where the S.H. 225 and S.H. 35 entrance ramps join the freeway. Congestion in this region lasts from about 7 - 8 a.m. and is most severe at about 7:30 a.m. Examination of the storage of vehicles required to prevent congestion at the S.H. 35 bottleneck (Table 5) indicates that, considering only the demand and capacity at this location, congestion should be clear by about 7:15 a.m. at this location. This indicates that most of the con-

TABLE 5

NUMBER OF VEHICLES REQUIRED
TO BE STORED TO PREVENT CONGESTION
ON THE INBOUND GULF FREEWAY

Time	Bottleneck Location				Total
	S.H. 35 Merge	Griggs Overpass	Downstream of Wayside on Ramp	Downstream of Telephone On Ramp	
6:55 a.m.	0		0	0	0
7:00 a.m.	1		1	10	12
7:05 a.m.	30	0	7	29	66
7:10 a.m.	4	31	49	20	104
7:15 a.m.	0	22	67	50	139
7:20 a.m.		0	73	98	171
7:25 a.m.			32	134	166
7:30 a.m.			0	150	150
7:35 a.m.				100	100
7:40 a.m.				55	55
7:45 a.m.				11	11
7:50 a.m.				0	0

gestion in this region is produced by a queue or shock wave on the freeway moving into this area from another bottleneck farther downstream. Examination of the storage at the Griggs overpass indicates that this bottleneck is probably not the most critical one since it should clear at 7:20 a.m. if a downstream interference would not prevent this.

Table 5 shows that most of the required storage is in the Wayside-Telephone area. Since the magnitude of this storage is so large in this area and since the entire freeway upstream of the Griggs overpass would clear by itself at about 7:20 a.m. (except for downstream interference), it follows that severe congestion in the Wayside-Telephone region backing over the Griggs overpass decreases the capacity there (shown earlier, see Figure 14). Thus the 171 vehicles of excess demand in the Wayside-Telephone area cause about 450-500 vehicles to be "stacked up" or stored on the freeway in between Griggs Road and Broadway as well as the congestion in the Wayside-Telephone area itself. This is a dramatic example of the diseconomy of allowing the excess demand to be stored on the freeway rather than at the entrance ramps on the frontage roads or streets.

USE OF DEMAND-CAPACITY ANALYSES TO DEVELOP A RAMP CONTROL PLAN

The first peak-period freeway traffic control study of the Houston Freeway Surveillance Project was an inbound control of five entrance ramps to the Gulf Freeway. The study was conducted from August 4-14, 1964.

The plan which was developed was a fixed-time control, that is to say that the controls were not traffic adjusted in any way. Historical traffic data were used to develop the plans.

The philosophy of the control was to try to prevent the development of congestion in the downstream portion of the system (in the Wayside-Telephone area) and hopefully eliminate the reduction in flow, which is normally caused by downstream congestion, at the Griggs overpass.

Because of considerations of the capacity on the frontage road, the decision was made to limit the control to the region from Wayside Drive into the C.B.D.

Essentially the technique which was used was (a) to estimate the demand upstream of each entrance ramp (b) to compare the demand to merging capacity to determine the allowable five-minute ramp volume and (c) assuming a metering rate each five minutes equal to the allowable ramp volume and knowing the historical demand, it was possible to estimate the queue that would be formed at the ramp. Extremely low metering rates and extremely large queues warranted closing the ramps.

The control plan which evolved from these considerations is outlined below:

Wayside entrance ramp closed from 7:00 - 7:25 a.m.

Telephone entrance ramp closed from 7:05 - 7:25 a.m.

Dumble entrance ramp metered at 10 veh/min from 7:05 - 7:45 a.m.

Cullen entrance ramp closed from 7:05 - 7:45 a.m.

VII. CONCLUSIONS

STUDY TECHNIQUE

The study technique using input-output counts on closed freeway sub-systems is an excellent method of quantifying the problem of congestion. The data also have a real application in "before and after" comparisons since total system travel time is one by-product.

When the counts at each input to the freeway are combined with origin-destination data it is possible to estimate the demand rate at each critical bottleneck. By comparing the demand rate to the capacity flow rate at a critical bottleneck, the duration and severity of control that would be required to prevent congestion there can be estimated as well as the number of vehicles that would have to be stored (queued) or diverted from the freeway there.

INBOUND GULF FREEWAY STUDIES

There are four critical bottlenecks on the inbound Gulf Freeway. They are (1) the S.H. 35 merge, (2) the Griggs Road overpass, (3) the area of the Griggs and Wayside entrance ramps and (4) the area of the Telephone Road entrance ramp and south HB&T Railroad overpass.

The freeway from Broadway to Griggs Road should be clear of congestion by about 7:20 a.m. Most of the congestion in this area after 7:20 a.m. is caused by the backup of congestion from the two downstream bottleneck areas. The most severe congestion in the Reveille interchange area occurs at about 7:30 a.m. and at that time the congestion is due entirely to the downstream bottlenecks.

Congestion at a freeway bottleneck can cause the flow rate there to decrease below its capacity level. It appears that time as well as the severity of the congestion plays a role in this decrease in flow. There

did not seem to be a well defined value of the "critical density".

Congestion at a freeway bottleneck can cause delays not only to vehicles which go through the bottleneck but also to some vehicles which exit upstream of the bottleneck.

The detections of accidents, disabled vehicles, etc. during peak period on freeway by freeway counts downstream of the impedement warrants further investigation.

REFERENCES

1. "Highway Capacity Manual," U.S. Department of Commerce, Bureau of Public Roads, 1950.
2. Edie, L. C. and Foote, R. S., "Traffic Flow in Tunnels," Proceedings of the Highway Research Board, pp. 334-344, 1958.
3. Edie, L. C. and Foote, R. S., "Effect of Shock Waves on Tunnel Traffic Flow," Proceedings of the Highway Research Board, pp. 492-505, 1960.
4. Wattleworth, J. A., "Bottleneck Throughput Study," presented to the Freeway Operations Committee of the Highway Research Board, 1963.
5. Wattleworth, J. A., "Peak-Period Control of a Freeway System - Some Theoretical Considerations," Doctoral Dissertation*, Northwestern University, 1963.
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7. Rothrock, C. A., and Keefer, L. E., "Measurement of Urban Traffic Congestion," Highway Research Board, Bulletin 156, pp. 1 - 13, 1957.
8. Drew, D. R., "A Study of Freeway Traffic Congestion," Doctoral Dissertation, Texas A&M University, 1964.
9. McCasland, W. R., "Traffic Characteristics of the Westbound Freeway Interchange Traffic of the Gulf Freeway," Texas Transportation Institute report to the Texas Highway Department, 1964.

* This same material also constitutes Report 9 of the Chicago Area Expressway Surveillance Project.

