EVALUATION OF THE OPERATIONAL EFFECTS OF AN "ON-FREEWAY" CONTROL SYSTEM

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I. INTRODUCTION

There are many concepts or approaches to real-time control of or communication to freeway traffic. One of the pioneering efforts involving the application of real-time control and communication to freeway traffic was made on the John C. Lodge Freeway in Detroit. In 1962, a system of overhead lane control signs, overhead changeable speed signs and ramp closure signs was installed on a 3.2 mile section of the Lodge Freeway between the Edsel Ford Freeway and the Davison Freeway. Figure 1 shows an installation with both the lane control signals and a speed control sign. Trained observers who watch fourteen closed circuit television monitors operate the signs.

This communication and control system was installed as part of a cooperative research project among four governmental agencies: the Michigan Department of State Highways, the City of Detroit Department of Streets and Traffic, Wayne County and the U.S. Bureau of Public Roads. The project later became the National Proving Ground for Freeway Surveillance, Control, and Electronic Traffic Aids (National Proving Ground).

This system represents both the "on freeway" communications and control concept and the ramp control (demand alteration) concept. Neither of the two communication and control concepts had been adequately evaluated in the past. The ramp control system utilized the total closure of selected entrance ramps to reduce or dissipate congestion on the freeway. At the time of its design and installation the entire system represented the latest state of the art and this type of ramp closure was forerunner of the ramp metering concept which has found acceptance in some cities.

National Cooperative Highway Research Program Project 20-3 was established for the 1967 year. One of the required objectives of this Project was to evaluate fully the National Proving Ground (NPG) Traffic Control System as an operational system. Specifically, the motorists' benefits of this Traffic Control System had to be determined. This paper presents the results of that evaluation.

The research reported here had three objectives:

1) to determine the motorists' responses to the NPG Traffic Control System (except the ramp closure signs) during the off-peak periods;

2) to determine the effects of the NPG Traffic Control System (excluding the ramp closure signs) on traffic operation during peak periods; and,

3) to perform a system analysis of the NPG Traffic Control System.

