Evaluation of Entrance Ramp Control on a Six-Mile Freeway Section

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•THE LEVEL of service on the inbound Gulf Freeway during the morning peak period has been well documented (1, 2, 3) as a result of research conducted by the Texas Transportation Institute in cooperation with the Texas Highway Department and the U. S. Bureau of Public Roads. In addition to the freeway studies, critical intersections on the arterial streets and freeway frontage road were studied and a capacity improvement was recommended at one very critical location (4). Several general techniques of studying freeway operations were also developed in order to complete the freeway analyses (5).

The operational studies on the inbound Gulf Freeway pointed to the need for some form of freeway ramp control. An initial control study (6) was conducted on a moderate scale in August 1964. The studies reported on here are an extension of this research effort.

Early operational studies (3) indicated that by controlling the inbound entrance ramps a significant improvement in the inbound freeway level of service could be achieved and the total travel time expended during the morning peak period could be greatly reduced. As a result of this research, a control study was initiated on five inbound freeway entrance ramps between Wayside Drive and Dowling Street (6). In this study four entrance ramps were closed and one entrance ramp was manually metered

control additional ramps between Wayside Drive and the Reveille Interchange to further improve freeway operations and to permit greater use of ramp metering and less use of complete ramp closure (by spreading the excess demand over more ramps). The present study was developed to fill this need and to allow the evaluation of a trial ramp control signal installation at the Dumble entrance ramp.

This report presents the development of, preparations for, and results of Inbound Gulf Freeway Ramp Control Study II which was conducted between January 26 and March 12, 1965. In addition, the traffic operation after the termination of the control study was also studied and these results are presented. Evaluation of the operation during the control period centered mainly on the freeway but also included the inbound frontage roads and the arterial street system.

BEFORE STUDIES

Freeway and Frontage Roads

Traffic studies were conducted on the inbound Gulf Freeway during 1964 and early 1965 in order to identify the critical bottleneck locations and to determine the duration and amount of excess demand at each of these locations. All studies were conducted during the 6:30 and 8:30 a. m. period between Broadway and Dowling streets.

Closed system input-output studies conducted during January, March, and April, 1964, provide much of the basic volume, density and system travel time data on which the before-and-after comparisons are based. Table 1 shows the dates of each input-output study which was used for the "before" data in the before-and-after comparisons. These studies have been reported previously (3) and were used in the development of the plans

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TABLE 1

1964 INPUT-OUTPUT STUDY DATA USED IN BEFORE-AND-AFTER COMPARISONS

System Boundaries	Data Used
Broadway-Griggs	Jan. 28-30, 1964
Griggs - S. HB&T RR	March 16, 17, 20, 1964
S. HB&T RR - Cullen	March 21, April 1, 2, 1964
Cullen - Scott	April 13, 17, 1964
Scott - Dowling	April 20, 23, 24, 1964

for the Inbound Gulf Freeway Ramp Control Study I (6) which was conducted in August 1964.

While the January 1964 input-output studies were being conducted, a specially equipped vehicle was used to obtain data on travel times for an individual vehicle. These data are presented in the form of travel time contours and are compared to similar data obtained during the control study reported herein.

Aerial photographs were also used in the collection of data during the summer of 1964 and during the January-April period of 1965. These data were used to supplement the density and system travel time data obtained from the input-output studies and to provide data on the operation of the frontage roads and arterial street intersections near the freeway. Such data from early 1965 were incomplete because the light was insufficient for good photography during the early part of the 7-8 a. m. peak period which was used in most analyses.

Arterial Streets

The term "Freeway Control" refers to the control of the input volumes to the freeway at the entrance ramps. Controls of this type increase traffic on the arterial street system, because of diversion from one entrance ramp to another, or to the street system for the entire trip. Also, the control system, if successful, will increase the output of the freeway so that exit ramp volumes may increase for short periods of time. The objective of this phase of the study was to determine the change in travel on the street system and to determine if traffic flow was impaired or penalized by the control system.

To determine the total effect of freeway control over the system of streets and freeways, the studies on all traveled ways had to be compatible, or comparable. However, input-output studies that describe so well the conditions on the freeway were not practical on the arterial streets. The numerous entrances and exits to a system of any length on arterial streets would require a very large number of observers. Aerial photography could provide the data if trees, buildings and shadows did not interfere with the line of sight.

A network of arterial streets essentially consists of sections of uncongested roadways and sections of congested roadways, even during peak traffic flows. The congested sections are the approaches to signalized intersections. A certain number of stopped vehicles is to be expected at almost any signalized intersection. Only when an approach becomes saturated, so that some vehicles are delayed for more than one cycle, can we say that the approach is congested. To estimate the effect of ramp closure on the arterial streets, approaches to many intersections on arterial streets considered to be located in the area influenced by the freeway were studied.

The procedure of study involved taking demand counts on the approaches from 6:30 a. m. to 8:30 a. m. for several days before the control study period. From the demand or input count and the output count on an approach to an intersection, the delay in vehicle minutes could be estimated, where "delay" is defined as the delay to vehicles not clearing the signal during the first green phase after arrival at the signal.

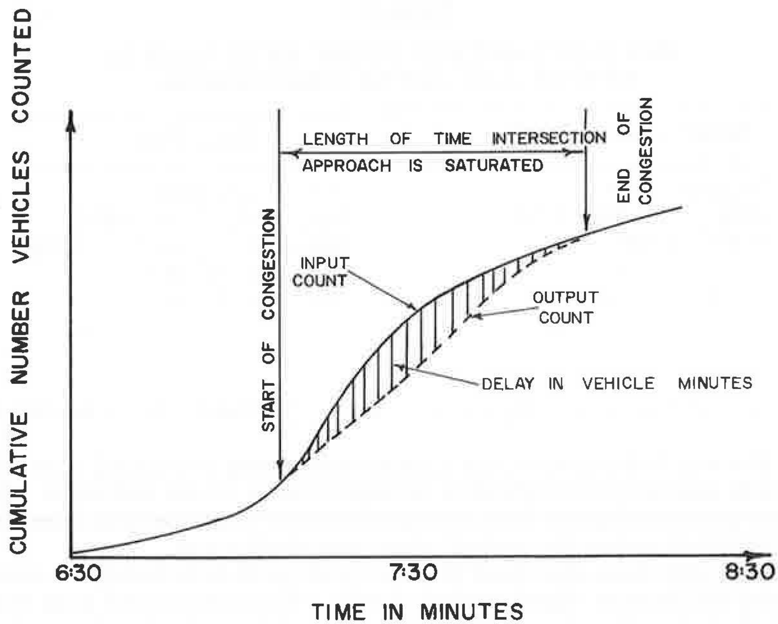

Figure 1. Capacity demand relationships.

This delay, or excess delay, can be illustrated by plotting the cumulative input and output counts as shown in Figure 1.

The shaded area represents the delay to vehicles, as defined above, in vehicle-

slightly over the time period. It is normally assumed that the capacity of an approach is constant, i. e., that this output count is a straight line. It was felt that accepting this as true would introduce only small errors in the estimates of delay. Furthermore, in view of the fact that the difference in delays before and during the study period were of primary interest, this assumption would probably introduce only negligible error into the estimated difference. The capacity of each approach under study was thus measured by taking output counts during saturated cycles and evaluating the average maximum output (capacity). Then only demand counts were required at the approaches under consideration.

This technique is not well refined and is not considered as a highly accurate estimate of the exact value of the delay, mainly because both the demand and the output are considered as continuous rather than discrete functions. However, any serious effect on the delay on an approach will certainly show up in such an analysis and it was thus considered adequate for the purposes of this study. In addition, travel time runs were made by individual vehicles to provide another means of determining the effect of the freeway control on traffic operations on the surface street system.

The closure of the Griggs Entrance Ramp for a 15- or 20-minute period during the peak hour was of major concern since 170 to 200 vehicles would be diverted to the city street system in an area that had several congested intersections. A license plate origin-destination survey of the ramp traffic was conducted to determine the alternate routes and ramps that this traffic would probably use to enter the freeway. The reassignment of this traffic was used to determine the time the Griggs Ramp should be open and the metering rates for the downstream entrance ramps.

DEVELOPMENT OF CONTROL PLANS

Philosophy of the Controls

The philosophy of Control Study II was essentially the same as that of Control Study I (6), namely that the demand be kept less than or equal to the capacity at each bottleneck. Demand and capacity both represent total directional flow rates (three lanes). In Control Study I the control area was limited to the region between Wayside Drive and Dowling Street, whereas in Control Study II all inbound entrance ramps between Broadway and Dowling were considered for control.

Upstream of each inbound entrance ramp (starting in the Broadway area and proceeding toward Dowling) the 5-minute demand rates were estimated (6, 7). For each entrance ramp, the difference between the estimated upstream demand and the estimated capacity provided the basis for metering or closing the ramp.

The capacity flow rates for the critical sections were based on counts obtained from March to August 1964. These capacities were somewhat higher than would have been obtained from the counts during January and Febraury 1964, since the January-February 1964 counts were found to be considerably lower than counts obtained at the same locations in the March-August 1964 period. The original control plan which was based on these higher capacities was tested during the first four days of the study (January 26-29, 1965). In this period the improvement in the freeway level of service was not as great as was anticipated so the controls were made slightly more restrictive at the beginning of the second week to compensate for the possible overestimation of capacities. Most of the discussions in this report refer to the revised control plan, since this was in effect much longer than the original plan.

Location and Severity of Controls

The demand estimates and various other studies showed that no controls were required at the Detroit Street entrance ramp or at any entrances upstream of this location. The congestion normally does not back upstream to the Broadway entrance ramp and the demand was found to be less than the capacity at the Detroit entrance ramp throughout the entire peak period. Similar considerations also indicated that control of the Scott entrance ramp was unnecessary.

Control was considered at each entrance ramp from S. H. 225 to Cullen Street, as shown in Figure 2. A discussion of the considerations leading to the final control plan at each ramp follows.

S. H. 225 Entrance Ramp.—This entrance ramp is a directional turning roadway which accommodates the right-turning vehicles from the southbound S. H. 225 (La Porte Freeway) to the inbound Gulf Freeway.

Some merging problems were anticipated at this location but the metering of this high-volume ramp would probably have created a queue which almost certainly would have backed onto the La Porte Freeway, blocking one of its two southbound lanes. Even though the volumes on the La Porte Freeway are less than the capacity of one lane, it was decided that the possible benefits to the Gulf Freeway traffic of metering this ramp did not outweigh the possible adverse effects (especially the accident hazards) to the La Porte Freeway traffic.

From a design standpoint the S. H. 225 entrance ramp is one of the best entrance ramps on the inbound Gulf Freeway. However, under normal operating conditions on the Gulf Freeway, many vehicles bypass the S. H. 225 entrance ramp and enter at Woodridge or Mossrose. By doing this, they miss a great deal of freeway congestion but tend to compound the problem by entering downstream at more critical locations. For this reason, it was deemed advisable to leave the S. H. 225 entrance ramp uncontrolled in order to encourage greater usage of it. Thus, for the purposes of Control Study II, the S. H. 225 ramp was not metered.

S. H. 35 Entrance Ramp.—The 5-minute demand rates upstream of the S. H. 35 entrance ramp were estimated based on count data from the input-output studies (Table 1). The allowable metering rate for each 5-minute period was calculated as the difference between the merging capacity and the upstream demand. A capacity of 475 vehicles per 5 minutes was used in the derivation of the initial control plan.

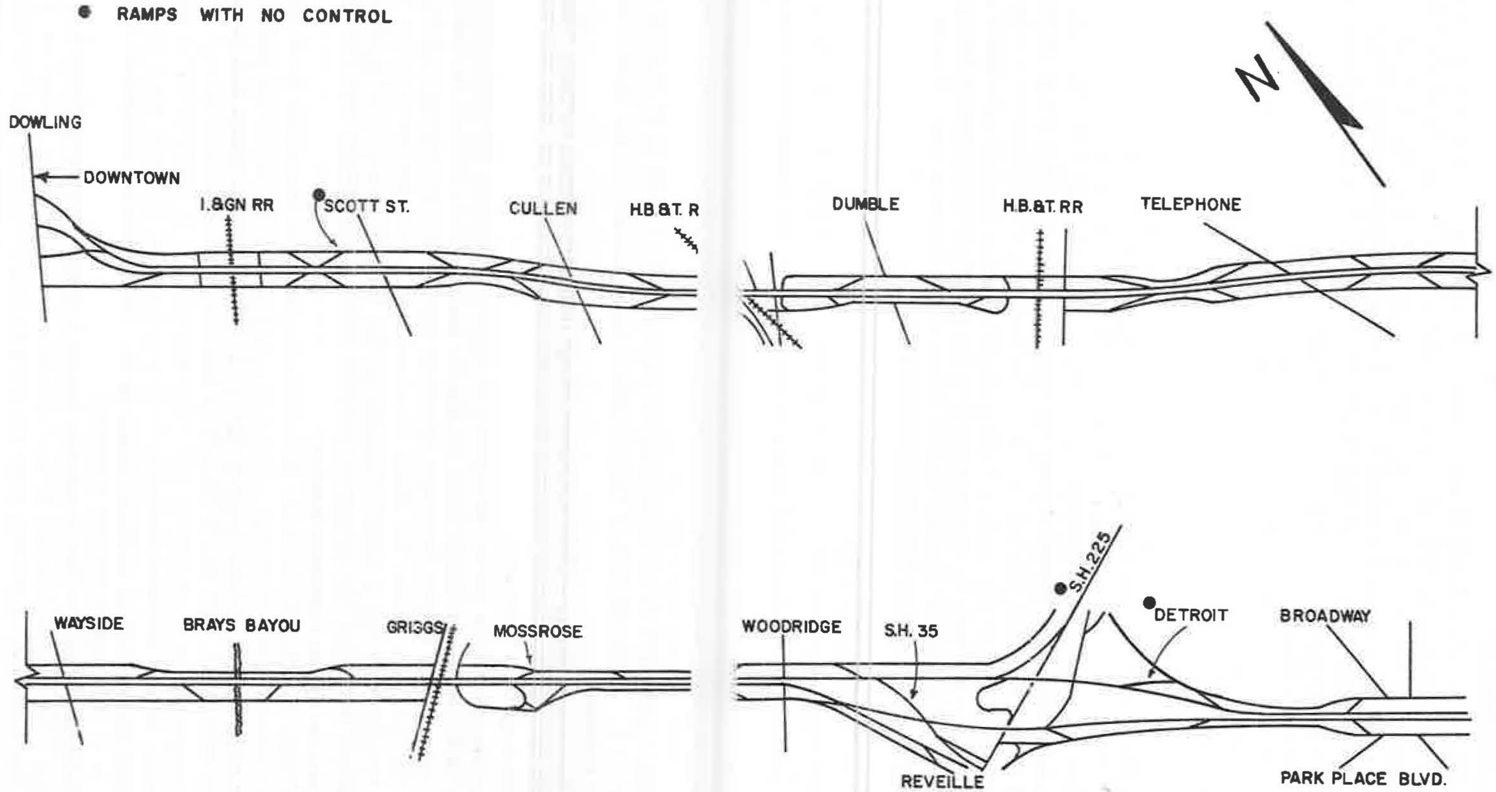

Figure 2. G[illegible] reeway study system.

The initial control plan was in effect during the first four days (January 26-29, 1965) of this study. The metering scheme used at the S. H. 35 entrance ramp during this period is shown below:

Time—a. m.	Metering Rate	
	Veh/5 min	1 Veh/x sec
6:55-7:00	75	1/4
7:00-7:05	50	1/6
7:00-7:15	75	1/4
7:15-7:30	100	1/3

The metering rates are shown in terms of both the number of vehicles per 5 minutes and the metering headway in seconds. In addition, the personnel operating the metering station were instructed to discontinue the metering if ramp vehicles had to stop before merging and queued in the merging area past a predetermined point (about 12-15 vehicles in the queue). When the queue cleared to another predetermined point (about 3 or 4 vehicles in the queue) the metering was resumed.

At the beginning of the second week of the control study, a slightly more restrictive control plan was initiated. This plan was in effect until the controls were terminated on March 12, 1965. The revised metering scheme at the S. H. 35 entrance ramp is shown below:

Time—a. m.	Metering Rate	
	Veh/5 min	1 Veh/x sec
6:55-7:20	50	1/6
7:20-7:45	75	1/4

The override for stopped vehicles in the merging area was also used in this scheme.

A queue of considerable length was anticipated at this location because of the high demand rate and the metering rates which were used. The storage of the vehicles in the queue was not considered critical because of the length of the ramp and the fact that up to 100 vehicles were queued at this ramp on some days when no controls were in effect.

Woodridge Entrance Ramp.—Under normal freeway operating conditions about 45 percent of the vehicles which enter the freeway at Woodridge did so after bypassing S. H. 225 entrance ramp. Thus, it was assumed that when the Woodridge entrance ramp was metered the vehicles would not bypass the uncontrolled S. H. 225 ramp to wait in the queue at Woodridge. It was anticipated, however, that about 20 percent of the vehicles which normally enter the freeway at Mossrose would choose to enter at Woodridge. Hence, the expected ramp demand at Woodridge during the control plan was 55 percent of the normal Woodridge demand plus 20 percent of the normal Mossrose demand.

The freeway demand was estimated upstream of the Woodridge entrance ramp and a merging capacity of 485 vehicles per 5 minutes was assumed in the calculation of the allowable metering rates. The controls at S. H. 35 were taken into consideration when the freeway demand was estimated. The metering scheme used during the first week of the controls at Woodridge was as follows:

Time—a. m.	Metering Rates	
	Veh/5 min	1 Veh/x Sec
6:55-7:10	30	1/10
7:10-7:20	50	1/6

During the remainder of the control study the rate of 50 vehicles per 5 minutes (1/6 seconds) was extended from 7:20 to 7:45 a. m. Otherwise, the control scheme at this location was unchanged.

An override to the metering, similar to that at the S. H. 35 ramp, was used to clear vehicles from the ramp which had to stop in the merging area to wait for an acceptable gap. When four ramp vehicles were stopped in the merging area the metering was temporarily halted until only one stopped vehicle remained. Then the metering was resumed. This same override to the metering was used at the Mossrose, Wayside and Telephone entrance ramps.

Mossrose Entrance Ramp.—The geometric features of the Mossrose entrance ramp make it one of the most critical merging areas on the inbound Gulf Freeway. The ramp itself is very short and provides a high-angle, direct entry onto the freeway. In addition, the ramp enters the freeway at the foot of the upgrade of the Griggs Road overpass structure on which a difference of elevation of about 30 feet occurs in a distance of about 1000 feet. Because of the upgrade, vehicles which have to stop or slow down drastically in the merging area have a severe adverse effect on the freeway traffic. Because of the high ramp volume (approximately 650 vehicles from 7 to 8 a. m.) and the inferior ramp geometrics, a great many ramp vehicles are forced to stop before merging.

The results of an origin-destination study conducted at this ramp (8) showed that about 80 percent of the vehicles which normally enter at Mossrose bypass either the freeway. Thus, only about 20 percent of the vehicles which normally enter at Mossrose should enter there; the other 80 percent should enter at S. H. 225 or Woodridge.

In addition to the demand-capacity philosophy used to plan the controls at the other ramps, other considerations were also made. An extremely low metering rate was considered desirable during the early part of the peak period at this ramp for three reasons: (a) a low metering rate would allow most of the ramp vehicles to enter the freeway at high speeds, (b) a low metering rate and its associated high delay would discourage vehicles from bypassing upstream ramps, and (c) the low metering rate at Mossrose was expected to produce a higher level of service on the freeway, thereby encouraging some vehicles to enter the freeway upstream of Mossrose rather than bypassing to Mossrose.

Considerable thought was given to the possibility of closing this ramp instead of metering it. One disadvantage of metering the Mossrose ramp was that the personnel and the various signs involved in the metering would be plainly visible to the motorists on the freeway. Thus, the possibility of the formations of a "gapers block" (a traffic slowdown caused by drivers looking at an accident, disabled vehicle or other distraction which is not actually blocking their path) existed. It was decided, however, that it would be better to meter than to close this ramp to avoid causing circuity of travel for approximately 125 vehicles whose trips originate near the ramp and for which the use of the ramp is most natural. The discontinuity in the frontage road at Griggs Road makes the Mossrose ramp especially important for these vehicles. It was reasoned, however, that a higher level of service on the freeway would probably have resulted from the closure of this ramp.