APPENDIX A

DECREASE IN OUTPUT OF EXIT RAMP

UPSTREAM OF A FREEWAY BOTTLENECK

The following example was conceived to demonstrate how the development of congestion at a bottleneck can decrease the output of upstream off ramps. Figure A1 shows a freeway with 3 on ramps and 3 off ramps.

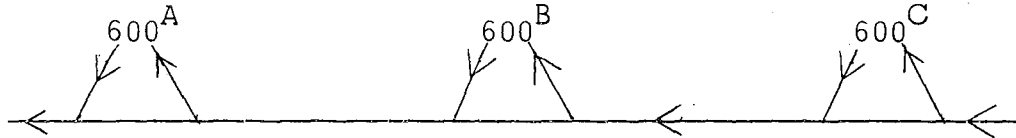


FIGURE A1

It is assumed that 1) the capacity of the freeway is 6000 vph at all locations, 2) the demand at each entrance ramp is 600 vph, 3) the demand at the upstream freeway input is 6000 vph and 4) 10% of the vehicles approaching each exit ramp leave via the ramp.

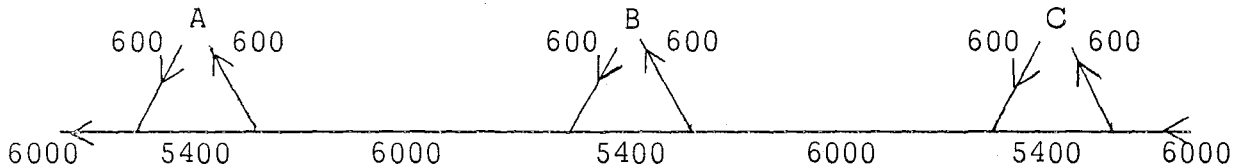


FIGURE A2

Figure A2 shows the flow on each ramp and freeway section in the system. Each exit ramp has a 600 vph output and the freeway output has a 6000 vph output, making the total output 7800 vph.

Now consider the same system with a 1200 vph demand at the A entrance ramp. Since the capacity of the ramp merge is 6000 vph and since the ramp demand is 1200 vph, the flow upstream of the entrance ramp will be 4800 vph. Since 10% of the vehicles upstream of exit A leave at A, 90% remain on the freeway between the two ramps at A. The 4800 vph in this area represent 90% of the flow upstream of exit ramp A so the flow upstream of exit A is 5333 vph ($4800/0.9$). Because 10% of these vehicles leave the freeway at exit A, the exit flow at A is 533 vph. The other flows are found in the

same manner and Figure A3 shows the flows at all points in the system.

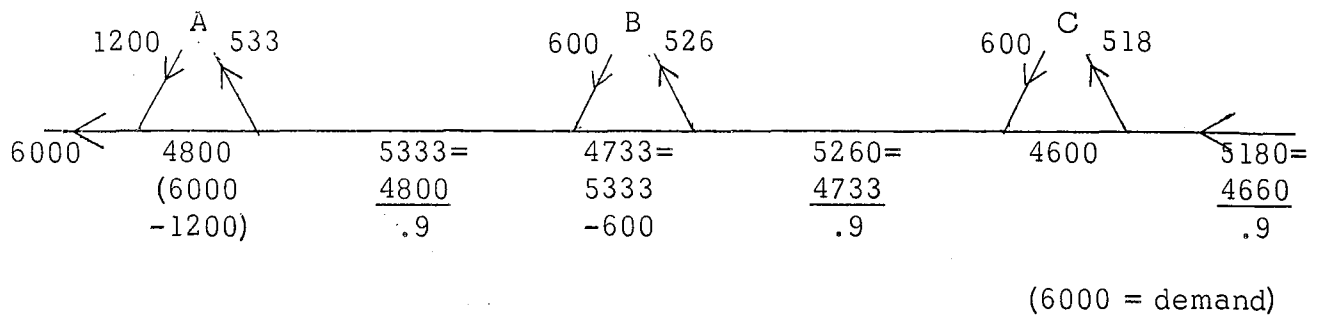


FIGURE A3

The off ramp outputs are as follows:

A	533
B	526
C	<u>518</u>
Total	1577

Thus the additional 600 vehicles at entrance ramp A decreased the system output by 233 vehicles per hour. A control technique which would prevent the storage of vehicles on the freeway (by limiting the entrance volume at A to 600 vehicles) could increase the system output by 233 vehicles.

APPENDIX B

APPENDIX TABLE B1
 ORIGIN-DESTINATION TABLEAU - UP TO 7:30 AM
 Percent Exiting

Entrances

Exits

	S.H. 225 Off	S.H. 35 Off	Woodridge Off	Exit 8	Wayside Off	Telephone Off	Lombardy Off	Calhoun- Elgin Off	Cullen Off	Scott Off	Sampson Off	Pease Dist.	Calhoun Dist.
Frwy. at Broadway	7.2	5.7	7.3	2.1	10.5	3.6	0.6	---	---	not_calculated	---	---	---
Detroit Entrance	---	---	7.8	2.4	12.1	4.1	0.7	---	---	not_calculated	---	---	---
S.H. 225 Entrance	---	---	0.5	---	---	---	0.6	7.8	3.8	2.2	5.5	41.2	38.4
S.H. 35 Entrance	---	---	---	1.3	4.6	1.3	2.6	5.3	2.0	3.3	7.2	41.2	31.2
Woodridge Entrance	---	---	---	---	2.8	1.4	1.4	7.0	2.1	2.1	6.3	42.7	34.2
Moosrose Entrance	---	---	---	---	15.6	4.0	3.5	5.5	2.5	2.5	8.1	41.7	16.6
Griggs Entrance	---	---	---	---	---	0.6	0.0	7.5	2.5	0.0	10.6	47.7	31.1
Wayside Entrance	---	---	---	---	---	1.2	1.2	12.5	5.0	2.5	5.0	38.8	33.8
Telephone Entrance	---	---	---	---	---	---	---	8.4	1.2	2.4	4.8	54.3	28.9
Dumble Entrance	---	---	---	---	---	---	---	---	2.0	0.0	12.2	38.8	47.0