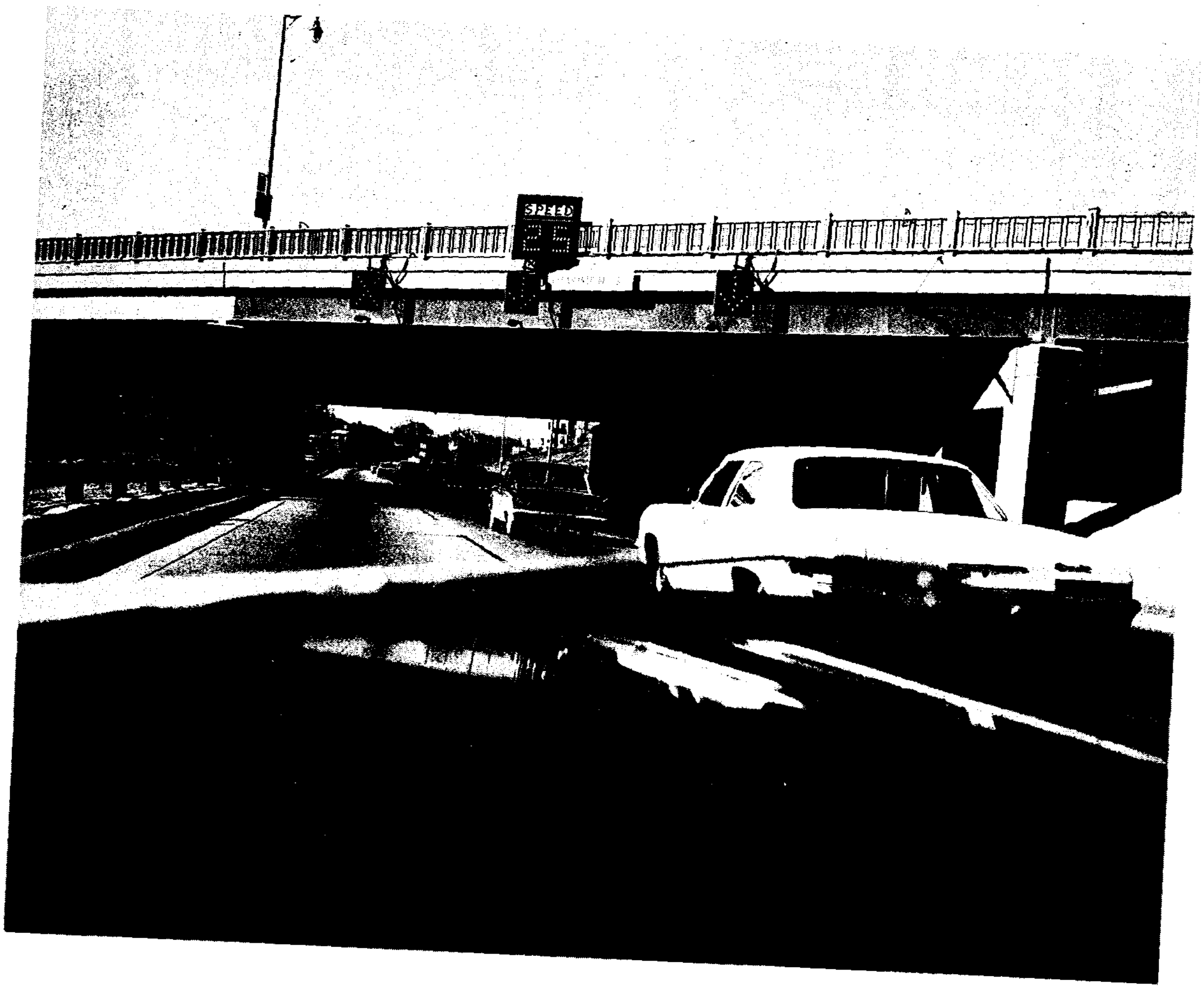


Figure 1. Typical Installation of Lane Control Signals and Speed Control Signs

II. NATIONAL PROVING GROUND TRAFFIC CONTROL SYSTEM DESCRIPTION

The NPG Traffic Control System is located in a 3.2 mile section of the John C. Lodge Freeway, known as the NPG TV Control Area. The Control Area is bounded by two major interchanges: 1) The Lodge-Edsel Ford Interchange on the south, and 2) the Lodge-Davison Interchange on the north.

The entire system consists of a closed circuit television subsystem, a traffic signal subsystem, a confirmation display subsystem, vehicle detection subsystem, a digital computer, a cathode ray oscilloscope, two operators and a transmission cable. The relationship of these elements appears diagramatically in Figure 2 (from Reference 1).

As is evident from the functional block diagram, this is a closed loop system. The feedback information is received via the closed circuit TV subsystem and to a limited extent via the vehicle detectors, computer, and a cathode ray oscilloscope. The operator is an adaptive element, i.e., he is subject to time delay, subjective decision making, and a certain amount of inconsistency (1).

The motorist is also an adaptive element with the characteristics mentioned above. The motorist's time delay and inconsistency can be estimated by an average because of the large number of motorists involved. The decision-making aspect, however, is subject to many influences other than traffic signals such as emotional state, road conditions, driving experience, etc. The significance of the previous statement is that the traffic signal must compete with many other stimuli for top priority (1).

There are two forward loops in this system. They are best understood by referring to the functional block diagram. The forward loop containing the traffic signals is the more significant. The loop containing Traffic Central (the police dispatcher) is in effect only when there is an accident or other emergency and at these times it affects operation by reducing the time of abnormal flow (1).

The control elements of the Traffic Control System are as follows:

1) Overhead lane control signs;
2) Overhead variable speed control signs; and,
3) Ramp closure signs.

These are located in both directions in the TV Control Area as shown in Figure 3 which is a schematic diagram of field locations of the entire Instrumentation System and Traffic Control System at the time NCHRP Project 20-3 began in early 1967.