During the first week of the control the following metering scheme was used at the Mossrose entrance ramp:

Time—a. m.	Metering Rate	
	Veh/5 min	1 Veh/x sec
6:55-7:10	20	1/15
7:10-7:20	30	1/10
7:20-7:30	50	1/6

During the remainder of the control study the metering scheme was changed as follows:

Time—a. m.	Metering Rate	
	Veh/5 min	1 Veh/x sec
6:55-7:20	20	1/15
7:20-7:45	50	1/6

In order to allow stopped vehicles from the ramp to clear from the merging area, the same override to the metering that was used at Woodridge was employed at Mossrose.

Griggs and Wayside Ramps.—Because of the proximity of the Griggs and Wayside entrance ramps and because there are no ramps between them, the controls imposed at one ramp would affect the controls needed at the other ramp. The demand upstream of the Griggs ramp and the capacity downstream of the Wayside ramp determine the allowable entrance volume for the two ramps together. This allowable volume could come from either ramp or a combination but the total volume entering from the two ramps must not exceed the total allowable volume. For this reason control considerations were made at the two ramps simultaneously.

If a large amount of traffic were allowed to enter the freeway from the Griggs ramp, it would have been necessary to impose a low metering rate on the Wayside entrance ramp. The problem of a traffic queue at Wayside, especially the possibility that it might back into the intersection of Wayside Drive and the inbound frontage road, made it unfeasible to have an extremely low metering rate at Wayside. As explained previously, the metering rate could be increased at Wayside only through a corresponding decrease in the metering rate at Griggs. Because of the high volume on the Griggs ramp (about 700 from 7-8 a. m.) a low metering rate there would have created severe queueing problems at this location. Even though the frontage road there could accommodate a large queue without having any intersections blocked, the possibility of a gapers' block formation on the freeway was considered to be great.

Since the allowable ramp volume at Griggs (with a high metering rate at Wayside) was so low during part of the peak period the ramp would have been essentially closed. This suggested the possibility of closing the ramp instead of metering it. The advantages of closure are its simplicity and the elimination of a large queue at this ramp. One disadvantage of closure is that the intersection with Wayside Drive is a critical bottleneck on the inbound frontage road (4) and the diversion of a large amount of traffic through this already congested intersection approach would certainly create an extremely bad situation.

It was decided that the frontage road congestion was less critical and the decision was made to close the Griggs entrance ramp. A reassignment of some of the traffic from this ramp indicated that most of this traffic could use more direct routes to other freeway ramps and would not use the frontage road between Griggs and Wayside. Demand-capacity analyses of the alternate routes to be used by most of the traffic diverted by the closure of the Griggs ramp indicated that until about 7:20 a. m. these routes could accommodate the extra traffic. However, after about 7:20 a. m. the additional traffic would be expected to cause severe congestion and excessive delay on many of the alternate routes.

Because of these considerations the decision was made to close the Griggs entrance ramp from 7:05 to 7:20 in spite of the fact that the demand would be close to or slightly over the capacity of the merging area of this ramp for several minutes after the ramp was opened. Were it not for the consideration of the effects on the arterial street system this ramp should desirably have been closed until 7:25 or 7:30 to preserve the high level of service on the freeway.

Demand-capacity considerations (assumed capacity 490 veh/5 min) at the Wayside entrance ramp, including the effects of the closure of the Griggs ramp on freeway and ramp demand, led to the establishment of the following metering scheme:

Time—a. m.	Metering Rate	
	Veh/5 min	1 Veh/x sec
7:00-7:05	30	1/10
7:05-7:20	50	1/6
7:20-7:25	38	1/8
7:25-7:30	50	1/6

After the first week of the study the following metering scheme was adopted:

Time—a. m.	Veh/5 min	1 Veh/x sec
7:00-7:25	30	1/10
7:25-7:45	50	1/6

The same override to the metering to clear stopped ramp vehicles from the merging area was used at the Wayside, Telephone and Dumble ramps while they were being metered.

Telephone Entrance Ramp.—A demand-capacity analysis at the merging area of the Telephone Road entrance ramp provided the basis for the metering plan which was used there. Consideration was made of all controls on upstream entrance ramps and the reassignment of the vehicles which would be diverted from the Griggs Road ramp during its closure period. About 50 percent of these were assigned to the Telephone Road entrance ramp and a merging capacity of 490 veh/5 min was assumed. The following metering scheme was developed for the Telephone entrance ramp:

Time—a. m.	Metering Rate	
	Veh/5 min	1 Veh/x sec
7:00-7:15	20	1/15
7:15-7:45	40	1/7. 5

Dumble Entrance Ramp.—The Dumble entrance ramp was selected as the location for testing a traffic signal for metering the ramp traffic. This installation will be discussed more fully in a later section.

A demand-capacity analysis of the merging area of the Dumble entrance ramp was made. It included the effects of upstream controls and the expected diversion of vehicles from their normal routes and assumed a merging capacity of 475 veh/5 min. This analysis yielded the following metering plan which was in effect during the first week of the study:

Time—a. m.	Metering Rate—Veh/5 min
7:05-7:10	40
7:10-7:15	30
7:15-7:20	25
7:20-7:25	40
7:25-7:30	50

During the second week of the study the rate of 50 vehicles per 5 minutes was extended until 7:45 a. m.

At the beginning of the third week an automatic timing device was installed at the signal to eliminate the necessity of having someone present to turn the signal on and off. At this time it was necessary to limit the metering to one rate during the entire period of control. The rate of 40 vehicles per 5 minutes was chosen.

Cullen Entrance Ramps.—The demand-capacity analysis at the merging area of the two Cullen entrance ramps indicated that these ramps should be closed from 7:05-7:30 a. m. each day. Because the closure of these ramps on two other occasions (1, 6) resulted in few, if any, problems to motorists normally using them, the decision was made to close the two ramps for the 25-minute period.

PRELIMINARY PREPARATIONS FOR CONTROLS

Advance Publicity

The details of the control plan were announced to the general public through a news release issued on January 19, 1965. The Appendix contains several articles regarding the controls which appeared in local newspapers. Also on January 19, signs were erected at each of the ramps to be controlled, displaying the date and time of control. A traffic bulletin was issued to each motorist who used the ramps in the study area during the morning peak period on January 25 as a reminder that the study would start the next day and also to indicate the extent of the study area. Figures 3 and 4 show samples of the ramp signs and traffic bulletins.

The effectiveness of the advance publicity was evident the first few days of the study by the changes in the pattern of traffic approaching the study area. In many instances the shift in traffic was not expected. Many motorists tried to bypass part of the control area to enter the freeway at downstream ramps.

Signing

In addition to the advisory signs erected at the ramps, alternate routing signs such as the one shown in Figure 5 were located at upstream entrance ramps and on the arterial streets at major intersections, and portable "stop" and "stop ahead" signs were placed at the ramps.

Signals

The signals at the Dumble entrance ramp were installed on Friday, January 22 and operated on flashing amber until the start of the control study January 26, as described in detail later.

Figure 3. Advisory signs erected at ramps to be controlled.

FREEWAY SURVEILLANCE AND CONTROL PROJECT

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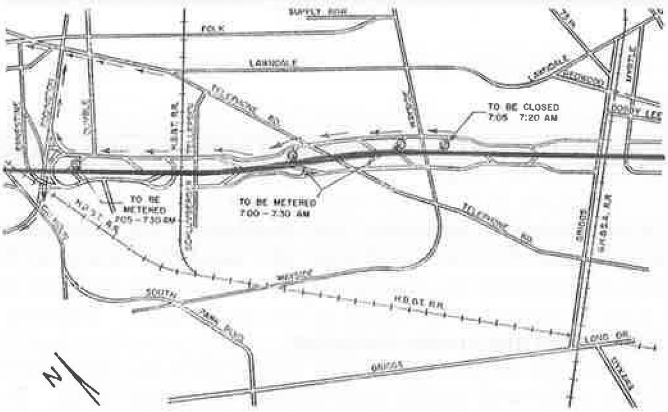
WITH
TEXAS HIGHWAY DEPARTMENT – CITY OF HOUSTON – BUREAU OF PUBLIC ROADS



As part of an Experimental Freeway Control System to improve traffic operations, the entrance ramps to the Gulf Freeway from State Highway 225 to Downtown will be controlled during the morning peak traffic demand. The traffic using this ramp will be metered by limiting the number of vehicles to enter the Freeway from 7:00 to 7:30 a.m. on weekdays from January 25 to February 5. This will result in some additional delay to ramp traffic during this time period. Motorists who prefer to bypass the control area are advised to take one of the alternate routes shown on the map above.

The map on the reverse side of this traffic bulletin indicates the controls to be placed on the other ramps. It should be noted that traffic diverting to one of the other ramps during the time of control may be delayed several minutes before entering the Freeway.

Figure 4. Traffic bulletin issued to motorists using ramps.

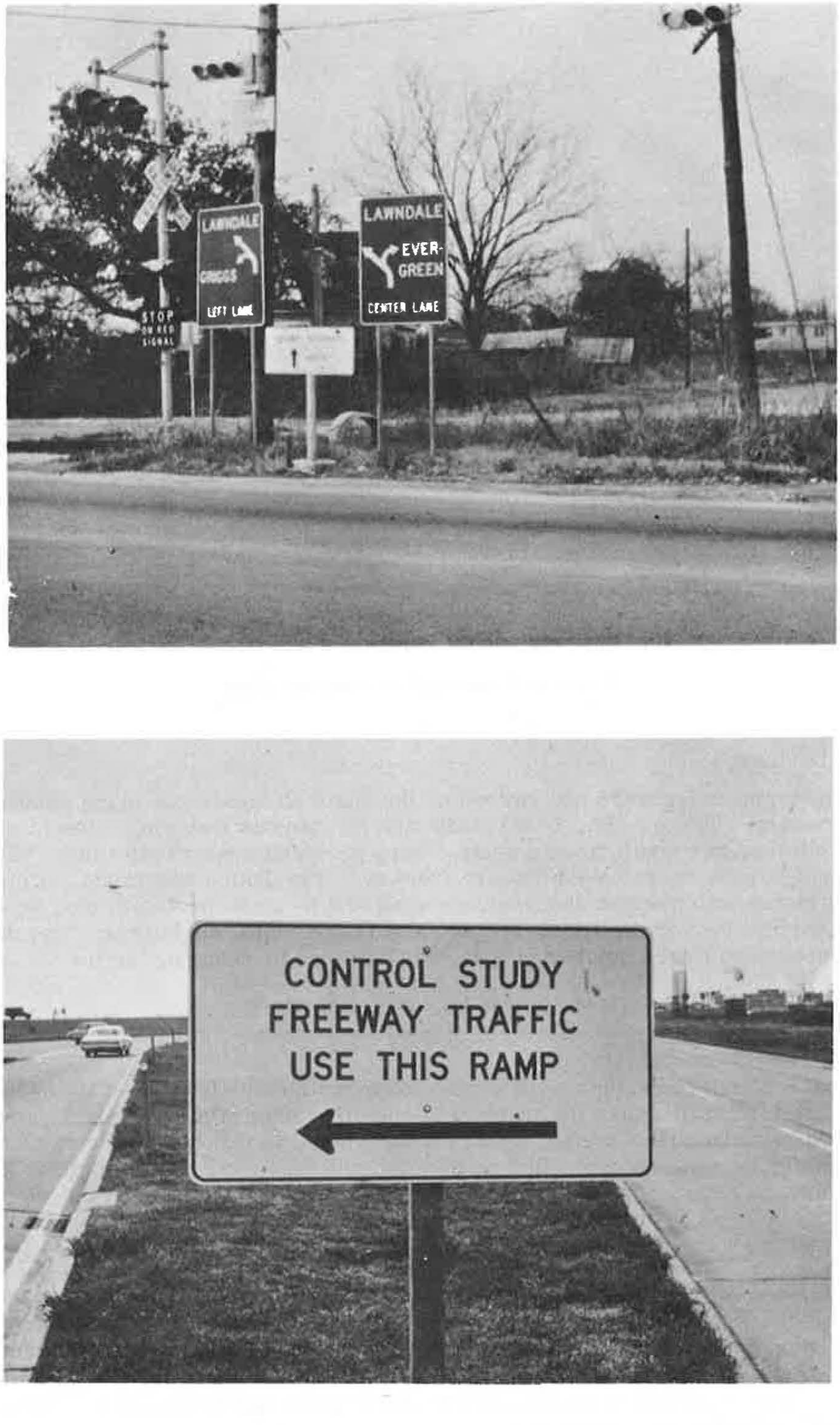


Figure 5. Advisory signs on alternate routes.

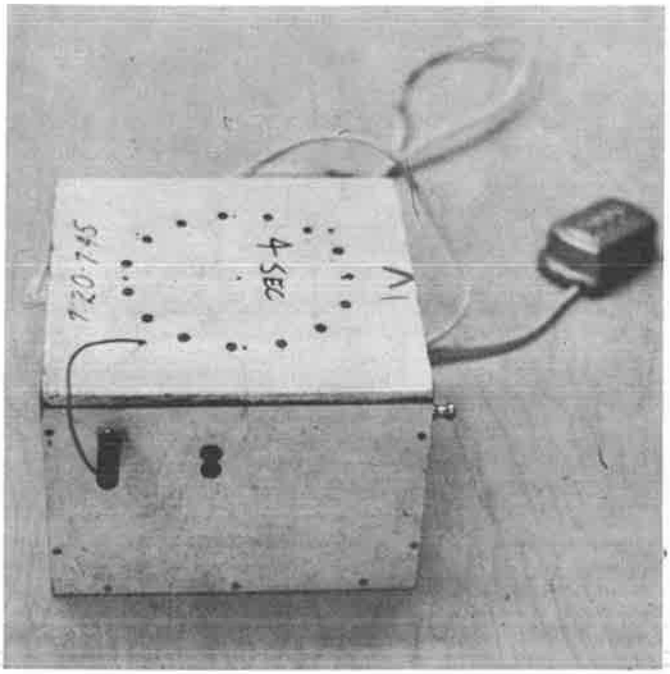


Figure 6. Timer used for ramp metering.

Timing Devices

The metering rates were determined on the basis of capacity-demand relationships on the freeway. Timers (Fig. 6) that indicated the various metering rates to the ramp control officers were built for the study. They provided a buzz each time a vehicle on the ramp was to be released onto the freeway. The design was crude but effective. A 6-volt motor with a speed of 1 rpm, mounted in a 6- by 6- by 4-inch box, powered a rotary switch. Pins in the lid of the box closed the circuit to a buzzer. The metering rate, represented by the number of pins, was adjusted by changing the lid.

OPERATION OF THE CONTROLS

Manual Metering

Five of the metered ramps were controlled by policemen from the City of Houston, who directed the traffic onto the freeway at specified intervals. The sixth ramp was controlled by a fixed time traffic signal for assigning the right of way to ramp traffic.

The metering stations controlled by the city policemen were located at the junction of the entrance ramps and the frontage road as shown in Figure 7. A stop-ahead sign was placed 200 feet in advance of the metering station. A stop sign was placed at the metering station, but it was easily seen by the freeway motorists and tended to cause a gapers' block. The stop signs were removed after the second day on all but one ramp.

The policemen were instructed to direct one vehicle onto the ramp each time the buzzer on the timer sounded. If the vehicles did not move directly into the freeway, but queued up at the merge point, the policemen were instructed to hold all vehicles at the metering station until only one vehicle remained on the ramp. The policemen changed from one metering rate to another at the times specified in the control plan by a simple adjustment of the timer.

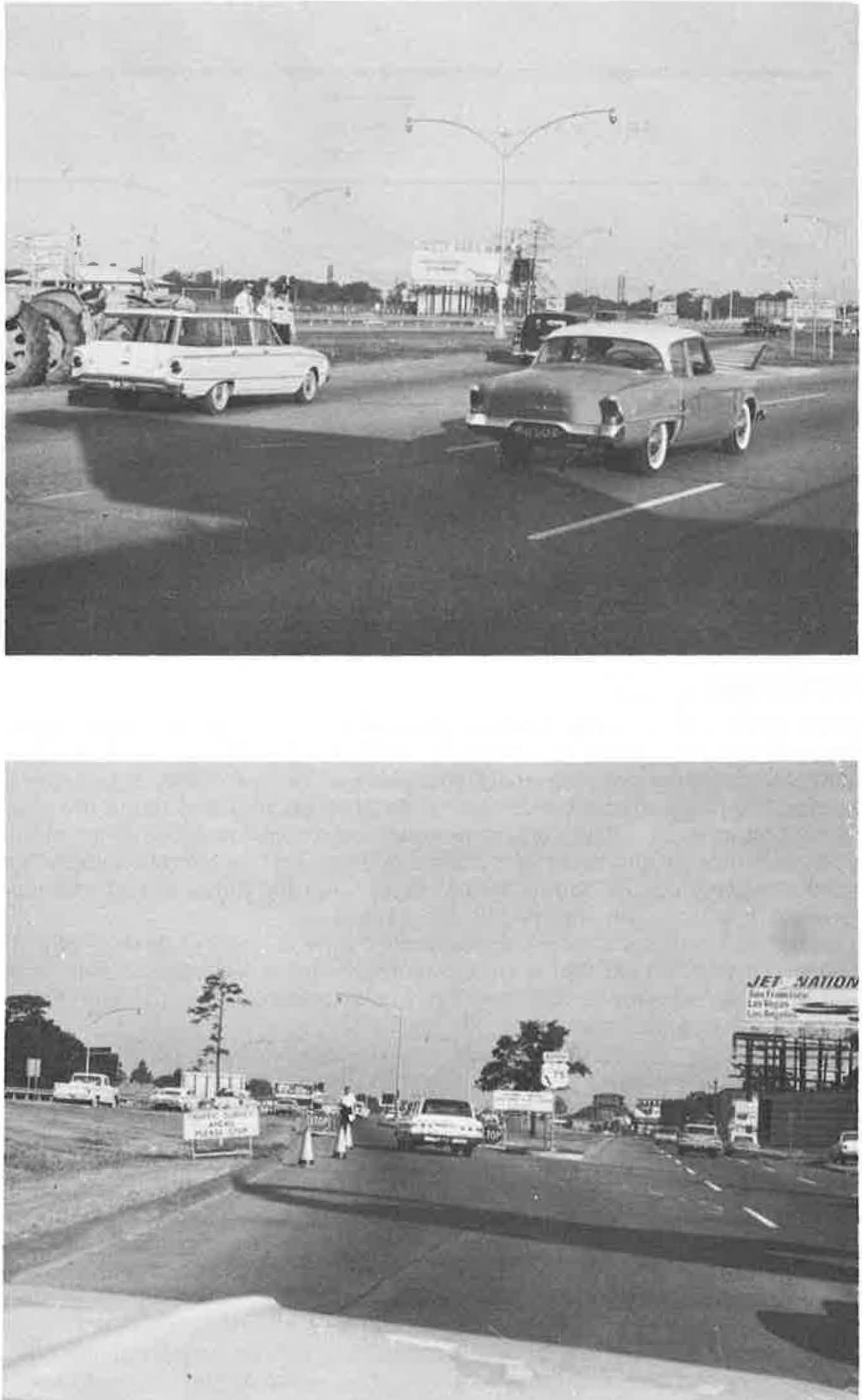


Figure 7. Ramp metering location.

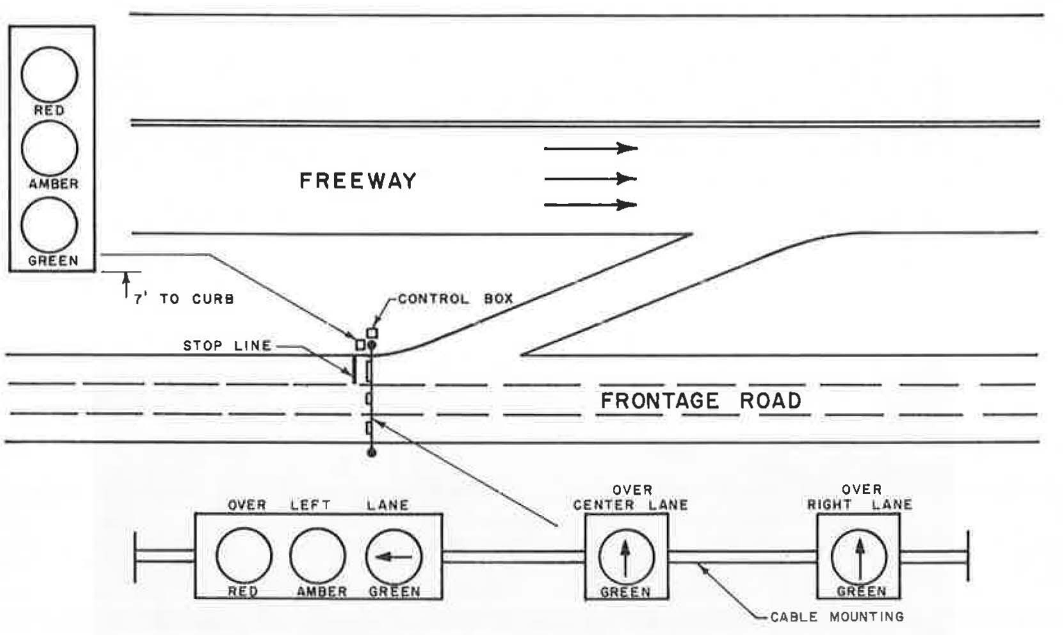


Figure 8. Schematic of signal installation at the Dumble entrance ramp.