APPENDIX TABLE B2
ORIGIN-DESTINATION TABLEAU - 7:30-8:00 AM

Percent Exiting

<u>Entrances</u>	<u>Exits</u>												
	S.H. 225 Off	S.H. 35 Off	Woodridge Off	Exit 8	Wayside Off	Telephone Off	Lombardy Off	Calhoun- Elgin Off	Cullen Off	Scott Off	Sampson Off	Pease Dist.	Calhoun Dist.
Frwy. at Broadway	7.2	5.7	7.3	2.1	10.5	3.6	0.6	---	not calculated	---	---	---	---
Detroit Entrance	---	---	7.8	2.4	12.1	4.1	0.7	---	not calculated	---	---	---	---
S.H. 225 Entrance	---	---	---	---	4.4	0.9	2.6	7.0	7.9	1.8	3.5	39.5	32.4
S.H. 35 Entrance	---	---	---	1.3	5.0	2.9	6.2	7.9	3.3	2.9	5.4	35.0	30.0
Woodridge Entrance	---	---	---	---	9.4	1.2	6.4	9.9	5.3	4.1	5.8	31.0	26.9
Mossrose Entrance	---	---	---	---	27.6	5.3	7.1	8.0	4.4	0.9	4.9	22.2	19.6
Griggs Entrance	---	---	---	---	---	2.4	5.8	7.7	2.4	4.8	11.1	41.6	24.2
Wayside Entrance	---	---	---	---	---	---	---	13.8	5.0	1.2	6.3	37.5	36.2
Telephone Entrance	---	---	---	---	---	---	---	13.2	4.8	3.6	4.8	36.2	37.4
Dumble Entrance	---	---	---	---	---	---	---	---	1.5	---	2.9	55.9	39.7

APPENDIX TABLE B3

ORIGIN-DESTINATION TABLEAU - 8:00-8:30 AM

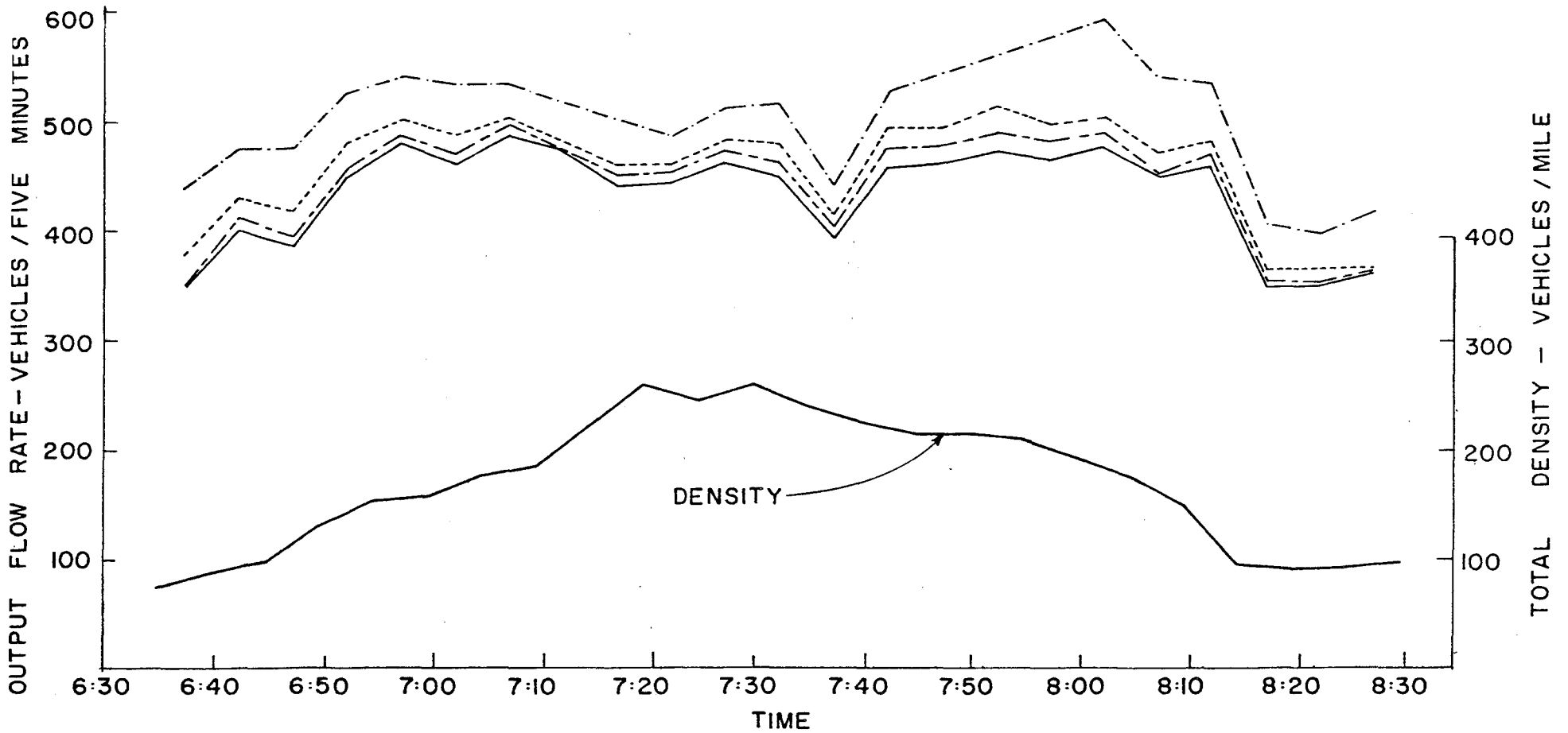
Percent Exiting

<u>Entrances</u>	<u>Exits</u>												
	S.H. 225 Off	S.H. 35 Off	Woodridge Off	Exit 8	Wayside Off	Telephone Off	Lombardy Off	Calhoun Elgin Off	Cullen Off	Scott Off	Sampson Off	Pease Dist.	Calhoun Dist.
Frwy. at Broadway	7.2	5.7	7.3	2.1	10.5	3.6	0.6	---	---	not calculated		---	---
Detroit Entrance	---	---	7.8	2.4	12.1	4.1	0.7	---	---	not calculated		---	---
S.H. 225 Entrance	---	---	---	0.9	4.6	0.9	0.9	9.3	5.6	3.7	7.4	34.3	32.4
S.H. 35 Entrance	---	---	---	1.9	9.8	4.4	2.0	6.4	5.9	2.0	5.9	34.3	27.4
Woodridge Entrance	---	---	---	---	18.3	1.4	1.4	7.0	8.5	0.0	5.6	31.0	26.8
Mossrose Entrance	---	---	---	---	32.1	8.9	3.6	8.9	3.6	1.8	5.4	23.2	12.5
Griggs Entrance	---	---	---	---	---	2.4	5.8	7.7	2.4	4.8	11.1	41.6	24.2
Wayside Entrance	---	---	---	---	---	---	---	13.8	5.0	1.2	6.3	37.5	36.2
Telephone Entrance	---	---	---	---	---	---	---	13.2	4.8	3.6	4.8	36.2	37.4
Dumble Entrance	---	---	---	---	---	---	---	---	1.5	0.0	2.9	55.9	39.7