Signal Installation at Dumble

One of the most crucial components of a ramp metering system is the type of con-
traffic control techniques not commonly encountered by motorists, it is especially necessary that the basic elements of control devices be realized in the development of a ramp control system. The control devices employed must therefore compel the attention of the motorist and must present a message that is clearly understood. Proper location of the control device should allow ample time for the motorist to respond and apply appropriate actions as required by the device.

Ramp metering requires a more sophisticated type of control device than fixed-time ramp closure. It is realized that a metering device must not only be able to meter effectively, but it is envisioned that the device must also operate to close a ramp completely at certain high volume periods on the freeway.

The objective of this phase of the study was to observe some of the characteristics associated with semiautomatic metering in order to determine equipment requirements for future automatic systems. Some aspects of metering considered in the design of the Dumble experiment were the location and type of control signal and the signal phasing.

The selected location of the metering control was on the frontage road as opposed to a location on the ramp. Three advantages were anticipated: (a) a ramp could be closed without trapping a driver on the ramp, (b) signalization of the frontage road-ramp would be similar to operation at a normal intersection and therefore be less of a novelty to the driver, and (c) there is less chance of a metered driver given the green to assume that he has the right-of-way in the merging situation with the freeway.

The initial study was directed toward determining driver requirements with respect to metering. Since driver responses to a signal using an amber phase following the green were to be evaluated, as against using just the red and green phases, a post-mounted traffic signal with red, amber and green lenses was installed adjacent to the stop line. Overhead signals mounted over each lane of the frontage road were employed to separate the two movements (ramp usage and frontage road usage). Figure 8 shows a diagram of the installation.

The phasing was designed for bulk-service metering. A three-dial pretimed controller was utilized with a constant 30-second cycle length. The three dials were set to give 10 ½, 8 and 13 ½ seconds of green with a constant amber of 2 ½ seconds. Dial No. 1 was used from 7:05 to 7:10 and from 7:20 to 7:25, dial No. 2 from 7:10 to 7:20 and dial No. 3 from 7:25 to 7:35.

In order to evaluate the proposed metering operation, the plan was (a) to measure starting headways in order to compare actual metering rates with the theoretical rates, (b) to record the number of violations by motorists who either ignored the signal or did not understand its significance and (c) to measure gap acceptance characteristics of ramp vehicles in the merging area and compare them to characteristics observed during normal operation.

Ramp Closure

Cones and barricades were placed in the outer separation at each of the three ramps that were closed. One city policeman was assigned to each ramp to effect the closure. At the time designated in the control plan, the cones were placed parallel to the frontage road across the entrances to the ramps, and the barricades were placed across the ramp roadway. The policemen were instructed to move away from the ramps and out of the line of sight of the freeway traffic.

At the end of the first two weeks of the control study, a reassignment of personnel was made to extend the study. It was decided at this time that the closure of the ramps did not require a person with police authority. The maintenance department of District 12, Texas Highway Department, which has the responsibility for closing the freeway when the roadway is made impassible by weather, accidents, or maintenance operations, assigned personnel to the project for the remainder of the study. During the final five weeks of the operation, the highway personnel encountered no difficulty in effecting the ramp closures at the specified times.

IMMEDIATE EFFECTS OF THE CONTROLS

The evaluation of the effects of the controls on freeway operation is divided into two time periods, the first two weeks of the study and the last five weeks, which include the entire seven weeks of the operation of the control study. The results obtained during the first two weeks are classed as immediate results while the results from the next five weeks are classed as long-term results.

The evaluation of the effects of the freeway controls on arterial streets is based on studies taken over the seven weeks of operation, but the results will be included in the section on immediate effects of the controls.

From 1500 to 2000 motorists were directly affected by the controls. That is, about 1500 to 2000 motorists normally entered the freeway at the ramps which were controlled during the time that each was controlled. It was anticipated that many motorists would search out new routes to avoid the controls or to enter the freeway at points further upstream because of improved freeway traffic operation. With such a large number of motorists suddenly having their normal travel routine changed, a period of transient system behavior was expected before a steady-state condition was achieved.

Such a transient condition was noted and is the reason for separation of the analysis of the data into two periods. During the first week of the study, the transient effect was especially evident as the freeway level of service consistently improved during successive days of the study. This can be seen in Figure 9. For this reason, only the data from the second week of the study were used in the freeway analyses of the immediate effects of the controls.

The transient effects on the arterial streets were not so noticeable. Therefore, it was decided to concentrate the studies on the freeway system to provide adequate coverage over the two time periods of control, and to continue all arterial street data obtained during control.

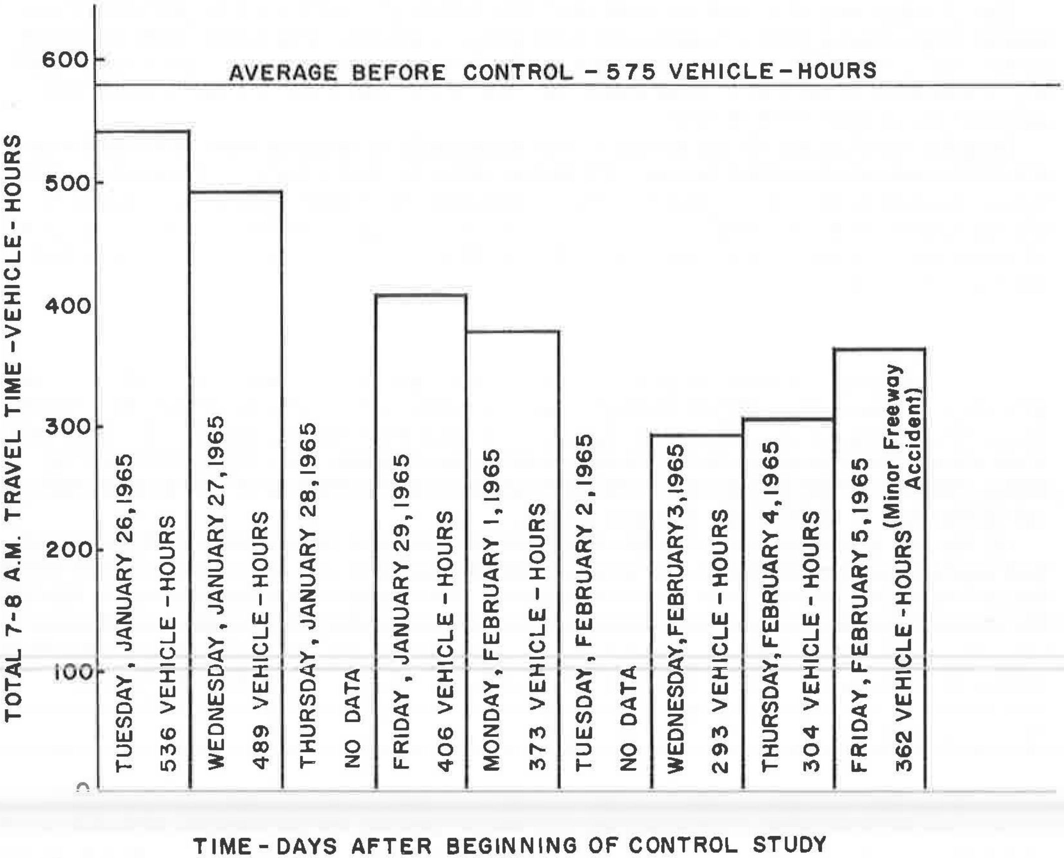


Figure 9. Transient behavior of total 7-8 a.m. travel time in Broadway-Griggs subsystem at the beginning of the control study.

Freeway and Frontage Roads

Three data collection techniques were used during this study—manual counts and speed recordings (most of which were part of the closed system input-output studies), aerial photography and moving vehicle travel time recordings. The aerial photography data were used exclusively in the frontage road studies and in the freeway studies from the South HB&T RR overpass to Dowling and were also used to supplement and to check the data from the (manual count) freeway studies. The basic analysis period is 7-8 a.m. but due to insufficient light conditions the aerial photographs did not encompass this entire period on some days. Hence, the frontage road data necessarily represent best estimates based on the photographs available. This same statement holds true for the evaluation of freeway operations from the South HB&T RR overpass to Dowling Street.

Table 2 contains the schedule of data used for the "after" portion of the before-and-after studies on the effects of the controls on the freeway and frontage road operation.

Total System Travel Time.—The total amount of travel time expended by all vehicles using a particular facility during the peak period is one good measure of its operational efficiency. The units of this travel time are vehicle-minutes or vehicle-hours. A vehicle-minute represents one vehicle in the system for one minute; a vehicle-hour represents 4 vehicles in the system for 15 minutes each, 5 vehicles in the system for 12 minutes each or some other combination totaling 60 vehicle-minutes.

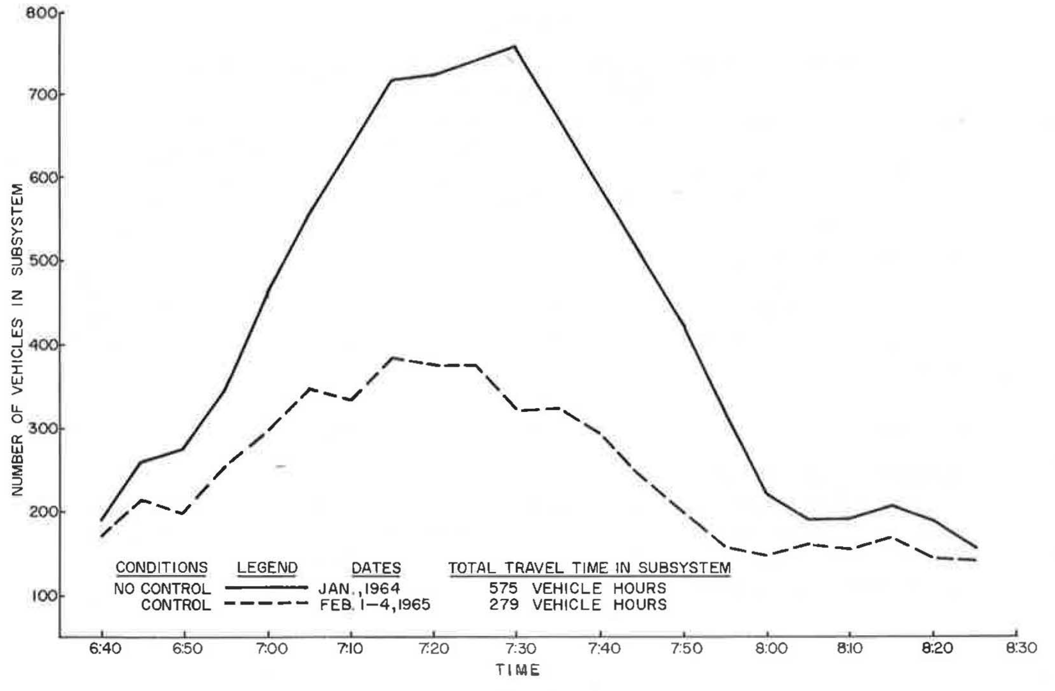


Figure 10. Number of vehicles on Broadway-Griggs subsystem.

TABLE 2

"AFTER" DATA USED TO DETERMINE IMMEDIATE EFFECTS OF CONTROLS

Manual counts (input-output)	February 2-4, 1965
Aerial photography	February 2, 3, 1965
Moving vehicle travel times	February 2-4, 1965

If the number of vehicles in a given system is a known function of time (such as a graph) the total travel time in the system is the integral of the time function (or the area under the graph) between the times of interest (3). This analysis was made during the 7-8 a. m. peak hour for the Gulf Freeway studies. Thus, for each freeway subsystem and the inbound frontage road the total travel time was calculated for the before-and-after comparisons.

The portion of the freeway on which the greatest operational improvement was anticipated was that between Broadway and Griggs (that is, the Broadway-Griggs subsystem). An improvement in the operations in this subsystem would be reflected by fewer vehicles in the subsystem (lower density). The number of vehicles in the Broadway-Griggs subsystem before and during the controls are shown in Figure 10. The number of vehicles in this subsystem decreased significantly during the control study and the 7-8 a. m. total travel time in this subsystem decreased from 575 vehicle-hours to 297 vehicle-hours, a 48 percent reduction.

Table 3 is a summary of the total travel time before and during the control study on the inbound freeway and frontage road. The total travel time on the inbound freeway was 371 vehicle-hours (30 percent) less than it was before the controls were put into effect. The travel time on the frontage road increased from about 190 to 201 vehicle-

TABLE 3

IMMEDIATE EFFECTS OF CONTROLS—TOTAL SYSTEM TRAVEL TIME, 7-8 A. M.

System or Subsystem	Total Travel Time, Vehicle Hours		
	Before Control	During Control	Difference
Inbound freeway			
Broadway to Griggs	575	297	-278 (-48%)
Griggs to S. HB&T RR	367	310	-57 (-16%)
S. HB&T RR to Dowling	302	266[a]	-36 (-12%)
Total inbound freeway	1244	873	-371 (-30%)
Inbound frontage road	190[a]	201[a]	+11 (+6%)
Total inbound freeway and frontage road	1434	1074	-360 (-25%)

[a]Based on incomplete data caused by inadequate light conditions which made aerial photography during the early parts of the 7-8 a.m. period impossible.

TABLE 4

AVERAGE 7-8 A. M. VOLUMES OF ENTRANCES TO THE FREEWAY

[illegible]	Before Control	During Control	
Freeway near Broadway	2831	3185	+354
Detroit on ramp	218	122	-96
S. H. 225 on ramp	559	649	+90
S. H. 35 on ramp[a]	818	726	-92
Woodridge on ramp[a]	426	398	-28
Mossrose on ramp[a]	643	318	-325
Griggs on ramp[b]	683	496	-187
Wayside on ramp[a]	335	332	-3
Telephone on ramp[a]	413	356	-57
Dumble on ramp[a]	345	294	-51
Cullen on ramps (combined)[b]	574	348	-226
Scott on ramp	63	257	+194
			(-5. 3%)
Total	7908	7481	-427

[a]Ramps which were metered.
[b]Ramps which were closed.

hours, a 6 percent increase. The total effect on the inbound freeway and frontage road travel time was a reduction of 360 vehicle-hours, which represents a 30 percent decrease.

Average 7-8 a. m. Freeway and Ramp Volumes.—The initiation of the control plan naturally caused some significant changes in the 7-8 a. m. volumes on the entrances to the freeway. Table 4 contains the average volumes before and during the control study. As can be seen, a large increase in volume took place on the freeway near

Broadway. This is attributable to the improved level of service on the freeway and to the controls on the downstream ramps. Some vehicles undoubtedly entered the freeway at or upstream of Broadway instead of entering at their usual ramps farther downstream because (a) the freeway trip was more attractive during the control study because of the reduced freeway congestion and (b) the use of downstream entrance ramps was less attractive because of the ramp controls which produced some delay on entering. Also the overall traffic possibly increased in the year's time between the studies.

The decrease of about 100 vehicles entering at the Detroit entrance ramp does not represent a decrease in freeway traffic but rather is a direct result of the improved freeway level of service. Normally, during the periods with no ramp control, about 100 vehicles between 7 and 8 a. m. exit at the S. H. 225 (northbound) exit and reenter at the Detroit ramp to avoid about 1500 feet of freeway congestion. During the control study, congestion did not develop in this region so the exit-reentry maneuver would not save the motorist any time; hence the decrease in the frequency of this maneuver. The number of vehicles exiting at the S. H. 225 northbound exit ramp decreased by 112 during this same time period, further substantiating the explanation of the decrease in the Detroit Street entrance ramp volume.

The increased volume on the S. H. 225 entrance ramp is explained by the fact that it was not controlled while the nearby entrance ramps which are alternate entrances for the La Porte Freeway traffic were controlled. Thus, the 90-vehicle increase represents diversion from other entrance ramps which were controlled.

All of the entrance ramps from S. H. 35 to Cullen had decreases in 7-8 a. m. volume. All of these ramps were controlled and the volume decreases were caused by the expected delays at the metered ramps or by the closure in the cases of the Griggs and Cullen ramps. At some ramps, such as Dumble, the decrease in volume was greater than the expected delay would seem to warrant, indicating a reluctance on the part of some motorists to undergo control. This could be caused either by rebellion or by reluctance to try something which is unknown, but also undoubtedly means that some good alternate routes on arterial streets were available. Otherwise, the rebellion or reluctance would have given way to the desire to reduce travel time.

The increase in volume at the Scott entrance ramp can be entirely attributed to the closure of the Cullen entrance ramps just upstream. Many of the vehicles which normally enter at Cullen during the closure period proceeded down the frontage road and entered at the Scott ramp.

The total decrease in the volume entering the inbound freeway was 427 vehicles (not correcting for the decrease in the frequency of the exit-reentry maneuver at the S. H. 225 exit and Detroit entrance ramps) which represents a 5. 3 percent decrease in traffic entering the freeway. From Broadway to Griggs (after correcting for the decrease in the frequency of the exit-reentry maneuver) the total entering traffic was virtually identical before and during the controls.

Vehicle-Miles of Travel and Average Speed Between Broadway and Griggs.—Just as the number of vehicle-hours in a system in a given time period represents the total amount of travel time spent by all vehicles in the system during the time period, the number of vehicle-miles accumulated in the same system in the same time period is the total amount of travel which took place. One vehicle mile is accumulated by one vehicle traveling one mile in the system in the time period of interest. The average speed of all vehicles in the system during the time period is the total number of vehicle miles of travel divided by the total number of vehicle-hours (the units are miles per hour).

Since changes in the volumes of most of the freeway entrance and exit ramps occurred during the control study, a change in the total amount of travel (vehicle-miles) was to have been expected; also a change in the total travel time was found. Thus, the average speed probably also changed. Table 5 contains a summary of these statistics for the Broadway-Griggs subsystem before and during the control study. From the table it can be seen that the total amount of travel between Broadway and Griggs from 7 to 8 a. m. increased 11 percent, from 7990 to 8865 vehicle-miles. This at least partly reflects a more efficient use of the system of streets and freeway caused by clearing the congestion on the freeway, thereby encouraging its greater use.

TABLE 5

VEHICLE-MILES, VEHICLE-HOURS AND AVERAGE SPEED OF BROADWAY-GRIGGS SUBSYSTEM, 7-8 A. M.

Category	Before Control January, 1964	During Control February, 1965	Difference
Total travel, vehicle-miles	7990	8865	+875 (+11%)
Total travel time, vehicle-hours	575	297	-278 (-48%)
Average speed, miles/hour	14	30	+16 (+114%)

Meanwhile, the total travel time decreased by 48 percent, from 575 to 297 vehicle-hours. These changes caused the average speed between Broadway and Griggs to increase from 14 to 30 mph between 7 and 8 a. m.

Individual Vehicle Travel Time.—Data on the travel time required for an individual vehicle to travel from various points on the freeway to the end of the freeway near Dowling Street were obtained in January 1964, before the controls, and again from February 1-5, 1965, during the control study. These data are presented in the form of average travel time contours (Figs. 11 and 12). Figure 11 is the average travel time contour map for January 1964, and Figure 12 represents conditions in February 1965, during the control study.

Figure 13 is a contour map of the average savings in travel time for a vehicle traveling from a certain point on the freeway at a certain time to the end of the freeway. A maximum of about 8 minutes was saved on the average by vehicles traveling from the Reveille Interchange area to the end of the freeway at about 7:30 a. m. Although not plotted, it was found that the maximum travel time between Broadway and Dowling

showed that before any controls were initiated the flow rates on the freeway at Griggs Road decreased as the peak period progressed. This decrease in flow was caused largely by the congestion from downstream backing over the Griggs Road overpass and was no doubt caused partly by the congestion forming upstream of this overpass. One objective of the controls initiated early in 1965 was to increase the flow rates over the Griggs Road overpass by (a) reducing downstream congestion by ramp controls at the Griggs, Wayside and Telephone entrance ramps and (b) reducing the congestion immediately upstream of the Griggs overpass primarily by strict control at the Mossrose entrance ramp.

Figure 14 shows the results of these attempts. The average flow rate over the Griggs Road overpass during the control study remained close to 450 vehicles per 5 minutes until about 7:25-7:30 a. m. The Griggs Road entrance ramp (down-stream) was reopened at 7:20 a. m. and caused a large part of the volume decrease after this time during the control study. Before the controls the 5-minute volumes dropped much sooner and to much lower values than they did during the control study. Thus, the controls did succeed in increasing the flow rate over the Griggs overpass. This was accomplished, not by raising the maximum flow rate (capacity), but by sustaining the maximum flow rate for a longer period of time, i. e., by preventing the large decrease in flow due to downstream congestion. The total inbound freeway volume at the Griggs overpass from 7:00-7:30 a. m. was increased from 2419 to 2699 vehicles during the control study, while the 7:30-8:00 a. m. volume decreased from 2451 to 2326. The total volume from 7-8 a. m. was increased by 155 vehicles.

Arterial Streets

The street system covered during the control study is shown in Figure 15. This section was selected for study because the traffic diversion expected from the Reveille area and the Griggs Road entrance ramp would have to move through the critical

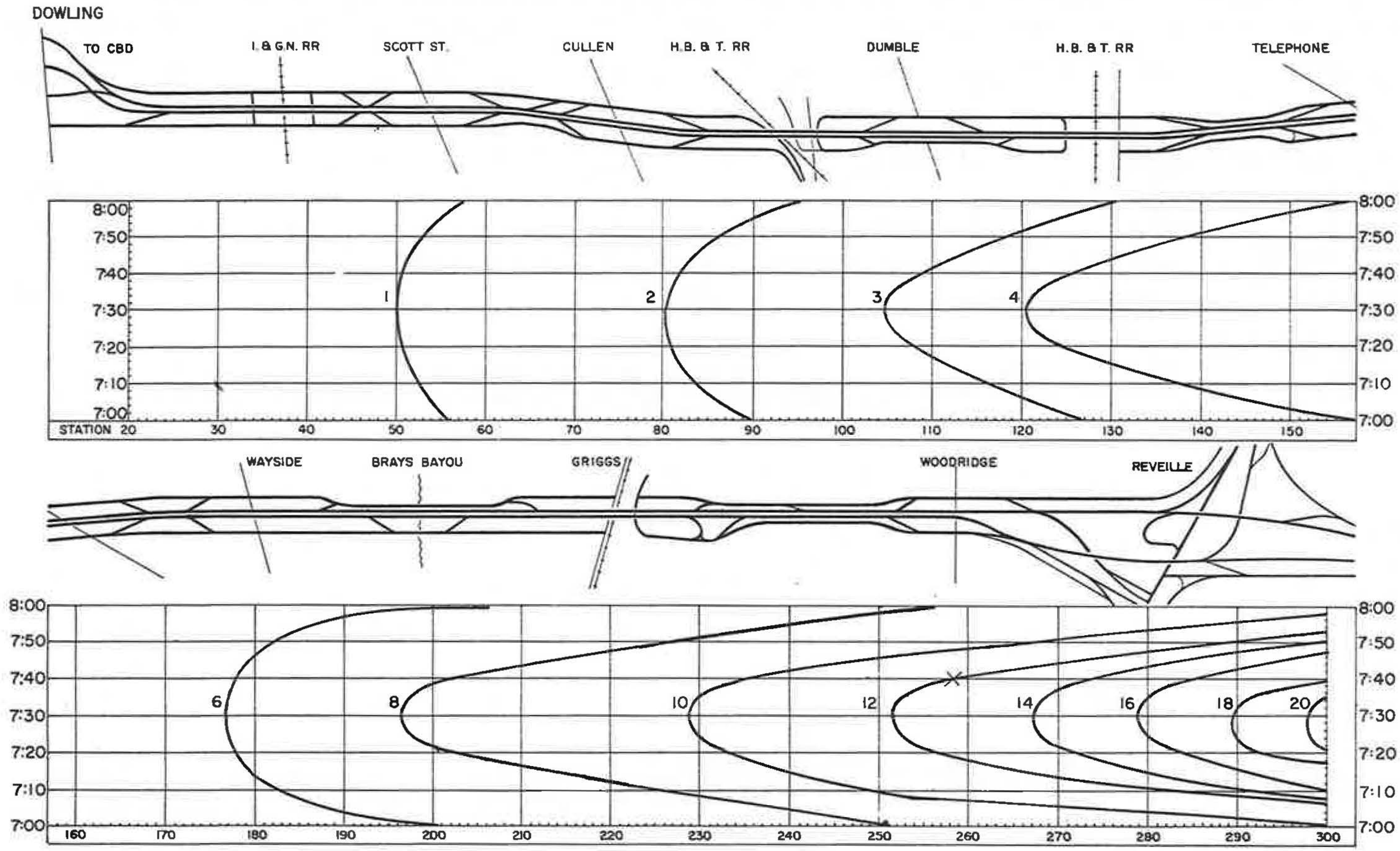


Figure 11. Average travel time (minutes) to end of freeway before control—January 28-30, 1964. Explanatory Note: Point X indicates that a vehicle traveling on the inbound Gulf Freeway at Woodridge at 7:42 a.m. would spend an average of 12 minutes on a trip to Dowling Street.

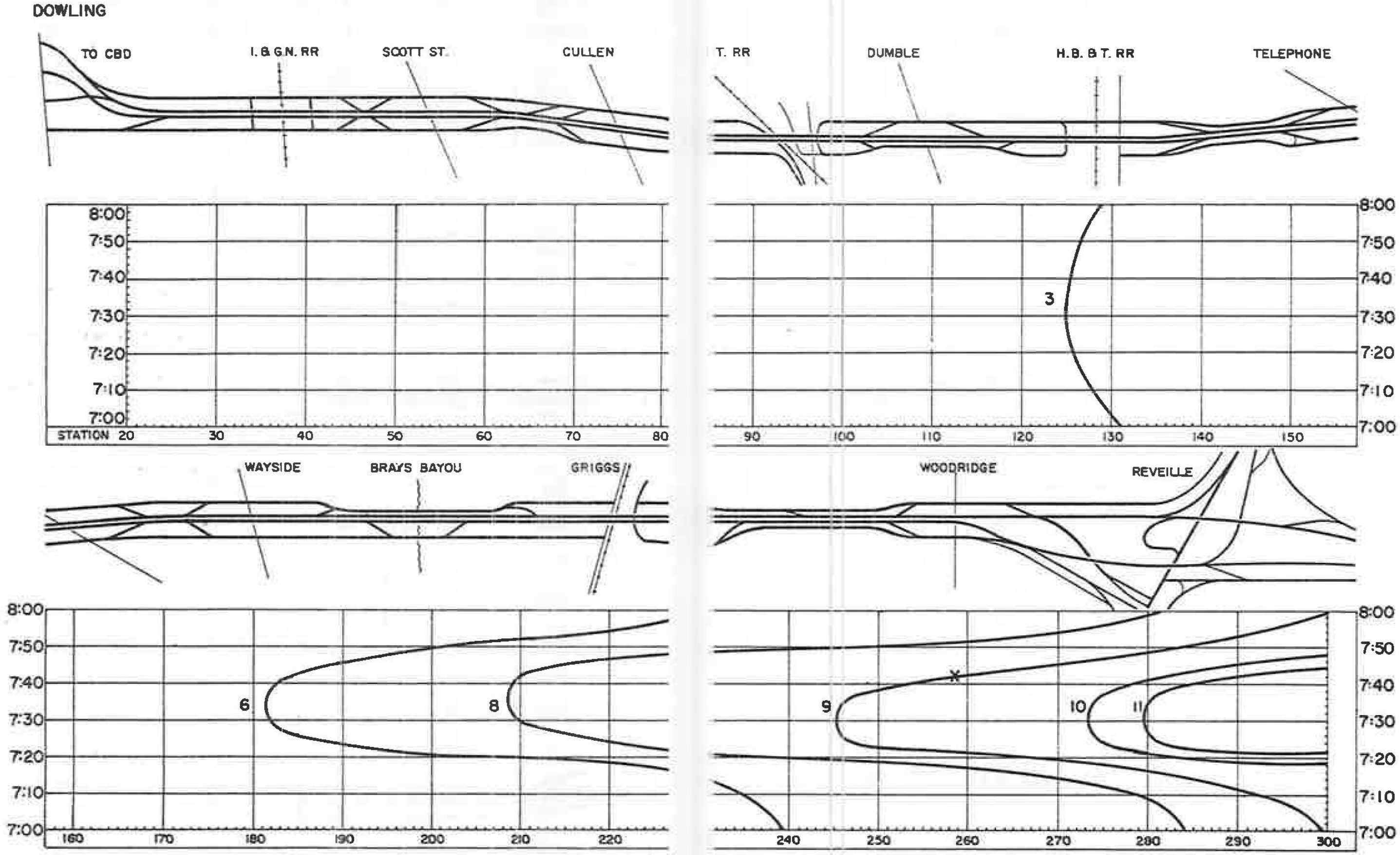


Figure 12. Average travel time (minutes) to end of freeway during con —February 2–4, 1965. Explcnatory note: Point X indicates that a vehicle traveling on the inbound Gulf Freeway at Woodridge at 7:42 c would spend an average of 9 minutes on a trip to Dowling Street.

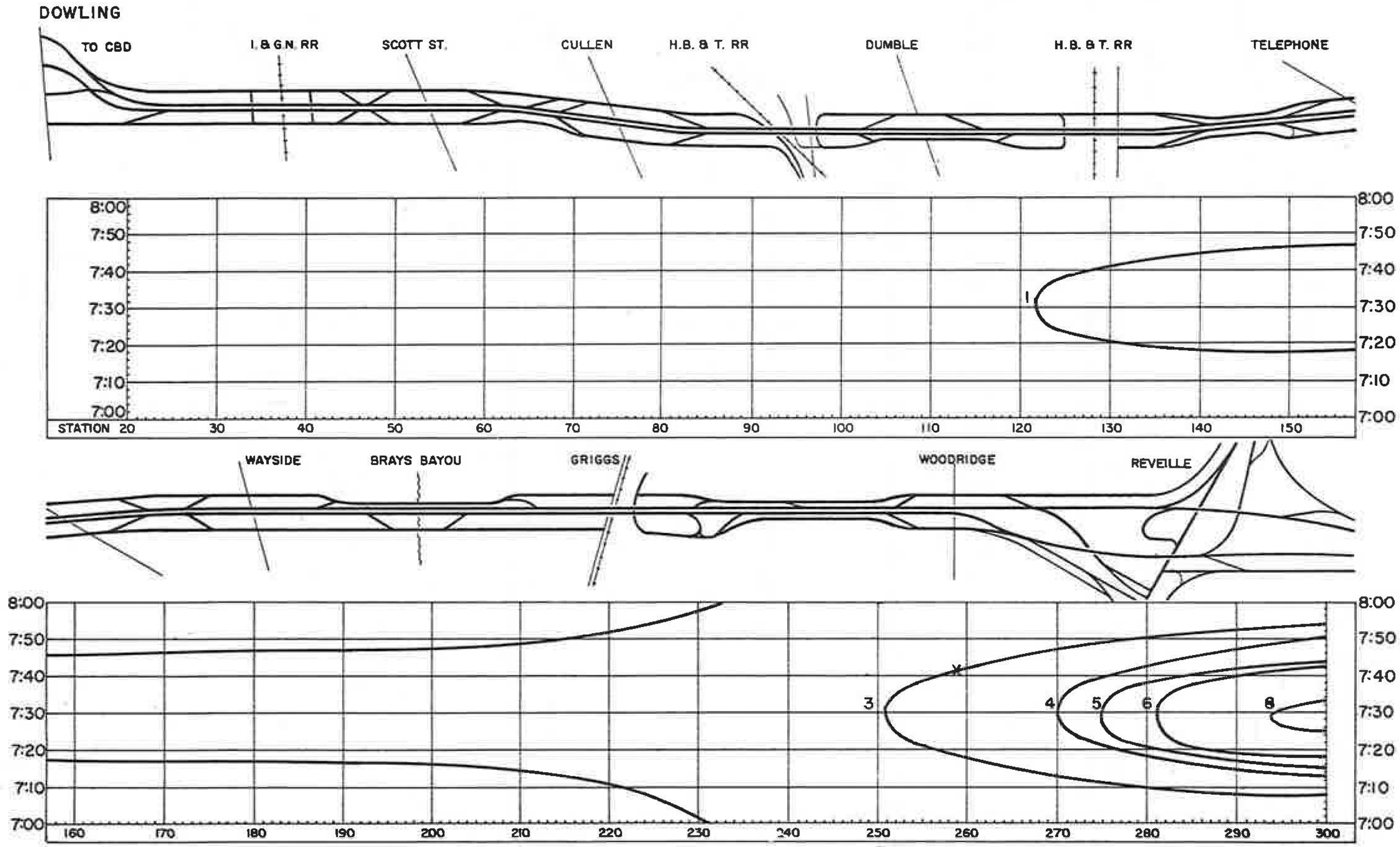


Figure 13. Saving in travel time (minutes) to end of freeway. Explanatory note: Point X indicates that a vehicle traveling on the inbound Gulf Freeway at Woodridge at 7:42 a.m. saved an average of 3 minutes during the control study on a trip to Dowling Street.

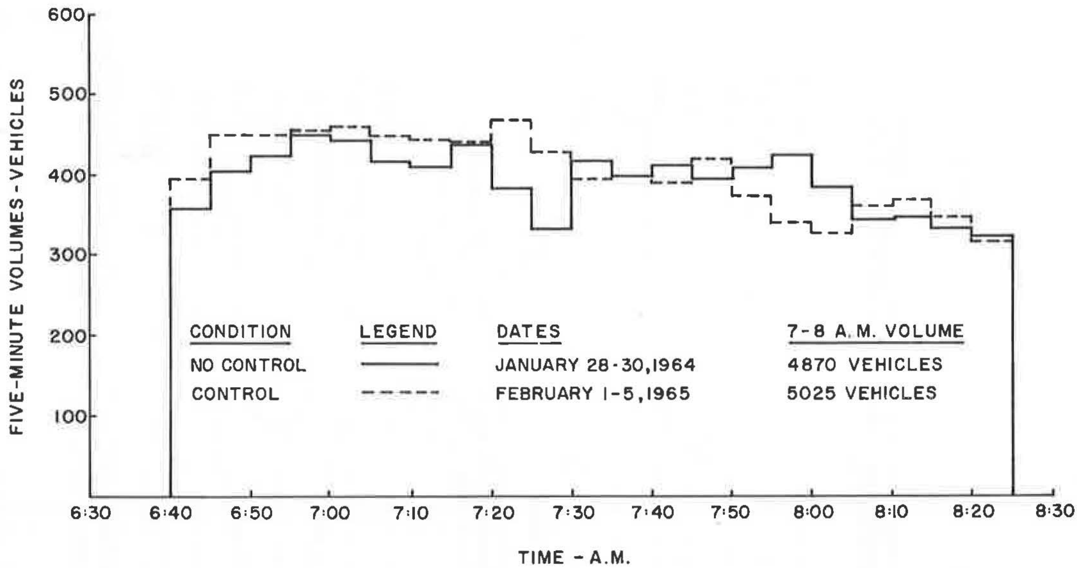


Figure 14. Five-minute volumes on Gulf Freeway at Griggs Road.

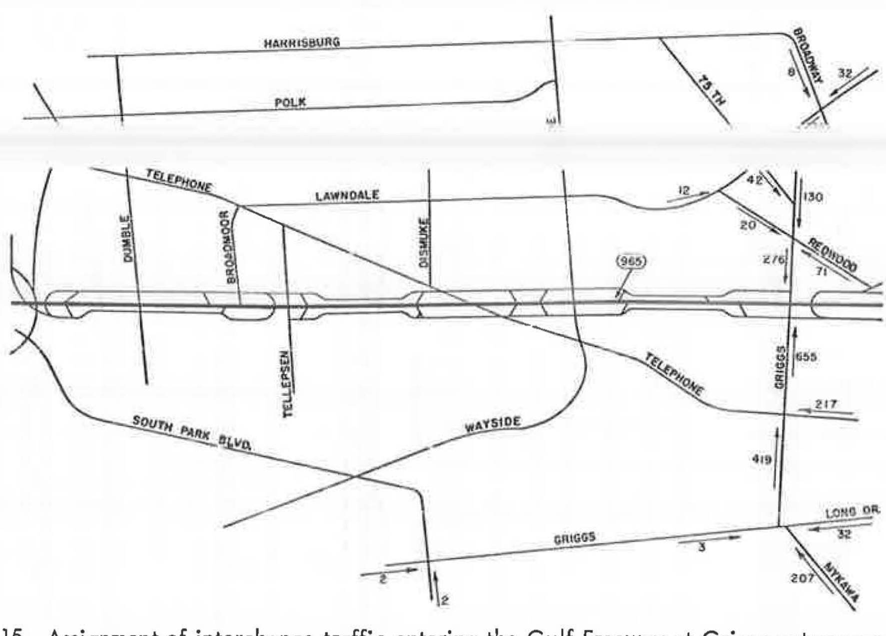


Figure 15. Assignment of interchange traffic entering the Gulf Freeway at Griggs entrance ramp.

intersections identified on the maps. Traffic diversion from other ramp locations would be accommodated on the frontage roads. Also indicated on the map are the approach volumes for the Griggs Road ramp which was closed for a 15-minute period.

Travel Time Runs.—Travel time runs were taken on the alternate routes before, during and after the control study to determine if the shift of traffic from the freeway created any problems on the street system. Only three or four runs were made during each time period for each alternate route. The average of these runs, which are sum-

TABLE 6

SUMMARY OF TRAVEL TIME RUNS ON ARTERIAL STREETS

1. Holmes Road to Gulf Freeway—Via Telephone Road			
	7:00-7:10	7:10-7:20	7:20-7:30
Before	7 min 0 sec	8 min 0 sec	9 min 0 sec
During	6 min 30 sec	9 min 15 sec	11 min 0 sec
After	6 min 30 sec	7 min 0 sec	9 min 0 sec
2. Mykawa-Griggs to Cullen Blvd.—Via South Park			
	6:45-7:00	7:00-7:15	7:15-7:30
Before	7 min 15 sec	11 min 0 sec	15 min 0 sec
During	7 min 0 sec	8 min 0 sec	11 min 0 sec
After	6 min 0 sec	6 min 30 sec	10 min 0 sec
3. Griggs Road to Broadmore—Via Lawndale			
	6:45-7:70	7:00-7:15	7:15-7:30
Before	5 min 30 sec	6 min 0 sec	6 min 0 sec
During	5 min 45 sec	6 min 0 sec	7 min 0 sec
After	6 min 0 sec	6 min 15 sec	6 min 15 sec

marized in Table 6, shows no significant difference in travel times, except in the times recorded on Mykawa-Griggs alternate route. The decreases in travel times are due to the small sample and the traffic signals that are not interconnected, and not to the effect of ramp controls. No large increases in travel times were recorded at any time during the study period on the city streets, indicating that the increased travel did not affect traffic operations.

Changes in Volume.—The shifting volume pattern on the street system is illustrated in Figure 16. There was a substantial shift in traffic the first week of the study, January 26-29, after which the volumes in most cases dropped back to the normal pattern. At the high-volume intersection, the increase in volume came during the time 7:00-7:30 a. m. when the normal demand on the intersection is low. This accounts for the low travel time runs even though the volumes at the intersection increased.

Traffic Delay.—Five major intersections on the alternate routes that operate at or near capacity were studied. The effect of diverting traffic through the intersections was noted by the time congestion began, the length of time the intersection was congested (see Fig. 1) and the total travel time for the traffic passing through the intersection. The results in Table 7 indicate congestion started earlier, but lasted about the same length of time as without control. The travel time was slightly increased, but this was primarily due to the increase in volume, rather than an increase in delay.

LONG-TERM EFFECTS OF THE CONTROLS

The control study was originally scheduled for a two-week period but was later extended for an additional five-week period. For the original two weeks a field crew of up to 20 men was available for the closed-system, input-output studies and for other counts on the freeway and arterial streets. The field crew consisted of hourly workers who are students from Texas A&M University and the University of Houston and some supervisory personnel from Texas A&M. After the initial two-week period the size of the field crew was reduced to eight because of costs and scheduling difficulties.