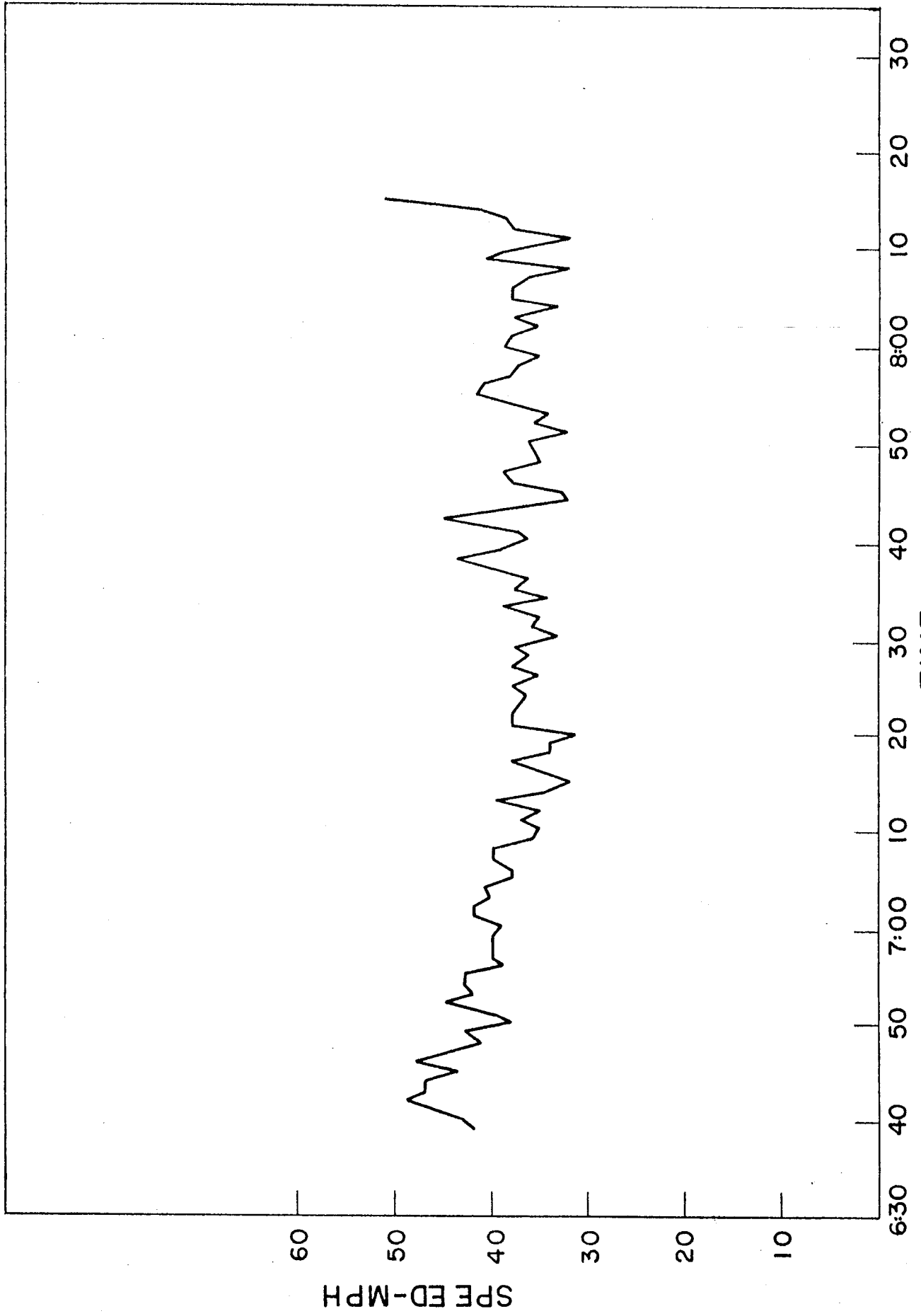
APPENDIX C

FLOW LEGEND

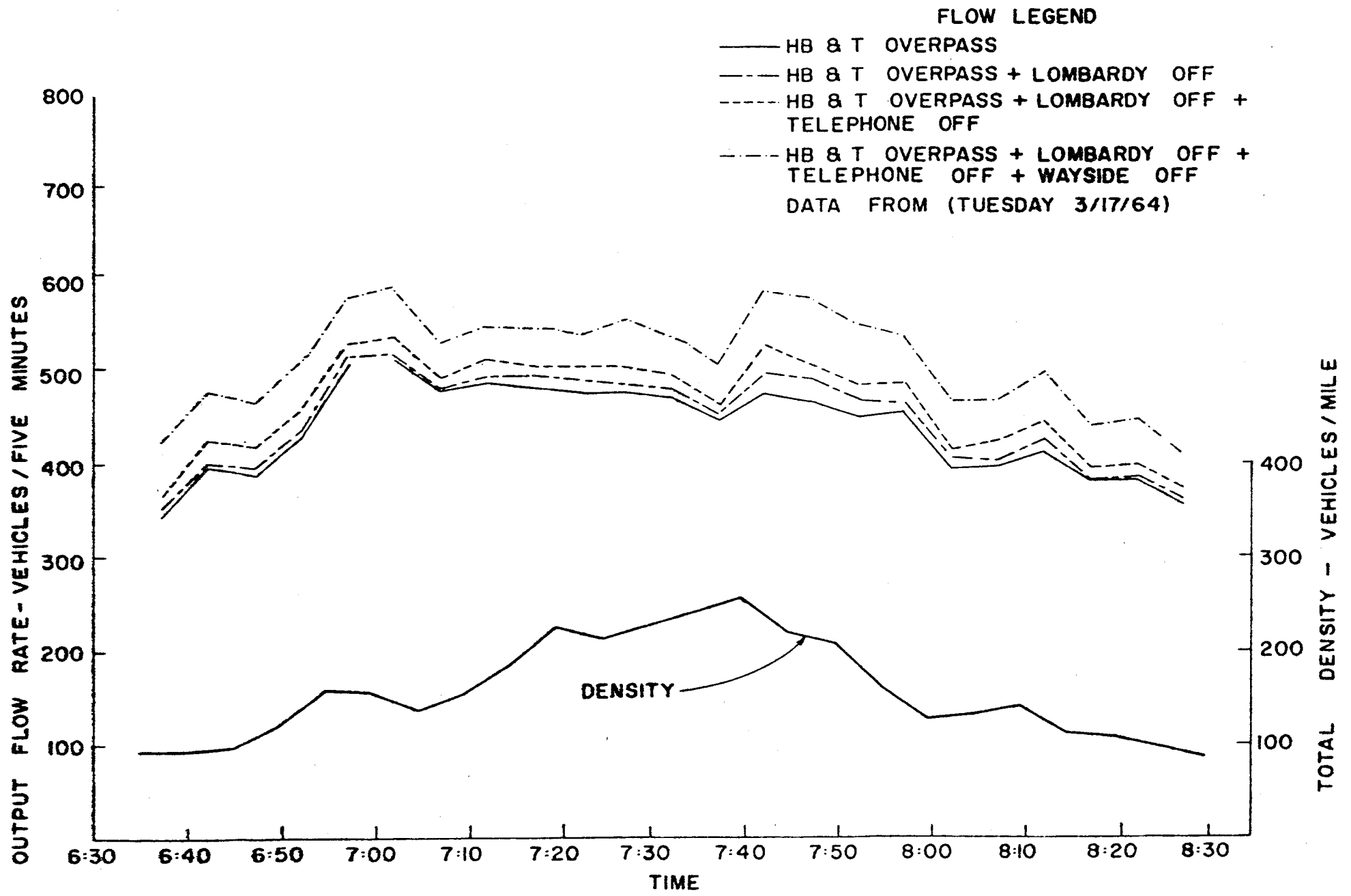
- HB & T OVERPASS
 - - - HB & T OVERPASS + LOMBARDY OFF
 - · - · HB & T OVERPASS + LOMBARDY OFF + TELEPHONE OFF
 - · - · HB & T OVERPASS + LOMBARDY OFF + TELEPHONE OFF + WAYSIDE OFF
- DATA FROM (MONDAY 3/16/64)