After February 5, the field crew was used for freeway and arterial street counts. The aerial photographs were used to obtain the total travel time on the inbound freeway and frontage roads. Moving vehicle studies were conducted to obtain trip time for individual vehicles.

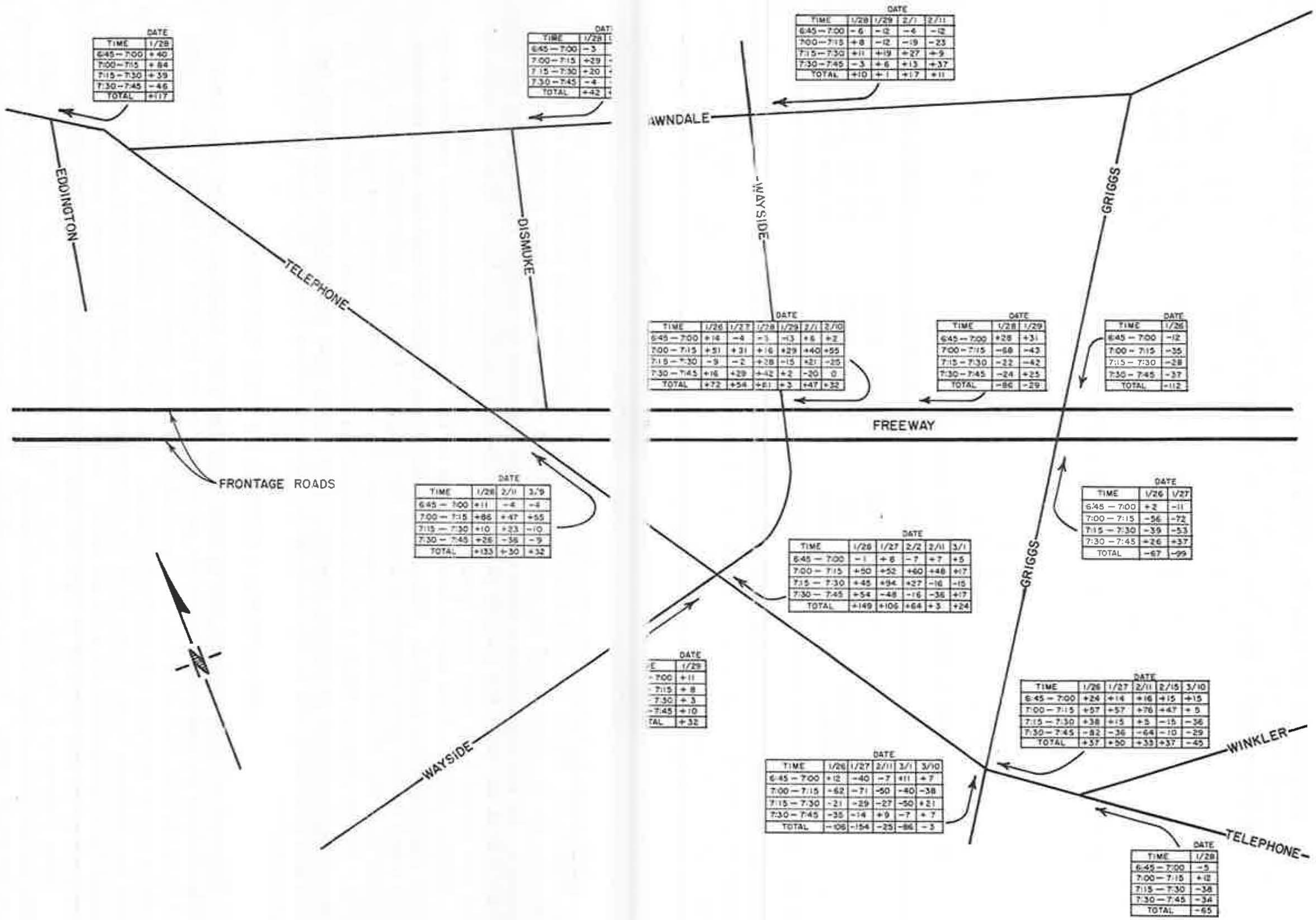


Figure 16. Change in traffic volumes during freeway cc l (volumes compared with 3-day average before control).

TABLE 7

EFFECTS OF CONTROL ON MAJOR INTERSECTION APPROACHES

Intersection	Start of Congestion (a. m.)	Length of Congestion (min)	Total Travel Time (veh-min)
South Telephone Approach to Griggs:			
Before Control	7:12	50	2123
During Control	7:09	47	2265
South Telephone Approach to Wayside:			
Before Control	7:23	37	1800
During Control	7:11	47	2805
South Telephone Approach to Gulf:			
Before Control	7:18	46	1030
During Control	7:10	45	1627
West Griggs Approach to Telephone:			
Before Control	7:18	25	380
During Control	7:24	17	262
East Lawndale Approach to Wayside:			
Before Control	7:17	48	1668
During Control	7:14	49	1409

TABLE 8

AVERAGE 7-8 A. M. VOLUMES ON ENTRANCES TO THE FREEWAY

Entrance to Freeway System	Before Control January, 1964	During Control Feb. 1-5, 1965	During Control Feb. 8 - Mar. 12, 1965
Freeway near Broadway	2831	3185	3274
Detroit on ramp	218	122	no data
S. H. 225 on ramp	559	649	707
S. H. 35 on ramp[a]	818	726	750
Woodridge on ramp[a]	426	398	361
Mossrose on ramp[a]	643	318	412
Griggs on ramp[b]	683	496	493
Wayside on ramp[a]	335	332	315
Telephone on ramp[a]	413	356	341
Dumble on ramp[a]	345	294	318
Cullen on ramps (2)[b]	574	348	296
Scott on ramp	63	257	no data
Total	7908	7481	7656[c]

[a]Ramps which were metered.
[b]Ramps which were closed.
[c]Assumes Detroit entrance ramp volume = 122 and Scott entrance ramp volume = 257.

Freeway and Frontage Roads

Total System Travel Time, 7-8 a. m.—During the remainder of the control study (February 8-March 12, 1965) aerial photographic data were obtained for the purpose of determining the total 7-8 a. m. travel time in the freeway and frontage road system. However, bad weather forced the cancellation of flights on several days and on each of the days in which aerial photographs were taken the data proved unusable because of freeway accidents or similar traffic disturbance. Since a field crew of sufficient size for the closed system input-output counts was not available, these studies were not made. Hence, no data for total freeway system travel time are available.

Freeway and Ramp Volumes, 7-8 a. m.—The average 7-8 a. m. volumes on the freeway entrance ramps and the inbound freeway at Broadway during three time periods are shown in Table 8. The average freeway volume during the February 8 to March 12 control period increased by about 90 vehicles over the February 1-5 control period. This probably reflects more motorists finding that the freeway operation had been improved and thereby being attracted to enter the freeway at a point farther upstream than normal.

An increase in volume of about 70 vehicles was observed at the S. H. 225 entrance ramp, again reflecting the improved freeway operation. A 35-vehicle decrease in the volume at Woodridge was found. These vehicles probably normally bypassed the S. H. 225 entrance ramp to enter at Woodridge to reduce the amount of congested freeway driving. However, when the effects of the controls became well known, some of these vehicles probably began entering at S. H. 225 since the freeway congestion was greatly reduced.

The volume at the Mossrose entrance ramp increased by about 100 vehicles in the latter control period. At least two factors may have contributed to this. The first is that the initial diversion from this ramp may have been greater than the delay would have warranted. The notices distributed before the start of the control study warned of very large delays at this ramp. During the first two weeks of the study, some vehicles did find large delays at this ramp but during some portions of the control period there was little or no delay at the ramp. Hence, during the latter control period some vehicles probably tried this ramp and found the delay tolerable. The second factor contributing to the increased ramp volume is the increase in the metering rate by the policeman in charge of metering this ramp. Instead of adhering to the predetermined metering rates, the officer used his judgment as to the proper rates. This usually resulted in an increase in the metering rate and reduced delay, resulting

resulted from this change in metering rates.

A slight increase in volume was observed at the S. H. 35 entrance ramp. The volume at the Griggs ramp was virtually unchanged from the first control period to the second.

Small decreases in volume were observed at the Wayside and Telephone ramps and a slight increase was found at the Dumble ramp indicating a slight change in the travel patterns in this area. At the Cullen ramps a decrease of about 50 in the 7-8 a. m. volume was found. One possible explanation is that some drivers found that use of the frontage road instead of the freeway between Cullen and Dowling Streets resulted in little increase in travel time.

No data were collected at the Detroit and Scott entrance ramps since anticipated volume changes at these ramps were slight.

Individual Vehicle Travel Time.—A contour map of travel time on the freeway to Dowling Street is shown in Figure 17. The contours are quite similar to those obtained during the February 1-5, 1965, control period. Thus, the data obtained during the February 1-5 period probably represented steady-state or equilibrium conditions.

Five-Minute Volumes on the Freeway at Griggs Road.—Figure 18 shows the 5-minute volumes on the freeway at the Griggs Road overpass. The solid line represents the data from January 1964, and the dashed line represents the data obtained during the last five weeks of the control study.

It can be seen that the 5-minute volumes during the control study are consistently higher than the corresponding volumes obtained in the "before" study up to about 7:30 a. m. and are approximately the same after 7:30 a. m. This means that during the control study more vehicles were able to get out of the congested Broadway-Griggs subsystem during the early period, leaving less storage to be cleared in the latter period.

The average 7:00-7:30 a. m. volume was 2703 vehicles during this period compared to 2414 vehicles before the control study. This represents a 12 percent increase in volume during this time period.

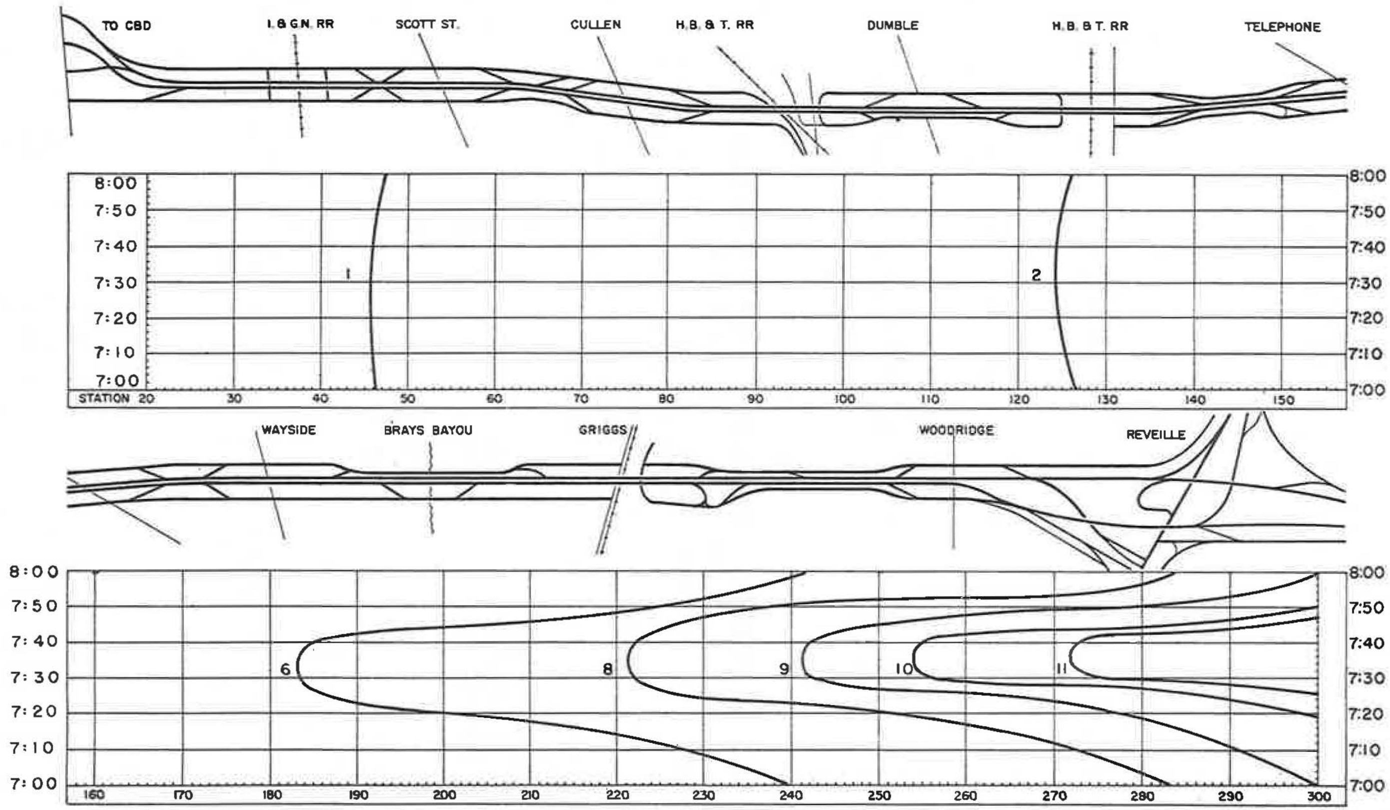


Figure 17. Average travel time (minutes) to end of freeway during control—February 8–March 12, 1965.

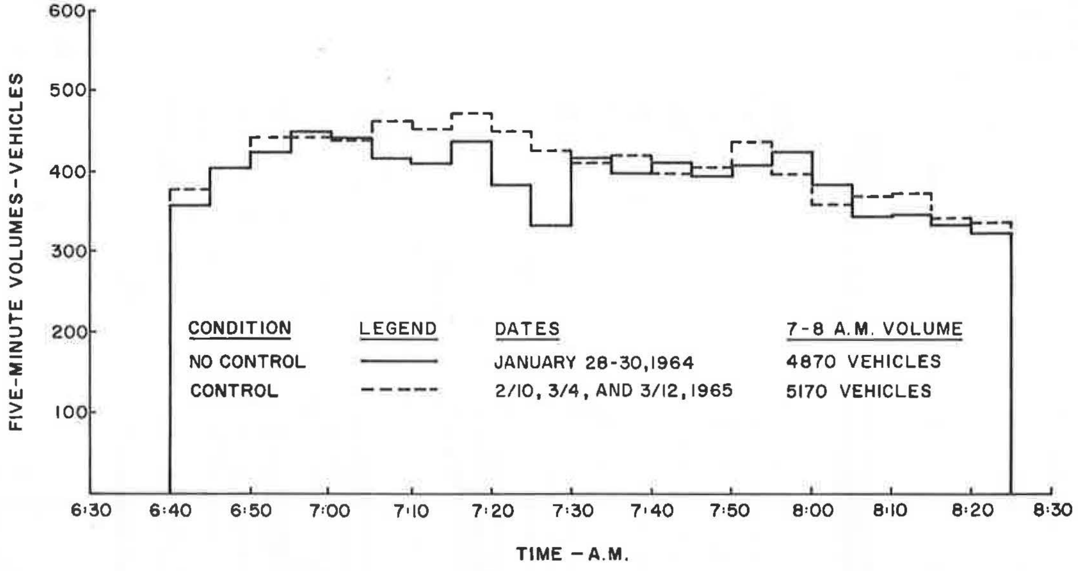


Figure 18. Five-minute volumes on Gulf Freeway at Griggs Road.

TABLE 9

TOTAL SYSTEM TRAVEL TIME BEFORE, DURING AND AFTER THE CONTROL STUDY

System or Subsystem	Before Control	During Control	After Control
Inbound freeway:			
Broadway to Griggs	575	297	578
Griggs to S. HB&T RR	367	310	386
S. HB&T RR to Dowling	302	266[a]	260
Total inbound freeway	1244	873	1224
Inbound frontage road	190[a]	201[a]	214
Total inbound freeway and frontage road	1434	1074	1438

[a]Based on incomplete data caused by inadequate light conditions which made aerial photography during the early part of the 7-8 a.m. period impossible.

Arterial Streets

The results of the freeway controls on arterial streets were not divided into immediate and long-term effects. However, the shift in traffic volume during the control period can be seen in Figure 16. After the first two days of control, the traffic pattern on the arterial streets did not appear to differ significantly from the conditions that prevailed before the controls were initiated.

OPERATION AFTER TERMINATION OF THE CONTROLS

The last day that the controls were in effect was March 12, 1965. Hence on Monday, March 15, the freeway returned to an uncontrolled state. This section contains the results of studies during the period of time from March 15 to April 30, 1965.

Freeway and Frontage Roads

Total System Travel Time, 7-8 a. m.—Several attempts were made to take aerial photographs for the purpose of determining the total system travel time from 7-8 a. m. after the controls had been removed. Adverse weather or unusual traffic conditions (due to accidents or other reduced-capacity situations) reduced the number of good days of data to one—April 28, 1965. This was approximately a month and a half after termination of the control study.

Table 9 shows the total 7-8 a. m. travel time on the inbound freeway and frontage roads on April 28, 1965, as well as comparable figures before the control study and during the second week of the control study. The data in this table indicate that, as far as the total travel time is concerned, the freeway conditions after the termination of the controls returned approximately to the conditions which existed before the beginning of the control study. However, it should be borne in mind that only one day's data were used in the "after" analysis.

Freeway and Ramp Volumes, 7-8 a. m.—Several counts were made at entrances to the freeway during the period March 15-April 30, 1965, after the termination of the controls. Table 10 contains the average 7-8 a. m. volumes at the entrances to the freeway before, during and after the control study.

It would seem that the traffic pattern would return to that which prevailed before the controls were initiated. Indeed, the total volume entering the freeway returned almost to the level of January 1964. Also the S. H. 225, Telephone and Scott on ramp volumes returned to the volumes obtained before the control study. However, the volumes at other locations did not return to the volume level of January 1964.

TABLE 10

AVERAGE 7-8 A. M. VOLUMES ON ENTRANCES TO THE FREEWAY BEFORE, DURING AND AFTER THE CONTROLS

Entrance to Freeway System	Before Control	First 2 Weeks	Last 5 Weeks	After Control
Freeway at Broadway	2831	3185	3274	3306
Detroit on ramp	218	122	—	—
S. H. 225 on ramp	559	649	707	549
S. H. 35 on ramp[a]	818	726	750	777
Woodridge on ramp[a]	426	398	361	343
Mossrose on ramp[a]	643	318	412	558
Griggs on ramp[b]	683	496	493	637
Wayside on ramp[a]	335	332	315	257
Telephone on ramp[a]	413	356	341	401
Dumble on ramp[a]	345	294	318	317
Cullen on ramps (2)[b]	574	348	296	509
Scott on ramp	63	257	—	71
Total	7908	7481	7646[c]	7847[d]

[a]Ramps which were metered.
[b]Ramps which were closed.
[c]Assumes Detroit entrance ramp volume = 122 and Scott entrance ramp volume = 257.
[d]Assumes Detroit entrance ramp volume = 122.

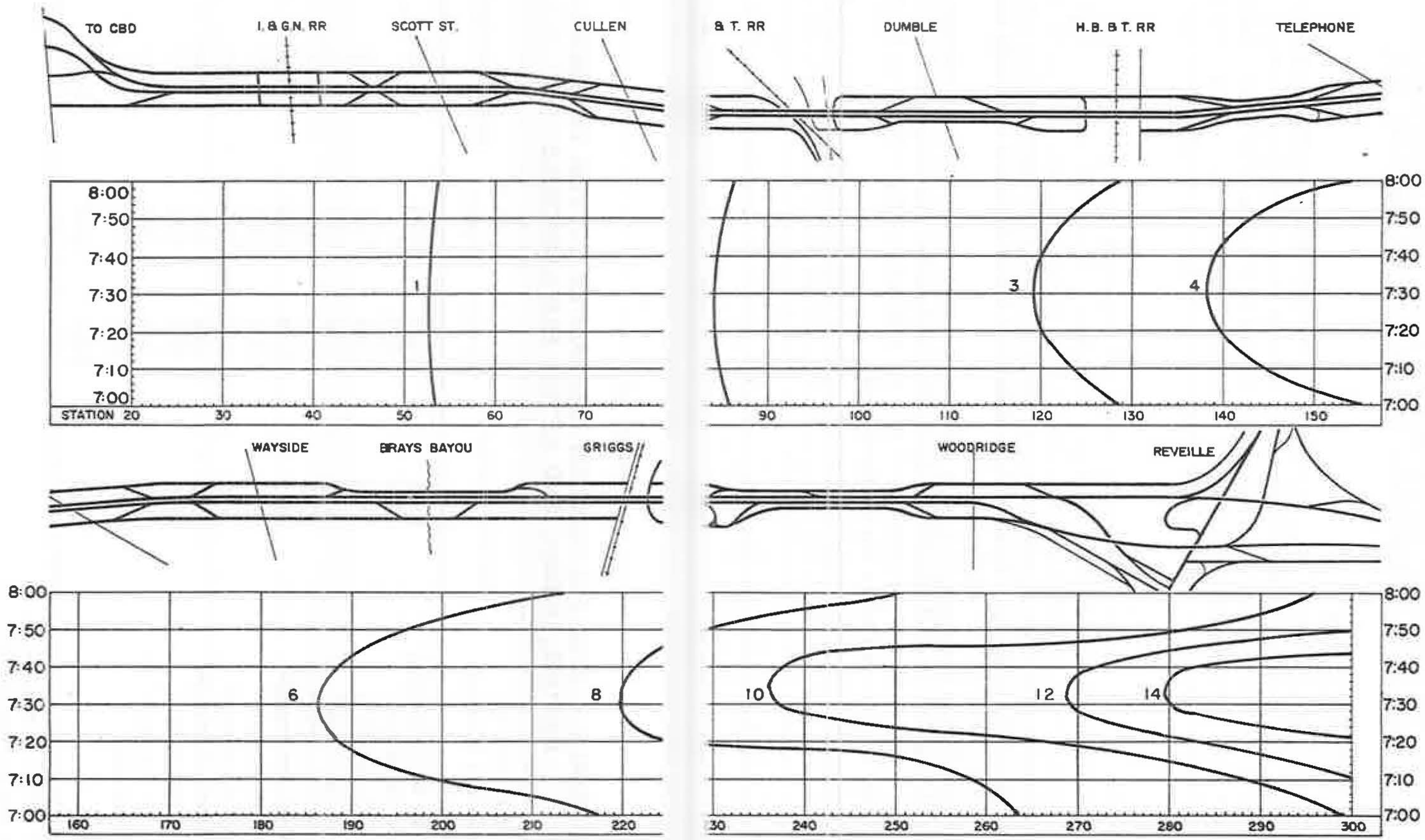


Figure 19. Average travel time (minutes) to ɛ ɔf freeway after controls—March 15-April 30, 1965.

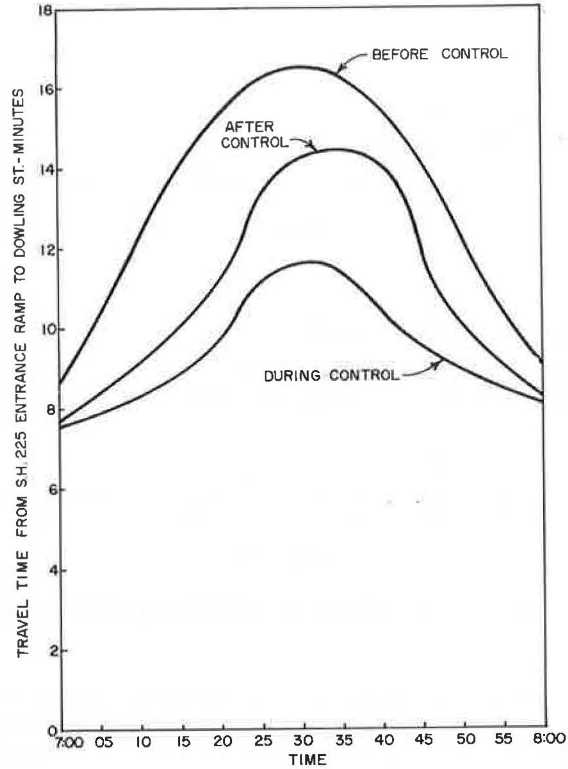


Figure 20. Average travel time from S. H. 225 entrance ramp to Dowling St. before, during and after control study.

The 7-8 a. m. volume on the freeway at Broadway remained about 475 vehicles greater than the volumes obtained before the controls. There was a decrease in volume on each of the S. H. 35, Woodridge and Mossrose entrance ramps with a total decrease of about 200 vehicles after the controls relative to the volumes in January of 1964. Thus, a net increase in volume of about 275 vehicles was found between Broadway and Griggs Road.

The volumes on the Griggs, Wayside, Dumble and Cullen ramps were also considerably lower (a total of about 215 vehicles) after the controls terminated than they had been before the start of controls. The volume on the Dumble entrance ramp remained virtually unchanged from the last 5 weeks of the control study after the termination of the controls. This seems to suggest that many motorists who normally used the Dumble entrance ramps and who diverted during the control study found alternate routes which they liked as well as their old freeway routes.

Individual Vehicle Travel Time.—The contour map of average travel time to the end of the freeway after the termination of the controls is shown in Figure 19. It can be seen that these conditions were somewhere between those before the controls and those during the control study. In other words, conditions were better after the termination of the controls than they were before the control study but worse than they were during the control study. Figure 20, which is a plot of the average travel time from the S. H. 225 entrance ramp to Dowling Street before, during and after the controls, clearly shows this. The line of average travel time from the S. H. 225 entrance ramp vs time after the controls falls between similar lines obtained from data taken before the controls and during the controls.

Five-Minute Volumes on the Freeway at Griggs Road.—Figure 21 shows the 5-minute volumes on the freeway at Griggs Road before the controls were initiated and after

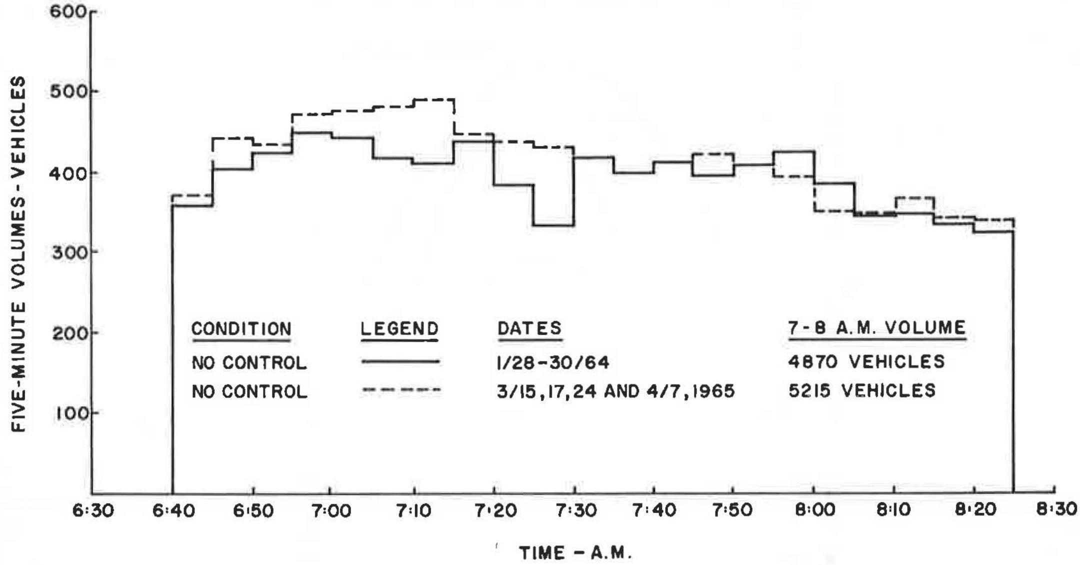


Figure 21. Five-minute volumes on Gulf Freeway at Griggs Road.

they were terminated. As can be seen, a substantial change occurred between the two time periods. Until 7:30 a. m. the volumes after the controls were terminated were higher than those of January 1964, and after 7:30 a. m. they were both about the same. The total 7-8 a. m. volume was about 350 vehicles greater in the latter period. The increased volume (after the controls ended) up to about 7:30 seems to come from two

suggesting a higher capacity (probably due to the better light conditions in the latter period). The second is the decreased severity of the volume decrease caused by downstream congestion.

Arterial Streets

Several counts were made on the arterial streets during the period March 15 to April 15, 1965, after the termination of the controls. Figure 22 shows the change in volume from 6:45 to 7:45 a. m. when compared to volumes before control.

It would seem that the total hourly volumes have in most cases returned to the level before control. There is still shifting of traffic away from the Griggs entrance ramp approaches during the 7:00 to 7:15 time period when the ramp was closed.

There was no significant change in travel times on the alternate routes after the controls were removed (Table 6).

PUBLIC OPINION

The objective of the numerous traffic counts, travel time runs, and aerial surveys was to determine the effect of the freeway control plan on the peak period traffic. The changes that are brought about in travel time or the length and severity of congestion may be readily evident to the researcher or the traffic engineer, but not to the individual motorist. Since public acceptance of a control system will be so vital to its successful operation, special attention was given to a study of this aspect. It was desired to obtain as much data as possible to evaluate the reaction of individual motorists to the operation of the controls.

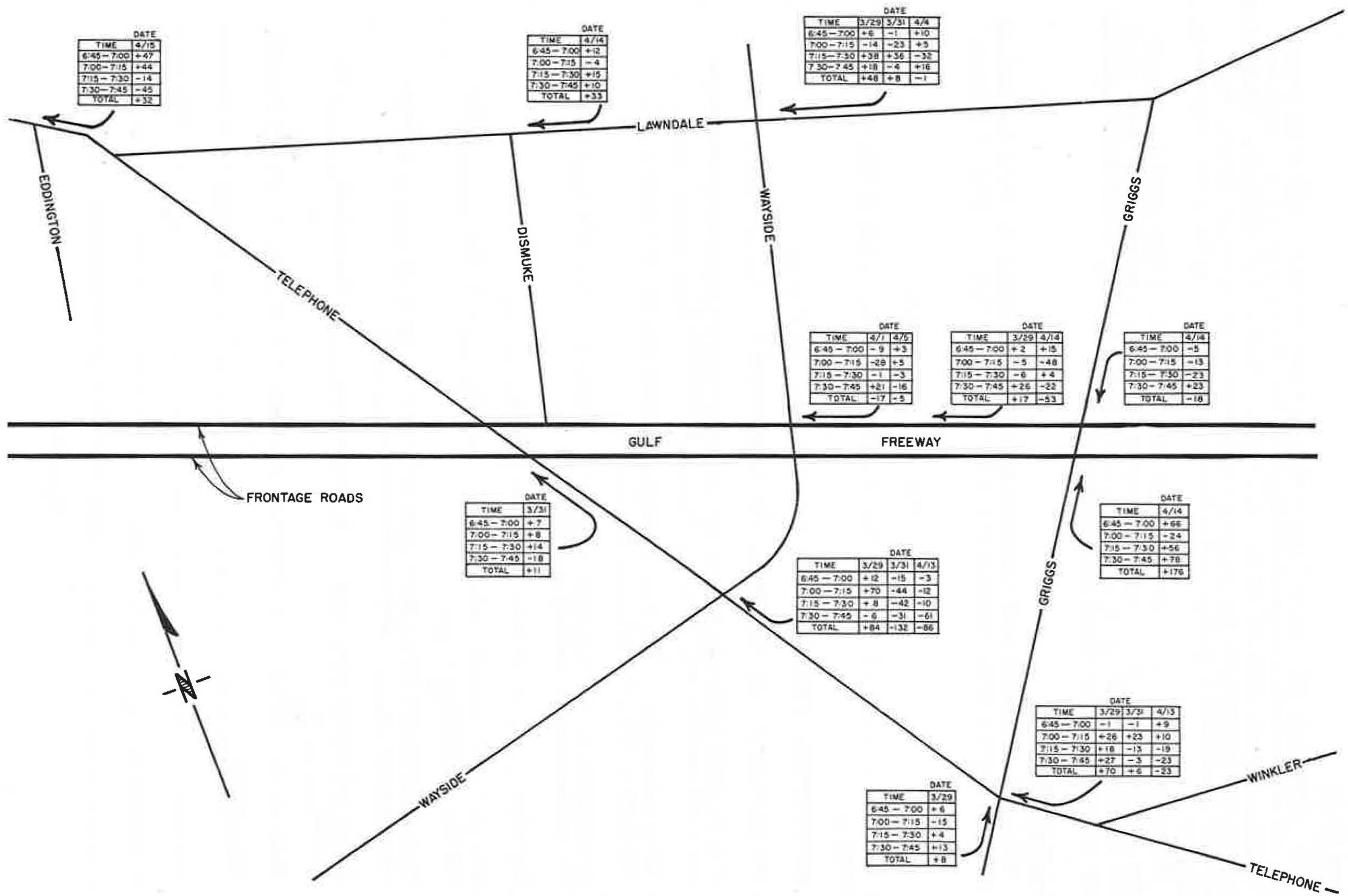


Figure 22. Change in traffic volumes after freeway control (volumes compared with 3-day average before control).

News Media

The newspapers and radio-television stations were given the details of the control plan in a news release on January 19 (Appendix A). No special effort was made to encourage support of the plan by the news media. Routine news articles were published and reported on radio and television one day before the control study began. No editorial comments or special news features were observed in the news media during the study.

Public opinion as expressed through the news media was represented by one comment, contained in a news article. A Houston City Councilman stated that the control plan was denying Houston taxpayers access to a public facility. No official complaints were received from the Councilman's office.

Questionnaire Study

The experience of the first control study conducted in August 1964 was that although significant improvements in traffic characteristics were made, the public did not ex-

FREEWAY CONTROL QUESTIONNAIRE

All questions below pertain to travel from 6:45 - 8:00 a.m. during the period, January 26 to February 5.

1. Did the freeway ramp controls affect your trip? Yes_____ No______

2. Did you avoid using the Gulf Freeway due to the controls? Yes_____ No_____

3. If you traveled on the Gulf Freeway, did you use a different entrance ramp than the one you would normally use? Yes_____ No_____ Name of Ramp______________________

the freeway controls? Yes_______ No_______

5. If you entered the freeway, please indicate your impression of the delay encountered at the entrance ramp by checking one of the following:

   No Delay_______ Slight Delay_______ Long Delay__________

6. Was the overall travel time of your peak trip reduced______, increased______, about the same as normal________.

7. Do you feel that the control plan greatly improved traffic operation_______, produced no noticeable change_____, made conditions worse________.

8. Do you feel that the control plan should be continued______, discontinued_______, no opinion________.

9. Please comment on the control plan giving any suggestions or criticisms you feel pertinent.

   COMMENTS:____

   ____

   ____

   ____

Figure 23.

press its opinion, one way or another. Except for a few phone calls to the Highway Department or City Hall, no criticism or praise of the control plan was received. Therefore, a questionnaire survey was conducted as part of the control plan of January 1965 in an attempt to determine the consensus of the motoring public involved in the study.

The survey was made of those persons who enter the freeway by one of the inbound entrance ramps from S. H. 225 to Dumble. It did not include traffic that entered the study area via the freeway lanes from upstream of the Reveille Interchange area.

Addresses of many of the motorists who entered the freeway by the ramps in the control area were obtained from origin-destination surveys (8) conducted during the past 18 months. A questionnaire (Fig. 23) with an attached letter of explanation was mailed to these addresses on February 3, two days before the end of the first two-week period. The forms were to be completed and returned by mail.

The distribution by mail had certain disadvantages, such as (a) occupants had moved or changed their trip, (b) addresses were incomplete or (c) addresses were copied down wrong. However, distribution at the ramps would have disrupted traffic while other field studies were being made to determine the effectiveness of freeway control.

Results of Questionnaire Survey

The results of the questionnaire survey are summarized in Tables 11 and 12. Because of the different volumes on the ramps and the different percent returns, the number of motorists responding to the questions are not easily compared. Table 12 presents the data in terms of the percent of total returned by each ramp.

As each question is summarized by entrance ramps, it is important to consider the 3000 vehicles that enter the study area upstream of S. H. 225. These motorists receive the maximum benefit of any control system that improves the flow on the freeway lanes, and suffer none of the disadvantages such as added delay at entry or diversion to other ramps. Yet it was impossible to contact these motorists since they had never participated in an origin-destination survey.

Percent Return.—The number of forms distributed and returned is indicated by ramp at the top of Tables 11 and 12. The total return of 28. 4 percent is considered good for a mailed survey. The percent return by individual ramps was close to the average with the exception of three ramps:

1. S. H. 225—The 16. 5 percent return could be attributed to the fact that this ramp was not controlled.
2. S. H. 35—The high return from this ramp, 38. 6 percent, can be attributed to two things. The metering control changed the operation of this ramp from a two-lane type to a one-lane type and thereby improved merging conditions. The motorists are very interested in methods for improving overall travel conditions. A very high return was received from this ramp for the origin-destination survey conducted in 1963.
3. Wayside—The low return of 18. 4 percent can be attributed to the fact that this ramp had the smallest number of forms distributed. A larger percent of forms was sent to motorists who, during the origin-destination survey, used the ramp during a time not affected by the controls.

Returns on Each of Eight Questions.—

Question 1—Did the freeway ramp control affect your trip?

The forms were distributed to persons who had used the ramp during the peak hour. Some of these persons had changed their trip or had entered the freeway when the controls were not in effect. Those returns that answered Yes (527 of 771) to question 1 were analyzed separately with the following results:

		Percent of Return
Diversion	Used City Streets	9. 5
	Used Different Ramp	18. 5
	Changed Time of Trip	20. 0
Delay at Ramp	No Delay	42. 0
	Slight Delay	43. 0
	Long Delay	6. 0
Travel Time	Reduced	63. 0
	Increased	18. 0
	Same	17. 0
Traffic Conditions	Improved	76. 0
	Made Worse	10. 0
	No Change	11. 0
Study Plan	Continue	76. 0
	Discontinue	15. 0
	No Opinion	9. 0

Question 2—Did you avoid using the Gulf Freeway due to the controls?

Traffic conditions on the city street system must be considered in the design of freeway control. The survey indicated that 7. 8 percent of the traffic diverted to the arterial streets. Volume counts made several days after the O & D survey was mailed indicated that this percentage decreased as the control study continued.

Question 3—Did you use a different entrance ramp during the control study?

Where continuous frontage roads and alternate routes on the arterial street system are available, the traffic moves from one ramp to another, depending on the condition [illegible] trol plan.

Question 4—Did you change the starting time of your trip?

To spread the traffic demand at the ramps, it was suggested that the motorists could avoid unusual delays at the ramps if the time of arrival was changed to miss the control period. The survey indicated that 16. 2 percent of the traffic changed the time of trip.

Question 5—Indicate your impression of the delay encountered at the entrance ramp.

A distinction between slight and long delays cannot be made in terms of time since the normal delay at one ramp may be 3 minutes and at another ramp, only 1 minute. Those that encountered long delays (4. 6 percent) were in most cases expressing their dissatisfaction with the control plan. For example, one-fourth of this group normally use the Griggs Ramp which was closed. Forty-one percent of the motorists indicated a slight delay at the entrance. This was anticipated in the design of the plan. However, only 7 percent of the 41 percent delayed also noted that the total travel time was increased.

Question 6—What effect did the control system have on the overall travel time of your trip?

The results indicated that 13. 5 percent (average for all controlled ramps) of the traffic entering the freeway by one of the controlled ramps had longer travel times. Half of this group, however, did not want the control study to be discontinued. It should be noted again that traffic entering the study area on the freeway lanes is affected by the control study. If a survey had been made of this traffic, the results should have approximated those from S. H. 35, except there would be no additional delays caused by metering the traffic.

Question 7—How do you feel that the control plan affected traffic operation?

Only 7 percent of the returns indicated that the control system made conditions worse. One-half of this group used the arterial street system during the control; the other half experienced long delays at the ramps and increased travel times. Many persons who indicated no change or increased travel times also noted an improvement in the traffic conditions. Comments received on these returns were of improved merging operations and a smoother, more uniform flow of traffic on the freeway lanes.

Question 8—Do you feel the control plan should be continued?

The returns indicate that 12.7 percent of the motorists were in favor of discontinuing the study. The ramps that benefit the most from the control plan are S. H. 225, S. H. 35, Woodridge and Mossrose. Only 6 percent of this traffic is in favor of discontinuing the controls, as compared to 25 percent of the traffic downstream of Griggs Road. The belief that the ramps in the Reveille area are favored over those downstream of Griggs Road is reason for the opposition to the plan. The closure of Griggs entrance ramp for 15 minutes is the major cause of the opposition.