APPENDIX FIGURE CI-OUTPUT FLOW RATES AND TOTAL DENSITY - GRIGGS - SOUTH HB & T RR SUBSYSTEM

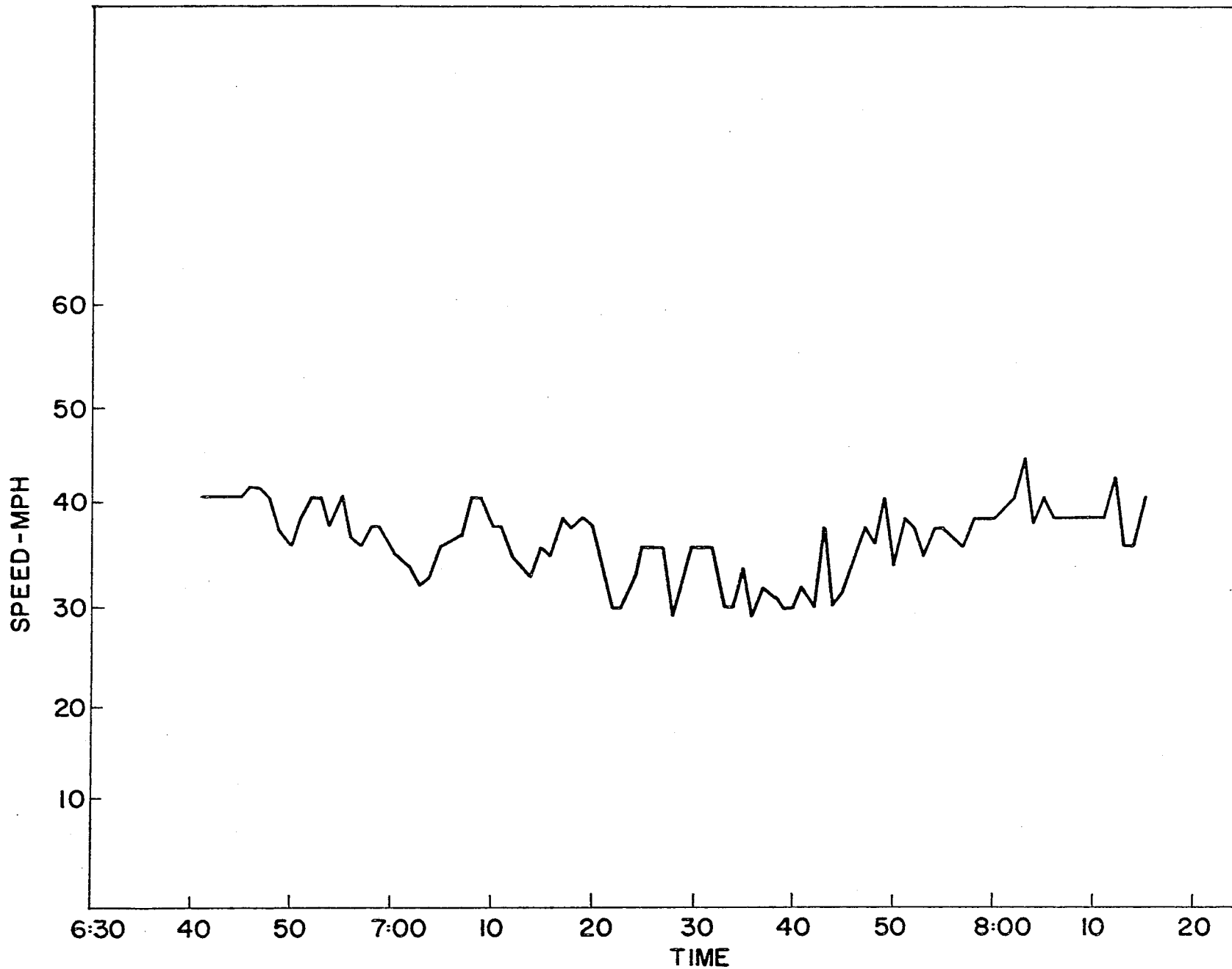


APPENDIX FIGURE C2 - AVERAGE SPEED AT SOUTH HR&T RAIL ROAD



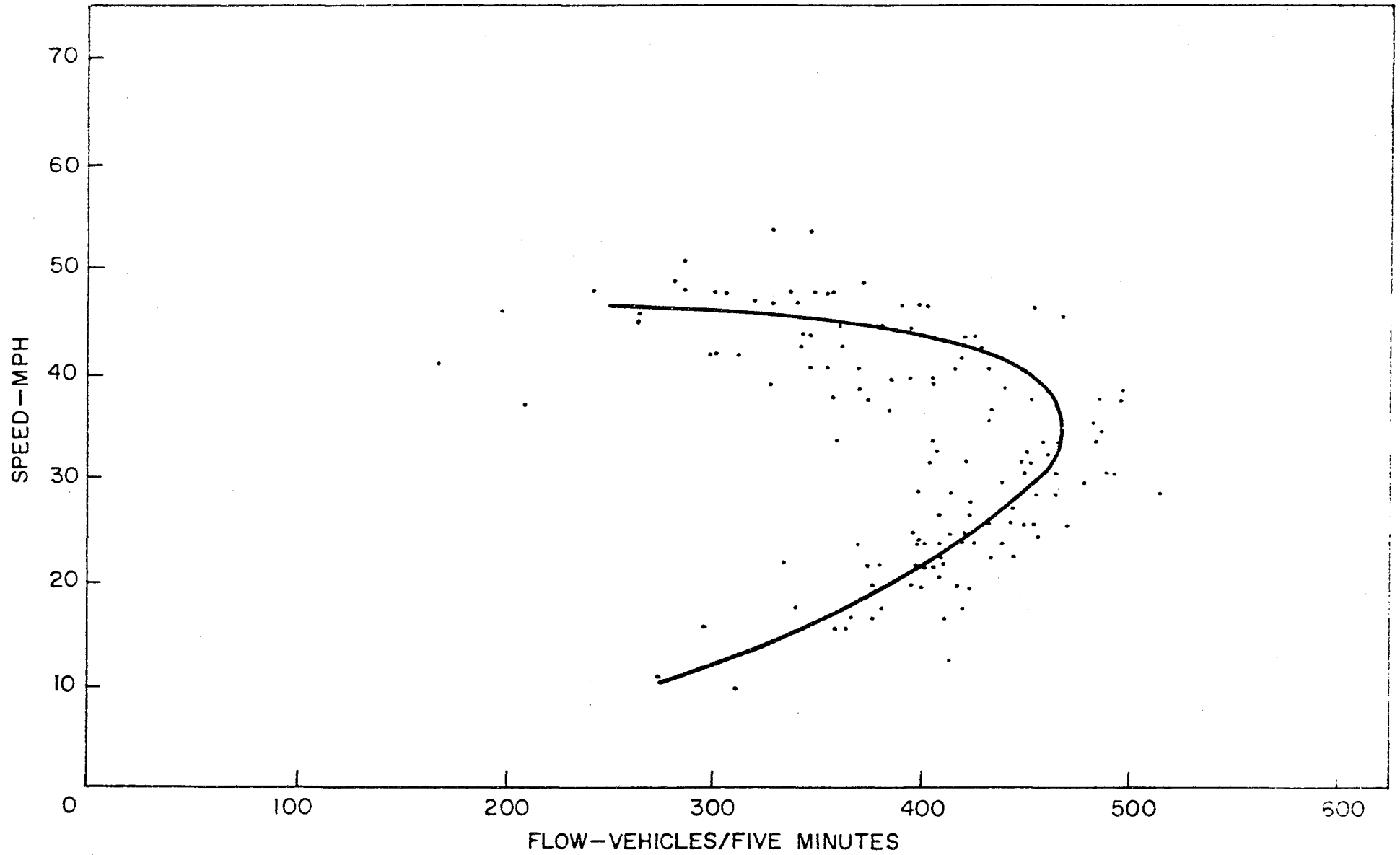
APPENDIX FIGURE C3-OUTPUT FLOW RATES AND TOTAL DENSITY - GRIGGS - SOUTH HB & T RR SUBSYSTEM