Questionnaire Conclusions.—Based on the results of the mailed questionnaire, the following conclusions are made concerning the freeway control plan:

1. A majority of the motorists indicated that the controls were effective in reducing travel time. Some additional delay was encountered at the entrance ramps but overall travel time was reduced.
2. The traffic operation on the freeway was improved.
3. The motorists were prepared to accept a freeway control system on a regular basis. Special emphasis should be given to informing motorists on ramps to be closed of the possible alternatives.
4. The returns from ramps S. H. 35, S. H. 225, Woodridge and Mossrose were more favorable toward the control plan.

DISCUSSION

General Control Plan

The control plan as developed and later amended worked very well, as an examination of the total system travel times will reveal. The estimates of demand and capacity were at least fairly accurate and the freeway level of service was greatly improved. The capacities at bottleneck locations were probably overestimated slightly (5 percent or so) for the January-February portion of the control study since the freeway volumes during these months (especially January) are lower than they are during the later (summer) months. This is probably due to the earlier sunrise; during the later months the entire peak period fell during good light conditions. In the January studies darkness prevailed until about 7:15-7:30 a. m., well into the peak period. Except for this minor difficulty, the demand-capacity approach provided a rational means of developing a control plan for a freeway system.

When the demands and capacities are estimated for a control plan, an inherent assumption is that these values will not be changed. However, accidents, adverse weather, etc., can change both the demands and capacities at several locations on the freeway. Because of the fixed-time nature of the control system, it was not flexible enough to handle these unusual situations. Such situations will undoubtedly tax the capabilities of the most sophisticated, traffic-adjusted control system that will be developed. However, the more sophisticated control systems will undoubtedly be much better able to cope with the reduced-capacity occurrences.

The opening time of the Griggs entrance ramp at 7:20 a. m. was probably somewhat early since the ramp vehicles normally precipitated congestion on the freeway there shortly after the ramp was opened. The opening time of 7:20 a. m. was actually a compromise in order to avoid diversion to the street system during its peak period. Perhaps this ramp should have been closed longer or metered for a period after 7:20 a. m.

TABLE 11

SUMMARY OF FREEWAY CONTROL QUESTIONNAIRE SURVEY—NUMBER OF RETURNS

	S.H. 225	S.H. 35	Woodridge	Mossrose	Griggs	Wayside	Telephone	Dumble	Total
NUMBER DISTRIBUTED	355	560	324	442	360	195	251	213	2700
NUMBER RETURNED	60	217	107	110	113	37	76	51	771
PERCENT RETURN	16.5	38.6	33.0	24.7	31.4	18.4	30.3	24.0	28.4
1. Did the Freeway ramp controls affect your trip?									
YES	37	153	75	84	75	20	42	31	517
NO	19	52	28	24	31	17	29	15	215
NO ANSWER	4	12	4	2	7	0	5	5	39
2. Did you avoid using the Gulf Freeway due to the controls?									
YES	1	16	3	3	14	4	7	12	60
NO	56	190	102	104	93	33	62	35	675
NO ANSWER	3	11	2	3	6	0	7	4	36
3. Did you use a different entrance ramp than the one you would normally use?									
YES	7	15	9	23	31	5	14	4	108
NO	48	182	94	80	70	31	52	41	598
NO ANSWER	5	20	4	7	12	1	10	6	65
4. Did you change the starting time of your peak hour trip to avoid the freeway controls?									
YES	4	29	11	14	31	8	14	14	125
NO	51	175	93	94	75	29	54	33	604
NO ANSWER	5	13	3	2	7	0	8	4	42
5. Indicate your impression of the delay encountered at the entrance ramp.									
SLIGHT DELAY	24	86	34	62	46	16	29	20	317
LONG DELAY	2	7	3	5	9	1	5	3	35
NO ANSWER	6	29	5	12	17	5	19	9	102
6. What effect did the freeway control have on the overall travel time?									
REDUCED	39	129	70	67	48	17	25	11	406
INCREASED	5	20	17	10	26	3	11	12	104
NO CHANGE	13	53	17	30	32	14	31	23	213
NO ANSWER	3	15	3	3	7	3	9	5	48
7. What effect do you feel the freeway control had on traffic operation?									
IMPROVED OPERATION	45	158	88	83	59	20	32	21	506
NO CHANGE	10	31	10	21	23	12	28	17	152
MADE CONDITIONS WORSE	2	9	5	2	22	2	5	6	53
NO ANSWER	3	19	4	4	9	3	11	7	60
8. Do you feel that the control plan should be continued?									
YES	48	166	87	82	54	22	29	17	505
NO	2	8	3	14	32	9	18	12	98
NO OPINION	8	21	13	12	16	4	21	17	112
NO ANSWER	2	22	4	2	11	2	8	5	56

TABLE 12

SUMMARY OF FREEWAY CONTROL QUESTIONNAIRE SURVEY—PERCENT OF RETURNS

	S.H. 225	S.H. 35	Woodridge	Mossrose	Griggs	Wayside	Telephone	Dumble	Total
NUMBER DISTRIBUTED	355	560	324	442	360	195	251	213	2700
NUMBER RETURNED	60	217	107	110	113	37	76	51	771
PERCENT RETURN	16.5	38.6	33.0	24.7	31.4	18.4	30.3	24.0	28.4
1. Did the Freeway ramp controls affect your trip?									
YES	61.6	70.5	70.1	76.4	66.4	54.1	55.3	60.8	67.1
NO	31.7	23.9	26.2	21.8	27.4	45.9	38.2	29.4	27.8
NO ANSWER	6.7	5.6	3.7	1.8	6.2	0.0	6.5	9.8	5.1
2. Did you avoid using the Gulf Freeway due to the controls?									
YES	1.7	7.4	2.8	2.7	12.4	10.8	9.2	23.5	7.8
NO	93.3	87.6	95.3	94.6	82.1	89.2	81.6	68.6	87.5
NO ANSWER	5.0	5.0	1.9	2.7	5.5	0.0	9.2	7.9	4.7
3. Did you use a different entrance ramp than the one you would normally use?									
YES	11.7	6.9	8.4	20.9	27.4	13.5	18.4	7.9	14.0
NO	80.0	83.9	87.9	72.7	62.0	83.8	68.4	80.4	77.6
NO ANSWER	8.3	9.2	3.7	6.4	10.6	2.7	13.2	11.7	8.4
4. Did you change the starting time of your peak hour trip to avoid the freeway controls?									
YES	6.7	13.4	10.3	12.7	27.4	21.6	18.4	27.4	16.2
NO	85.0	80.6	86.9	85.5	66.4	78.4	71.1	64.7	78.3
NO ANSWER	8.3	6.0	2.8	1.8	6.2	0.0	10.5	7.9	5.5
5. Indicate your impression of the delay encountered at the entrance ramp.									
NO DELAY	46.7	43.8	60.7	28.2	36.3	40.5	30.3	37.3	41.1
SLIGHT DELAY	40.0	39.7	31.8	56.4	40.7	43.2	38.1	39.2	41.1
LONG DELAY	3.3	3.2	2.8	4.5	8.0	2.7	6.6	5.9	4.6
NO ANSWER	10.0	13.3	4.7	10.9	15.0	13.6	25.0	17.6	13.2
6. What effect did the freeway control have on the overall travel time?									
REDUCED	65.0	59.4	65.4	61.0	42.5	45.9	32.9	21.6	52.7
INCREASED	8.3	9.2	15.9	9.1	23.0	8.1	14.5	23.5	13.5
NO CHANGE	21.7	24.4	15.9	27.2	28.3	37.9	40.8	45.1	27.6
NO ANSWER	5.0	7.0	2.8	2.7	6.2	8.1	11.8	9.8	6.2
7. What effect do you feel the freeway control had on traffic operation?									
IMPROVED OPERATION	75.0	72.8	82.2	75.4	52.2	54.1	42.1	41.1	65.6
NO CHANGE	16.7	14.3	9.3	19.1	20.4	32.4	36.8	33.3	19.7
MADE CONDITIONS WORSE	3.3	4.1	4.7	1.8	19.5	5.4	6.6	11.8	6.9
NO ANSWER	5.0	8.8	3.8	3.7	7.9	8.1	14.5	13.8	7.8
8. Do you feel that the control plan should be continued?									
YES	80.0	76.5	81.3	74.5	47.8	59.5	38.2	33.3	65.5
NO	3.3	3.9	2.8	12.7	28.3	24.3	23.7	23.5	12.7
NO OPINION	13.4	9.5	12.2	11.0	14.2	10.8	27.6	33.3	14.5
NO ANSWER	3.3	10.1	3.7	1.8	9.7	5.4	10.5	9.9	7.3

TABLE 13

TIME INTERVALS BETWEEN SUCCESSIVE VEHICLES, DUMBLE SIGNAL INSTALLATION

Vehicles	No. Observed	Interval (sec)
0-1	147	3. 3
1-2	93	2. 7
2-3	51	2. 4
3-4	5	2. 2

TABLE 14

COMPARISON OF THEORETICAL AND OBSERVED METERING RATES, DUMBLE SIGNAL INTALLATION

Time	Theoretical 5-Min Rate	Observed 5-Min Rate
7:05-7:10	40	35
7:10-7:20	25	24
7:20-7:25	40	35

Operation of the Controls

Two problems did arise with the manual metering operation. One was that the officers were visible from the freeway and the freeway traffic tended to slow down slightly in the vicinity of the metering point. The second was the tendency on the part of some of the policemen to change the metering rates according to their subjective evaluation of the freeway and merging traffic conditions. The tendency which was noted was an attempt to reduce the length of the queue at the metering point when, in some cases, one object of the control may have been to develop a long queue (to discourage the use of that ramp). In some instances the officer's judgment may have been superior to the fixed-time plan (especially in the case of upstream accidents) but their changes in the controls conflicted somewhat with the research objective of evaluating the operation under a particular control plan.

Signal Installation at Dumble.—The starting headways for metered vehicles at the Dumble signal installation are summarized in Table 13. These values are

headways at typical signalized intersections which may be attributed, in part, to the conservative reaction of drivers in an unfamiliar situation.

Table 14 is a comparison of the observed metering rates at Dumble with the desired theoretical rates established by the master freeway control plan. The observed rates are seen to be slightly lower due to the comparative sluggishness in the starting headways as explained above.

Two police officers were stationed at the signal to enforce metering on all but one day. On that day metering was accomplished by the signal alone and out of 123 vehicles metered, only 5 violations were observed. There was no significant difference in the starting headways or the number of violations with or without the policemen.

The effect of the bulk-service technique of ramp metering on the critical gap for merging ramp vehicles is illustrated in Figure 24. The critical gap for bulk service metering is seen to be 3. 1 seconds compared to 2. 5 seconds for normal operation. The reason for this is not clear, but it is suspected that (a) metered vehicles have a greater relative speed and (b) metered drivers are more conscious of the merging maneuver and are therefore more cautious.

The general conclusions of those observing the operation were that if metering is to be accomplished on the frontage road, the amber phase is a necessity. However, the inclusion of an amber phase in each cycle limits the maximum metering rate. In order to obtain higher metering rates using the bulk service technique, the cycle length must be increased allowing several vehicles to arrive at the freeway merging area at one time. This creates a platoon of ramp vehicles and raises the critical acceptance gap which for a given ramp and freeway volume will result in a lower merging level of service than that obtained during normal operation or during single-vehicle metering. For these reasons, it is suggested that in the future the metering station be located on the ramp, and that vehicles be metered one at a time using just the red and green phases.

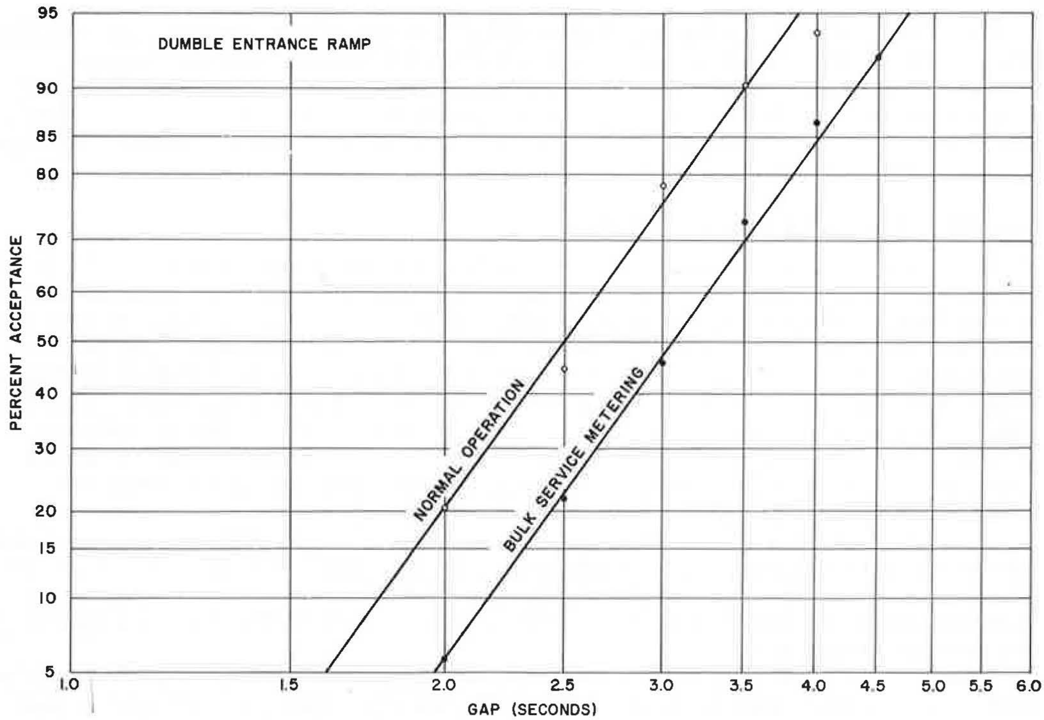


Figure 24. Comparison of percent acceptance for moving merging vehicles during normal and controlled operation.

Ramp Closure.—The personnel responsible for closing and reopening the three entrance ramps (with barricades) were very dependable and the actual closure times were very close to the desired closure times each day. This ramp closure technique, while somewhat crude, worked extremely well, and created no special problems.

Overall Effects of the Controls

The overall effect of the controls was a sizable improvement in the traffic operation on the inbound Gulf Freeway during the morning peak period. The total travel time on the inbound freeway and frontage roads was reduced by about 360 vehicle hours, roughly a 25 percent reduction, while a 48 percent reduction in travel time was accomplished on the freeway between Broadway and Griggs. Most of the additional travel time on the arterial streets naturally appears in the form of delay at the critical intersections. Delays at five critical intersections were studied and a total increase in delay of 23 vehicle-hours was found at these intersections. Thus, the overall decrease in travel time was about 320-330 vehicle-hours which, assuming an average vehicle occupancy of 1. 5 persons per vehicle, represents a savings of about 475-500 man-hours per day.

The observed changes in the travel patterns were not unexpected. Generally the volumes decreased on entrance ramps that were controlled and increased on uncontrolled ramps and the freeway near Broadway. The total volume using the freeway from 7-8 a. m. decreased about 5 percent, although between Broadway and Griggs the total 7-8 a. m. volume using the freeway was virtually unchanged.

Individual vehicles saved a substantial amount of time on inbound freeway trips in the 7-8 a. m. period, especially between Broadway and Dumble Streets. Travel time savings on a trip between Broadway and Dowling were as much as 10 minutes.

The additional delay occurring at the critical arterial street intersections was slight. Thus, a considerable system travel time reduction was produced by the controls.

The questionnaire sent to the ramp motorists revealed that about 70 percent of the ramp motorists felt that the freeway traffic operations were improved by the controls and that the controls should be continued. This indicates the readiness of the motorists for some type of freeway ramp controls.

Direction of Future Ramp Control Work

The two control plans which have been evaluated to date have both been of the fixed-time type. Time alone determined the type and degree of controls which were in effect at each ramp. Historic traffic data obtained from previous studies were used to estimate the demands at the various locations. While this type of demand-capacity analysis provides a rational basis for a control system and was an excellent first step in developing a control system, it is not at all flexible and cannot respond to reduced-capacity occurrences nor even normal fluctuations in demand or daily variations in demand. This fairly simple type of control system was necessary to determine the order of magnitude of the benefits to the peak-period traffic and to determine the responses or reactions of the motorists to these controls.

Thus the study shows that one of the next steps should be research on a control system which will respond to traffic conditions on the freeway. This type of control system can base the individual ramp controls on what the freeway traffic conditions are at the particular instant of time rather than what they were at that time on a typical day several months ago.

This can best be accomplished by immediate installation of ramp control signals at each of the inbound entrance ramps. This will permit studies to determine the best type of ramp signal and the best operation of the signals. The first signal installation should be capable of manual operation and should also have several fixed time settings available. With the signals, the problem of subjective decisions of the police officers personnel at the ramps will be greatly reduced. The differences in freeway level of service under one-at-a-time or two-at-a-time metering can be tested.

Such a signal system could be operated at one or two locations according to traffic conditions on the freeway as detected manually. Thus the proper variables (gaps, 3-lane volume, 1-lane volume, density, etc.) to be detected and the proper detector location can be determined. This determination is, of course, necessary before a fully automatic control system can be developed.

The final step in an automatic control system is the interconnection of all control locations so that they can truly be operated as a system. Some form of computer or real time control system may be required to accomplish this.

CONCLUSIONS

1. The control plan which was tested was quite successful at reducing the Gulf Freeway congestion during the morning peak period. Overall freeway travel time was reduced about 25 percent.
2. The control plan tested produced little adverse effect on the arterial street system near the Gulf Freeway.
3. The total 7-8 a.m. volume using the inbound Gulf Freeway decreased about 5 percent during the control study.
4. Individual vehicles saved as much as 10 minutes in traveling between Broadway and Dowling during the control study.
5. The demand-capacity technique provides a good method for determining a fixed-time control plan.
6. A fixed-time control plan lacks the flexibility to deal with reduced-capacity situations such as accidents and adverse weather.
7. The motorists complied extremely well to the police-operated metering controls.
8. It is desirable that ramp metering signals release vehicles onto the freeway one at a time rather than allowing multiple entries.

9. Public acceptance of the controls was good and the study indicates that the motorists are prepared to accept a freeway control system on a continuing basis.

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Appendix

A news release (Fig. A-1) was issued to the newspapers and radio and television stations on January 19 by the Texas Highway Department. This release described the control study and listed the times and dates of control for the two-week study. The news articles that appeared in the two Houston newspapers are shown in Figures A-2 and A-3.

At the end of the first week of operation, it was apparent that a longer study period was required to reach a steady-state condition in traffic patterns. The news agencies were informed by phone of the extension of the control study. The resulting news article (Fig. A-4) did not contain specific times on the controls.

The statement by the City Councilman in that article was the only published criticism of the study.

OFFICIAL NEWS RELEASE

The second in a series of freeway control studies, conducted by the Texas Highway Department, City of Houston, and the Texas Transportation Institute of Texas A&M University under the sponsorship of the U. S. Bureau of Public Roads, will be placed in effect on the Gulf Freeway during the morning peak periods from January 26 to February 6, 1965.

The controls will consist of closing three ramps and metering, or limiting the number of vehicles that enter the freeway at the other ramps from State Highway 225 to Dowling Street. The following control plan for the time and type of controls to be placed on each ramp was developed from the results of numerous studies completed during the last twelve months:

Ramp	Type of Control	Time Control Is In Effect
State Highway 35	Meter	6:55 - 7:30 a.m.
Woodridge	Meter	6:55 - 7:30 a.m.
Mossrose	Meter	6:55 - 7:30 a.m.
Griggs	Close	7:05 - 7:20 a.m.
Wayside	Meter	7:00 - 7:30 a.m.
Dumble	Meter	7:05 - 7:30 a.m.
Cullen (South)	Close	7:05 - 7:30 a.m.
Cullen (North)	Close	7:05 - 7:30 a.m.

Previous studies in Houston and other cities have proven the need for some type of traffic control during the periods of peak traffic demand to maintain a high level of efficiency on urban freeways. The objectives of these studies are to provide the information necessary to develop an automatic freeway control system.

The results of the first control study conducted last August and limited to a short section of the Gulf Freeway substantiated the claim that traffic flow can be improved by controlling the critical entrance ramps during the time of peak loading. That study also indicated that the small number of motorists who are diverted from the freeway during the control period can be accommodated on the city street system. The second control system which will include all ramps in the congested area of the Gulf Freeway is expected to produce similar improvements but over a longer section of roadway and for a greater number of motorists.

Figure A-1.

THE HOUSTON CHRONICLE

Tuesday, January 19, 1965

Jan. 26 Until Feb. 6

Close Few Gulf Freeway Ramps

Some ramps for inbound traffic on the Gulf Freeway will be either closed or the amount of traffic regulated by the State Highway Department beginning Jan. 26 and continuing until Feb. 6.

The ramps admitting traffic on the freeway from Reveille, Woodridge and Mossrose will meter traffic from 6:55 a.m. to 7:30 a.m.; the Griggs Rd. ramp will be closed from 7:05 to 7:20 a.m.; the Wayside and Telephone ramps will meter traffic to the freeway from 7 a.m. to 7:30 a.m.; the Dumble ramp will meter traffic from 7:05 to 7:30 a.m., and the Cullen ramp will be closed from 7:05 a.m. to 7:30 a.m.

"Metering" is a process whereby traffic will be allowed on the freeway by state highway engineers as gaps appear in freeway traffic.

Traffic will have the option at those ramps of either waiting or taking alternate routes into the downtown area.

Traffic must use alternate routes where ramps are closed.

District Highway Engineer W. E. Carmichael said that beginning Wednesday, signs will be put up at the inbound ramps affected, giving directions to motorists.

Last August a similar study was made between Wayside and Dowling. Carmichael said this is an expanded study.

Figure A-2.

THE HOUSTON POST
WEDNESDAY, JANUARY 20, 1965

Gulf Freeway Ramps Will Be Closed in Another Test

Nine ramps on the Gulf Freeway will be closed or curtailed during morning rush periods from next Tuesday through Feb 6.

This is the second in a series of tests aimed at relieving rush-hour hardening of the traffic artery.

THE NEW TEST, more extensive than the first, will close or limit traffic on all ramps between Gulfgate Shopping City and Dowling Street downtown.

Motorists who normally use these near-downtown ramps will be diverted to other routes leading downtown. The idea is that everybody will get to town faster if the short-trip freeway drivers are eliminated.

This appeared to be the result in the first freeway closing test last August.

The Texas Highway Department reported recently that freeway traffic got to town 25 per cent faster during the first test, even though the freeway was carrying more traffic.

THESE RAMPS and times are involved in the new test:

State Highway 35, Woodridge and Mossrose—limited traffic from 6:55 to 7:30 AM.

Griggs—closed from 7:05 to 7:20 AM.

Wayside and Telephone—limited traffic from 7 to 7:30 AM.

Dumble — limited traffic from 7:05 to 7:30 AM.

Cullen—both ramps closed from 7:05 to 7:30 AM.

Figure A-3.

THE HOUSTON CHRONICLE

Saturday, February 6, 1965

3 Freeway Ramps To Close an Hour

The State Highway Dept. will close three Gulf Freeway ramps on an "indefinite" basis to facilitate the free flow of downtown traffic between 7 and 8 a.m.

State Dist. Highway Engr. Wiley Carmichael said the ramp at Griggs Rd. and two ramps at Cullen will be closed during the peak periods.

Six other ramps, at Reveille, Woodridge, Moss Rose, Wayside, Telephone and Dumble, will be regulated by traffic patrolmen during the morning rush period. The officers will permit traffic to enter these ramps only when it will not interfere with through traffic.

These ramps were closed in August on a test basis. The test was so successful, said Carmichael, that the ramps will now remain closed on an "indefinite" basis.

City Councilman Bill Elliott protested that city drivers, who pay the bulk of the taxes, are being penalized for the benefit of rural dwellers who work in Houston.

Figure A-4.

Discussion

PATRICK J. ATHOL, Project Supervisor, Expressway Surveillance Project, Oak Park,

periment on the Gulf Freeway. It is refreshing to read of practical experimentation in a field where the theory to date has mushroomed faster than the supply of experimental data.

As the authors point out, this paper represents only one phase of their continuing control effort. The paper limited its ramp control scope to a pretimed system based on historical capacity data. This type of system is excellent for manual techniques where the data sample is selected subsequent to the control experiment. However, there are certain prevailing operational and environmental conditions on most freeways which lead me to think that some adaptive control system will evolve for general application. Such commonplace occurrences as rain, snow, bright sunshine, darkness, accidents and other flow disturbances vary the critical control parameters. These variations require some adaptive control scheme if the system is to prevent congestion consistently.

The evaluation of freeway performance using the measure of vehicle miles of travel and vehicle minutes of travel time is simple, effective and independent of the control scheme. The technique can be readily applied to conventional manual or automatic detection volume records. The authors note a closing error of less than one percent between the input and output volumes in the manual counting procedure. Experience with automatic detection systems (9) shows agreement well within the same error range. However, a one-percent error between input and output volumes, for a total input volume of 10,000 vehicles, amounts to 100 vehicles or more nearly a 14 percent error in the storage calculation of 700 vehicles. Adjustments may be made for systematic errors at the end of the control period, but this limits the evaluation technique as a control parameter. It is not until after the study that one can assess the reliability of the data and the magnitude of the closing error.

The authors at one point summarized their data in terms of speed derived from vehicle miles of travel and vehicle minutes of travel time. Speed would appear to have the advantage of combining total travel with total travel times, thereby differentiating data samples with equal travel time, but varying total travel. The plot of vehicle vs vehicle minutes for a section of freeway gives a curve similar to the conventional volume density graph.

The results presented clearly show the significant benefits to be derived from control. There appear to be two points which should be carefully considered in future experiments: first, the occurrence of benefits related to the time of control and, second, the selection of comparable data samples. From the report it appears that benefits were ascribed to control at times when no control was exercised. At 7:00 a.m., with control, the data showed about 150 fewer vehicles stored in the system, and yet effective control was only necessary after 7:00 a. m. These benefits should probably be ascribed to other variables not recorded. As a parallel example, a study of freeway operations (9) showed, in the comparison of two samples of 33 days each, at the same location, a significant improvement in operations where no control was exercised in either sample. The changes could only be ascribed to seasonal variations in demand, but these changes could not be detected from the input-output data. If any noneffective control had been used at that time, significant benefits might have been attributed to the control scheme. The evaluation technique of input and output with zero closing error is in no way a control measure in comparing data samples. Under all conditions of weather and freeway incidents there will be a zero closing error with accurate counting. The closure error only reflects the accuracy of the counting procedure. Freeway operations studies are still sadly lacking in measures of experimental control. Data are collected in the same manner that a physicist would measure the volume of a gas oblivious to the effects of temperature and pressure.

The selection of data was based on incident-free days, which are difficult to define, and the data showed considerable daily variation. From a practical standpoint, control will have to survive days with incidents, and indeed the numerical saving may be highest at those times. Perhaps the concept of potential performance may assist in describing data. Results would then be related to potential performance. There may be two potential levels, a higher level with control and another level without control. The range of values for daily performance with or without control will probably overlap. A good day without control would often show an improvement over a bad day with control. Thus, days with incidents need not be simply discarded, but rather related to the potential level. Data samples under varying conditions may then be compared to potential levels without selecting "special days" in a qualitative manner.

The authors have used a test area in which the surface street traffic may readjust with minimal difficulty. There are probably many urban areas where the contiguous streets are less permeable to diverted traffic. Where this exists diverted traffic may radically reduce the time savings benefits to the control system. Indeed there may be areas of negligible system time savings where the improved safety of operation through control will justify the system.

The growth of freeway ramp control must surely increase; improvements have been verified in many areas and the continuing debate will perhaps center around the extent of those benefits. There seems to be a glaring need to establish the causative parameters in freeway operations. The traditional before-and-after studies are limited in value if variations in results go unexplained. Evaluation measures may be adequate in summarizing effects, but are inadequate in pinning down cause-and-effect relationships.

Looking to the future, the astute administrator might reap the greatest harvest by installing control years before congestion develops (10). The system itself would then modify the growth of traffic demand at the various ramp loading points. Prevention is usually better than cure, and the case of congestion may be no exception.

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HUGH C. KENDALL, Director of Research, General Railway Signal Co., Rochester, New York—The traffic corridor linking Houston and its suburbs to the south consists of the Gulf Freeway and parallel surface streets. The authors demonstrated that, by using a simple fixed time control program on nine entrance ramps to the freeway, a substantial improvement in the quality of traffic flow in the corridor could be achieved during the morning peak period. Specifically, 360 vehicle-hours travel time was saved on the freeway due primarily to an increase in speed at approximately the same volume. Travel time on the surface streets was increased by 30 vehicle-hours. Net travel time savings in the corridor amounted to 330 vehicle-hours.

The fixed time control plan was designed using the demand-capacity concept, in which the capacity of each bottleneck area was estimated to be the highest 15-minute volume over a number of days of observation. The estimated demand at each bottleneck area was ascertained from historical data concerning the character of the freeway volume input function, as well as origin-and-destination studies of freeway traffic. The success of the control plan is a tribute to the ingenuity of the authors, and to the cooperation of the 1500 to 2000 motorists which it is estimated were directly affected by the ramp controls each day. In the opinion of this discussor, great good has come from simple means. Possibly five years from now, we will be able to establish the point of diminishing returns between complexity and simplicity in the optimization of corridor operations. The time is not now. Too many hypotheses remain to be proven. I am encouraged by the mounting number of reports covering studies in the field of freeway operations alone.

I would like to commend the authors for their excellent report covering their corridor studies, and spend the remaining moments on the subject of traffic-responsive corridor control. I am not unmindful of the thoughts of the authors in this regard, nor of the suggestions which have been made by others in the field in their reports and discussions at this meeting. Many ideas have been suggested. It may take some time, however, to establish the economic justification of some of these ideas in terms of benefits gained as applied to corridor operation.

speeds are high, they become the backbone of any corridor. Freeways which are exposed to uncontrolled demand frequently shift from high volume-high speed operation to high volume-low speed operation as demand approaches or exceeds practical capacity. It has been shown that practical capacity is a function of adverse weather and prevailing driving conditions. Furthermore, practical capacity can be severely limited by a disabled vehicle or accident. To sustain a high volume-high speed condition on a freeway, therefore, requires an up-to-date knowledge of its practical capacity at all points. The fixed time control program demonstrated by the authors worked well, due primarily to the ability of the program to hold demand as a function of time at some level below the predicted practical capacity in the critical areas of the freeway. In other words, good agreement between the expected and what actually happened was evident.

Improvements to the control system demonstrated by the authors could be reasonably expected by introducing means for determining the up-to-date practical capacity of each critical area. Using this information, demand in these areas could be aligned with practical capacity on a continuously updated, rather than on a historically preselected basis. I do not wish to imply here that means are at hand to reliably accomplish this objective under normal free flow conditions. Many studies concerning the dynamic relationship between volume, speed, density and lane occupancy under typical free flow conditions have been made. These studies have shown wide variations of volume associated with a fixed value of average speed, density or lane occupancy, making the reliable prediction of practical capacity from these variables very difficult. Refinements in instrumentation used to measure these and other variables may well point the way toward better prediction of practical capacity from current traffic stream measurements.

On the other hand, the automatic detection of the occurrence of a temporary capacity restriction on a freeway due to an accident or disabled vehicle appears promising today from what has been learned thus far. Such restrictions are usually accompanied by a marked discontinuity in either volume or lane occupancy immediately downstream of the restriction.

As a first step toward improved control, the authors might well consider modifying the present Mark I fixed time system to include the relatively simple logic, the necessary interconnect, and a modest number of sampling detectors along the center lane of the freeway to automatically detect such discontinuities. In the opinion of this discussor, the benefit-to-cost ratio would be high. The metering rates of ramps both upstream and downstream of a capacity restriction could be automatically adjusted to take account of the restriction. Metering of traffic on downstream ramps could be temporarily suspended. Metering on upstream ramps could be set to minimum. Motorists approaching the freeway upstream of the restriction could be advised through appropriate signing, to use the surface streets in their own best interest to bypass the restriction. Splits and cycle lengths at critical intersections could be adjusted to accommodate a temporary increase in traffic demand along the corridor. With the removal of the temporary capacity restriction on the freeway, normal ramp metering and operation of the critical intersections could be resumed.

The modified or Mark II control system would operate as a multiple mode fixed time system. A number of modes could be automatically selected by the logic associated with the traffic flow discontinuity detection equipment. Manual overide or mode selection due to other inputs could also be provided. One such input could be the prevailing weather conditions on the freeway.

The strengths in the Mark II system would lie in its simplicity and its predictable behavior under traffic conditions which are relatively simple to measure and observe, yet are extremely important to take into consideration in minimizing overall corridor travel time through control. The weaknesses would lie in the thought of possibly being able to do a better job through more sophisticated traffic-responsive control, in which the measured behavior of traffic at all points in the system is tightly coupled to the control decision-making process. Let us refer to this system as Mark III, and possibly the ultimate.

There are those who advocate a Mark III corridor control system consisting of a large network of vehicle detectors, high-speed digital computer, and staff of programmers as a present-day solution to the problem. As a supplier of systems of transportation control, we find ourselves involved in the design of many types of systems whose operation could be regarded as falling within the framework of Mark I, Mark II or Mark III. We of course are most interested in Mark III systems, since large amounts of equipment are involved which keep our shipping room busy. We are called upon, however, to furnish handbooks of operating instructions for all our systems. We are well along on handbooks covering systems of the Mark I and Mark II variety as applied to the control of vehicular traffic. It is only fair to tell you, however, that we are experiencing some difficulty in the completion of the programming section for our Mark III system. We hope that you will help us write it.

DONALD O. COVAULT, Professor of Civil Engineering, Georgia Institute of Technology, Atlanta—This discussion will not specifically concern itself with the content of the excellent paper presented by Pinnel, Drew, McCasland and Wattleworth, but will be concerned with a philosophical discussion of the decision-making processes which might be involved in the problem of ramp control on a freeway section.

The decision to close or meter a ramp should initially be based on certain objective criteria which can be easily measured. These criteria usually are concerned with the use of travel time and travel distance as measures of effectiveness of freeway and arterial street operation. Of great importance also is the concept of system evaluation in measuring travel time and travel distance; i.e., one must consider the arterial streets and freeway as a system in developing the decision-making processes for ramp control.

The use of subjective criteria for ramp metering and ramp closing must also be considered before such an operational procedure as ramp control is initiated. Included in the subjective criteria would be the need for routes for fire and police vehicles and other emergency vehicles and the compatibility of the closing or metering of a ramp with land use and other usually nonmeasurable aspects of transportation.

Also related to the subjective problem of ramp closing and ramp metering is the problem of street management itself. Some city traffic engineers may look upon the arterial street systems as basically the problem of major concern in street management and that freeway operation is a problem which in many cases is associated with the operation of a system outside their authority; that is, this system "belongs" to the State Highway Department. Consequently the city traffic engineer may concentrate much of his efforts on the movement of vehicles on arterial streets and may mitigate the importance of the freeway itself. The problem of optimization quickly appears when one considers the relationship of street management to the operation and management of the freeways. The question that must be answered here is: Must one close ramps and meter ramps in such a way as to optimize travel or travel time on the freeway or to optimize travel or travel time on the arterial streets or to optimize these parameters on the arterial streets and the freeway system? From studies made on the Atlanta freeway system it was found that simultaneous optimization of both freeway operation and arterial street operation by ramp closing was not possible. In all cases where entrance ramps were closed, the operation of the freeway improved in terms of travel time but rather serious congestion problems were created, mainly through turning movements, on the arterial street system.

The problem of public acceptance of ramp metering and ramp closing must also be considered in the decision to close or not close or to meter a ramp. Although objective criteria may indicate that the optimum way to operate a freeway and arterial street system would be to close or meter ramps, public opinion may prevent this from happening because of preconceived ideas as to ways of driving, vested interests, etc.

[illegible]

entrance ramps, which may be undesirable during peak periods, be permitted during off-peak periods. These ramps may provide for optimum street management which could not otherwise be provided if the ramps were not allowed to operate. Furthermore, when these ramps are permitted to operate normally during the off-peak periods they do not create the problems to freeway traffic flow that occur when traffic flows are approaching breakdown densities.

Because ramp closing and ramp metering may create rather extreme changes in the operation of a freeway and arterial street system, it is highly desirable that the general public have prior knowledge as to the location and timing of ramp metering and ramp closing. The provision for complete automatic control may be too flexible for the driver to accept. That is, he would have no assurance that once he came to a particular ramp that this ramp would be open for him to have use of the freeway; or he may have to wait a considerable length of time in a queue on a metered ramp in order to get on the freeway. Furthermore, it is quite usual for unusual things to happen on the freeway. From this point of view it may be desirable to permit the freeway to operate on a fixed-time control system so that the driver can expect certain ramps to operate in the same manner at a certain time each day.

In conclusion, ramp control appears to be highly feasible. Ramp control, however, should be used with a great deal of discretion and one must be very careful that problems are not overlooked which may be created on the arterial streets associated with the ramp closure or metering when these control measures are adopted.

CHARLES PINNELL, DONALD R. DREW, WILLIAM R. McCASLAND, and JOSEPH A. WATTLEWORTH, Closure—The authors would like to express their thanks to the three discussers for their stimulating and considered comments on the paper.

Mr. Athol expresses a great enthusiasm for the motorist benefits which can be achieved with peak-period freeway control. The authors certainly share this enthusiasm and also share his belief that the peak-period controls should be of the traffic-adjusted type rather than of the fixed-time type reported in this study. The ramp control plan described in this report represents merely one step or phase in our program to develop a final control system. Subsequent to this study several traffic-adjusted metering systems have been tested and others will be tested in further developmental work toward a final control system design.

Like Mr. Athol, we regret that the traffic researcher cannot collect data with the same precision and under the highly controlled conditions as can the scientist in his laboratory. Until it is possible to do this the traffic researcher must use the best techniques at his disposal. The study techniques used in the evaluation of the effects of the controls in this study are admittedly not perfect, but they are believed by the authors to be highly reliable and better than other techniques which were available for this purpose.

Mr. Athol raises the question of the adequacy of the statistical sample sizes of the number of days of data used in the before-and-after evaluations of the effects of the controls. His comments are based on his experience in Chicago in which the operation during some days of control is worse than during some days without control. Our experience on the Gulf Freeway, based both on the study reported here and eight months of subsequent operation of the ramp controls, is somewhat different. The operation was very consistent both before and during the controls; daily variations in each case were small, but seasonal variations were noticed. Barring transient effects when a control study is initiated and barring adverse weather and accidents, the operation on any day during control is better than any day without control. However, this is related to the severity of congestion on the facility before controls were initiated and this experience would vary from one facility to another.

In perhaps a related point Mr. Athol commented on the fact that the data were based on incident-free days, i.e., days on which no accidents, stalled vehicles, adverse weather or other factors affected the traffic flow. Several factors affect the traffic flow, among them: (a) the operation of ramp controls, (b) weather, (c) light conditions, (d) accidents and (e) disabled vehicles. We were trying to isolate the effects of just one of them, namely the operation of the ramp controls, so it seemed appropriate to hold constant the effects of the other factors, and this is the reason for selecting incident-free days for the before-and-after analysis. Most traffic researchers believe that ramp controls can produce the greatest motorist benefits when a severe capacity reduction prevails on the freeway, such as when an accident or adverse weather affects the traffic flow. Thus, the use of incident-free days in the before-and-after evaluation perhaps provides a conservative estimate of the motorist benefits resulting from peak-period ramp controls.

Mr. Kendall raised the very important question of the determination of the point of diminishing returns on investment in control equipment. This is somewhat surprising coming from a manufacturer's representative but is nevertheless a good point.

All the authors can say regarding this point is that we don't know where the point of diminishing returns is but that finding it is an important part of our current research program. Our approach is to determine the magnitude of the benefits to the motorists that can be derived from control systems of varying levels of sophistication. Using Mr. Kendall's terminology, we have at the present time looked at the "Mark Ia" and "Mark Ib" systems and hope to experiment a little with "Mark II" and "Mark III" before deciding where the optimal investment point may be. We are also trying to write our own handbook for the "Mark III" system.

The "horseback" methods which we have tried have yielded good results and it could be that it will be hard to improve on them. In this research stage, however, we feel that more sophisticated methods should be evaluated.

Dr. Covault has rightfully raised some of the very important practical, political considerations which can become very important. Research on traffic control is not an "ivory tower" situation; the very useful, practical, beneficial results must be "sold" to someone, be it the governing political agency or the people themselves.

We were very fortunate in Houston to get almost 100 percent cooperation from the motorists; at least, very few have voiced opposition. We were also fortunate to be working with two extremely cooperative agencies, the Texas Highway Department and the City of Houston, each of which recognizes its own responsibility and each of which has adopted the "systems approach" to the Gulf Freeway problem.

Again the authors would like to thank the three discussers for their thought-provoking comments on this paper.