DENSITY - GRIGGS - SOUTH HB & T RR SUBSYSTEM

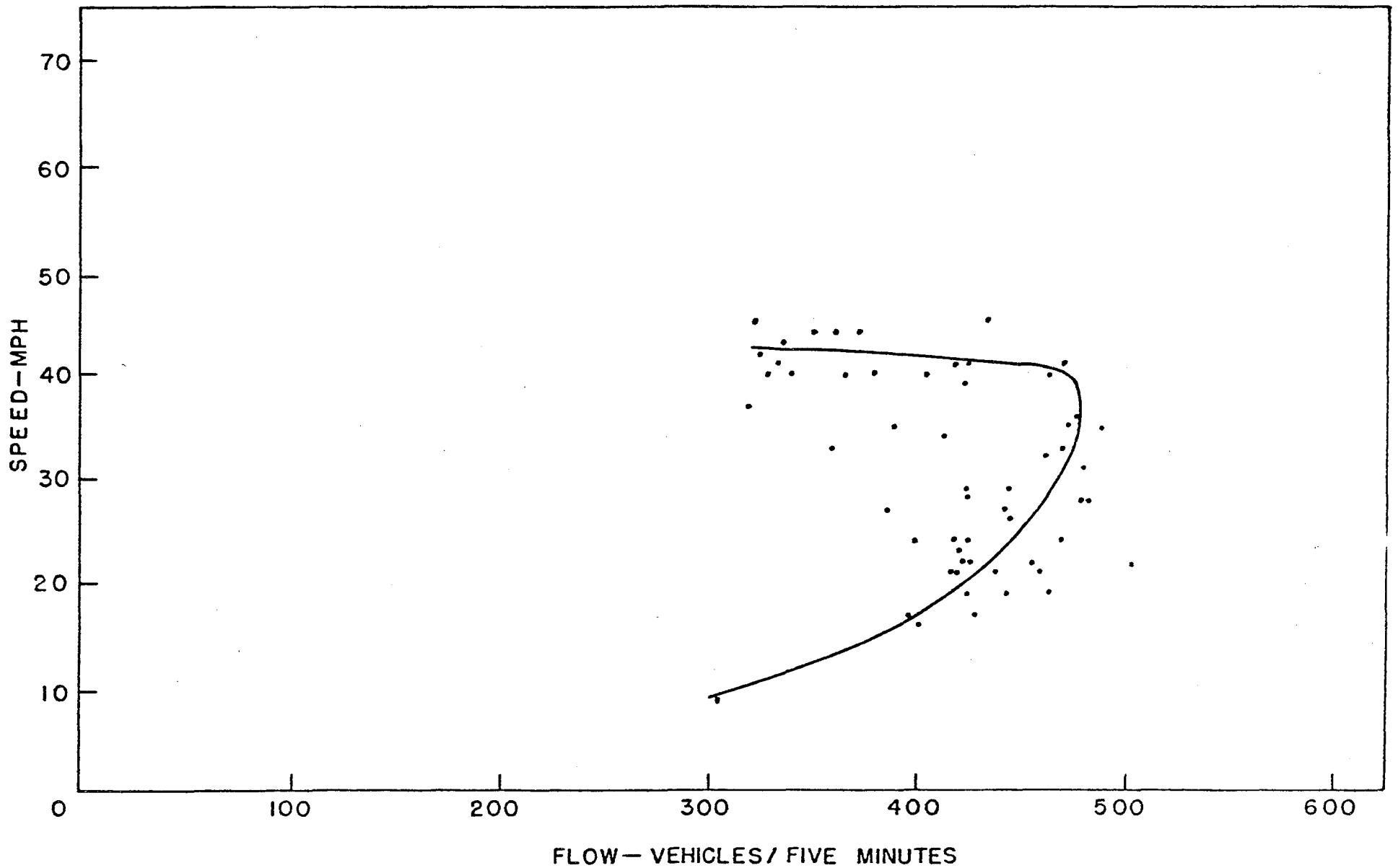


APPENDIX FIGURE C4 - AVERAGE SPEED AT SOUTH HB & T RAILROAD

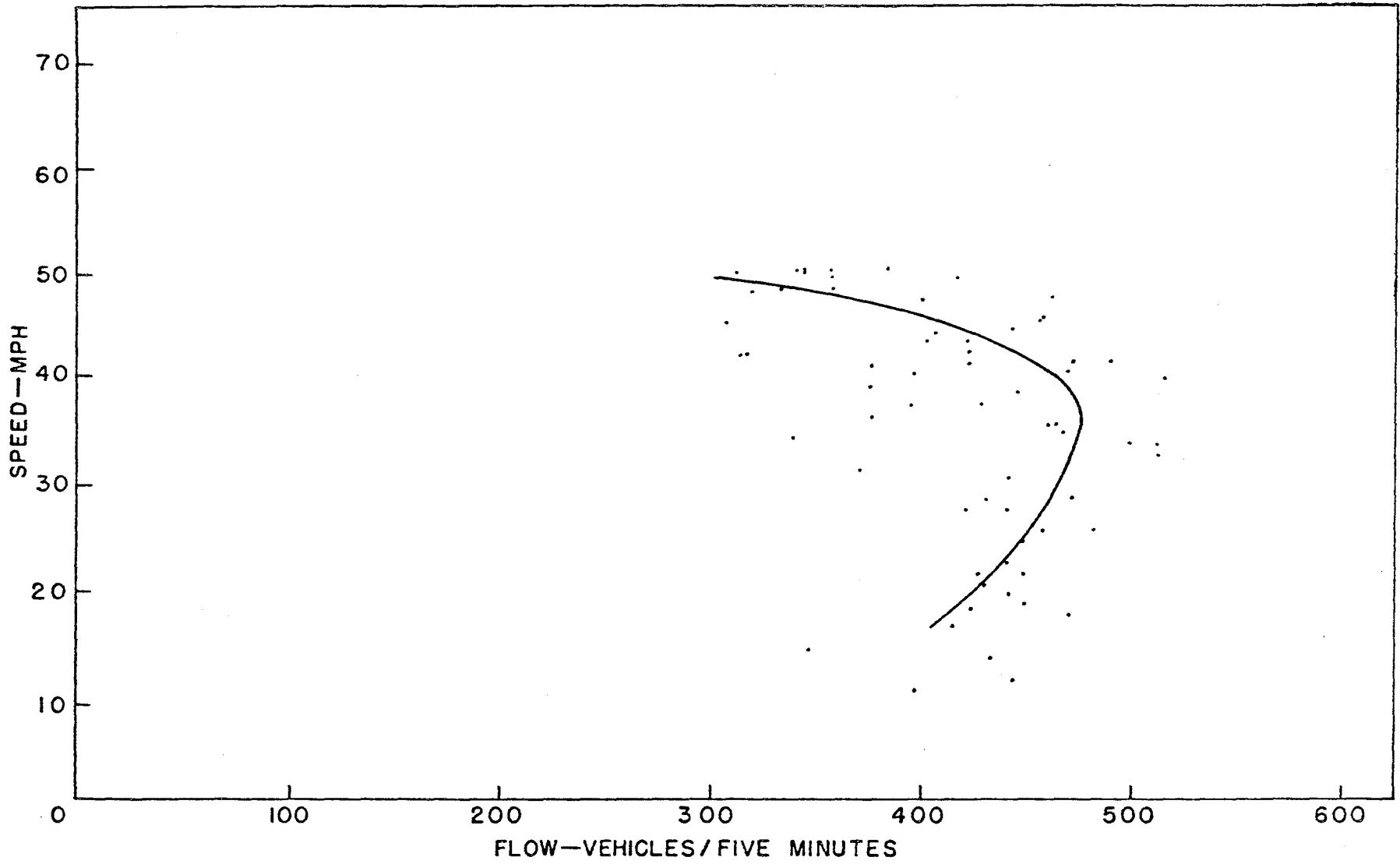
APPENDIX D



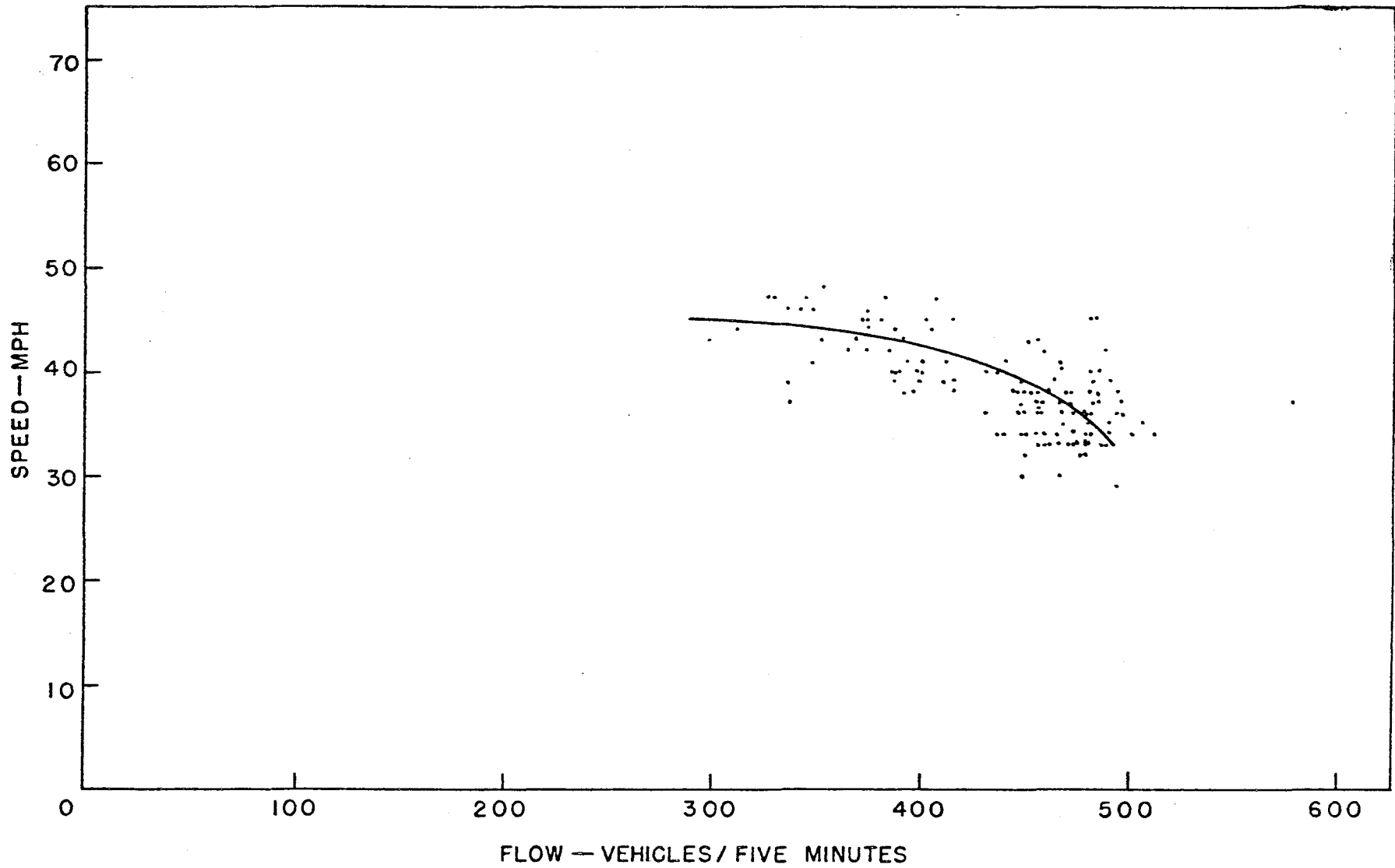
APPENDIX FIGURE D2—SPEED-FLOW DATA AT GRIGGS



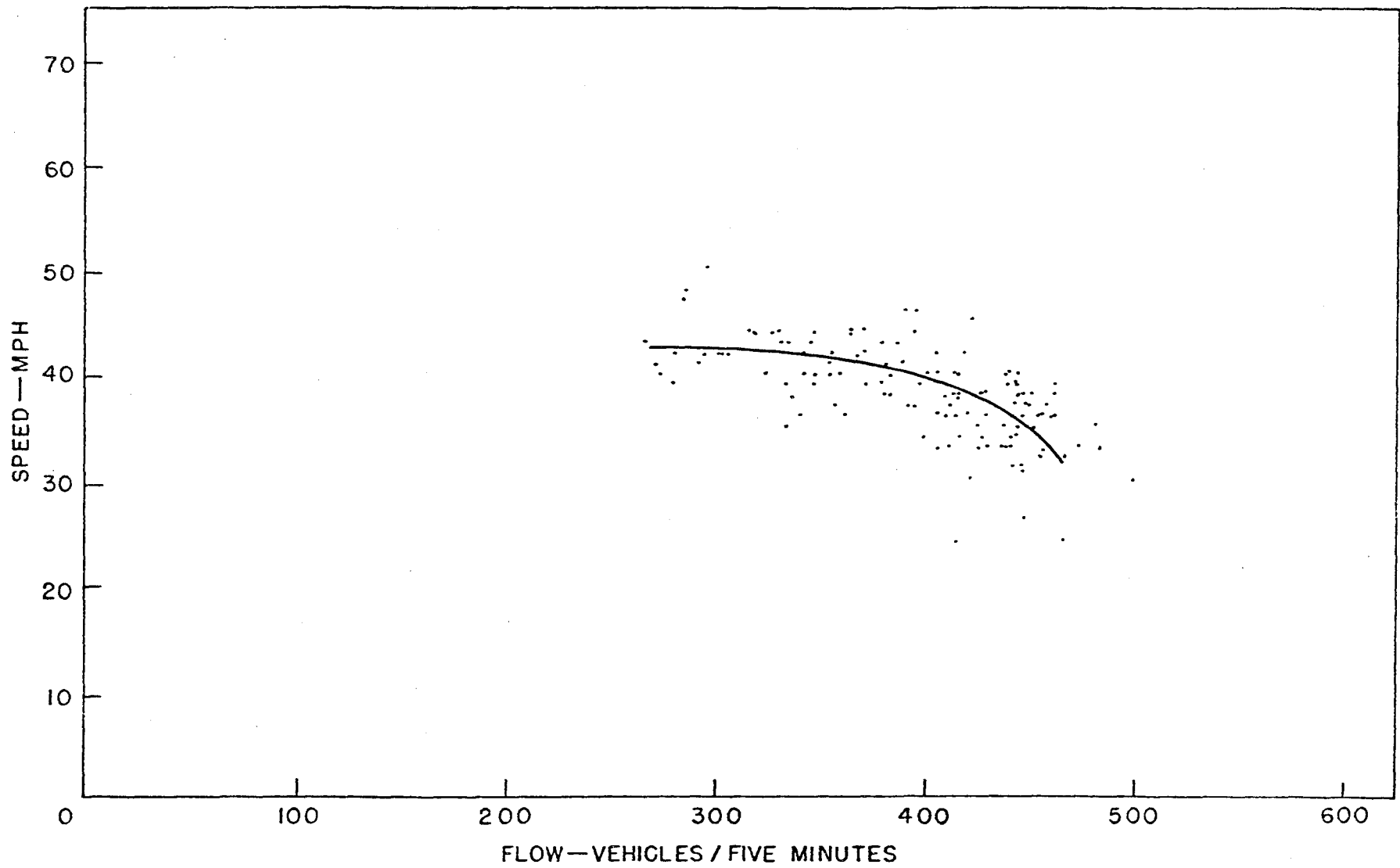
APPENDIX FIGURE D3-SPEED-FLOW DATA NEAR WAYSIDE



APPENDIX FIGURE D4—SPEED—FLOW DATA UPSTREAM
OF TELEPHONE ENTRANCE RAMP



APPENDIX FIGURE D5—SPEED—FLOW DATA AT
SOUTH HB & T OVERPASS (DOWNGRADE SIDE)



APPENDIX FIGURE D6—SPEED—FLOW DATA
UPSTREAM OF CULLEN ENTRANCE RAMP

PUBLICATIONS

Project 2-8-61-24 Freeway Surveillance and Control

1. Research Report 24-1, "Theoretical Approaches to the Study and Control of Freeway Congestion" by Donald R. Drew.
2. Research Report 24-2, "Optimum Distribution of Traffic Over a Capacitated Street Network" by Charles Pinnell.
3. Research Report 24-3, "Freeway Level of Service as Influenced by Volume Capacity Characteristics" by Donald R. Drew and Charles J. Keese.
4. Research Report 24-4, "Deterministic Aspects of Freeway Operations and Control" by Donald R. Drew.
5. Research Report 24-5, "Stochastic Considerations in Freeway Operations and Control" by Donald R. Drew.
6. Research Report 24-6, "Some Considerations of Vehicular Density on Urban Freeways" by John J. Haynes.
7. Research Report 24-7, "Traffic Characteristics of the Westbound Freeway Interchange Traffic of the Gulf Freeway" by William R. McCasland.
8. Research Report 24-8, "System Demand-Capacity Analysis on the Inbound Gulf Freeway" by Joseph A. Wattleworth.