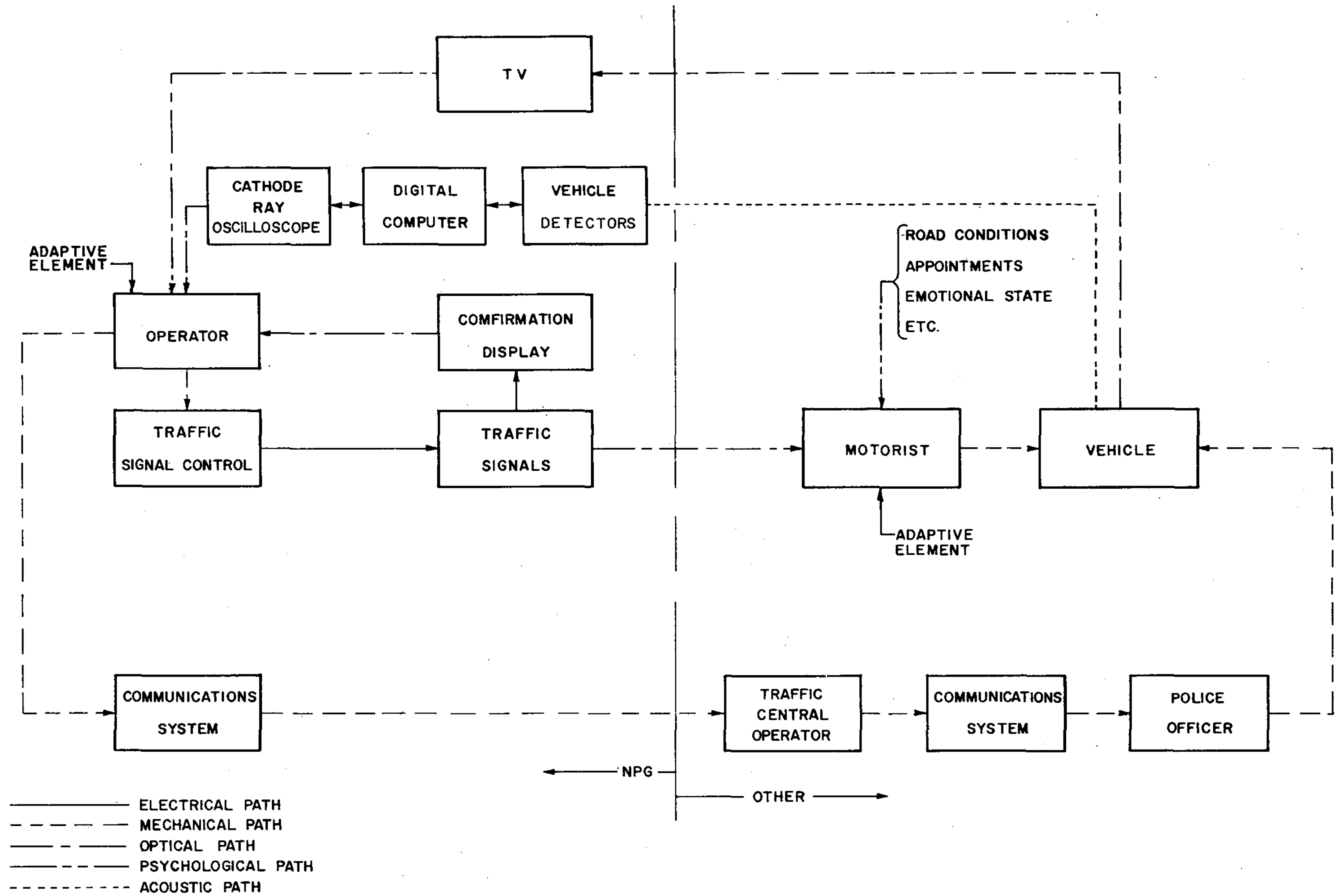


Figure 2. Functional Block Diagram of National Proving Ground Traffic Control System.

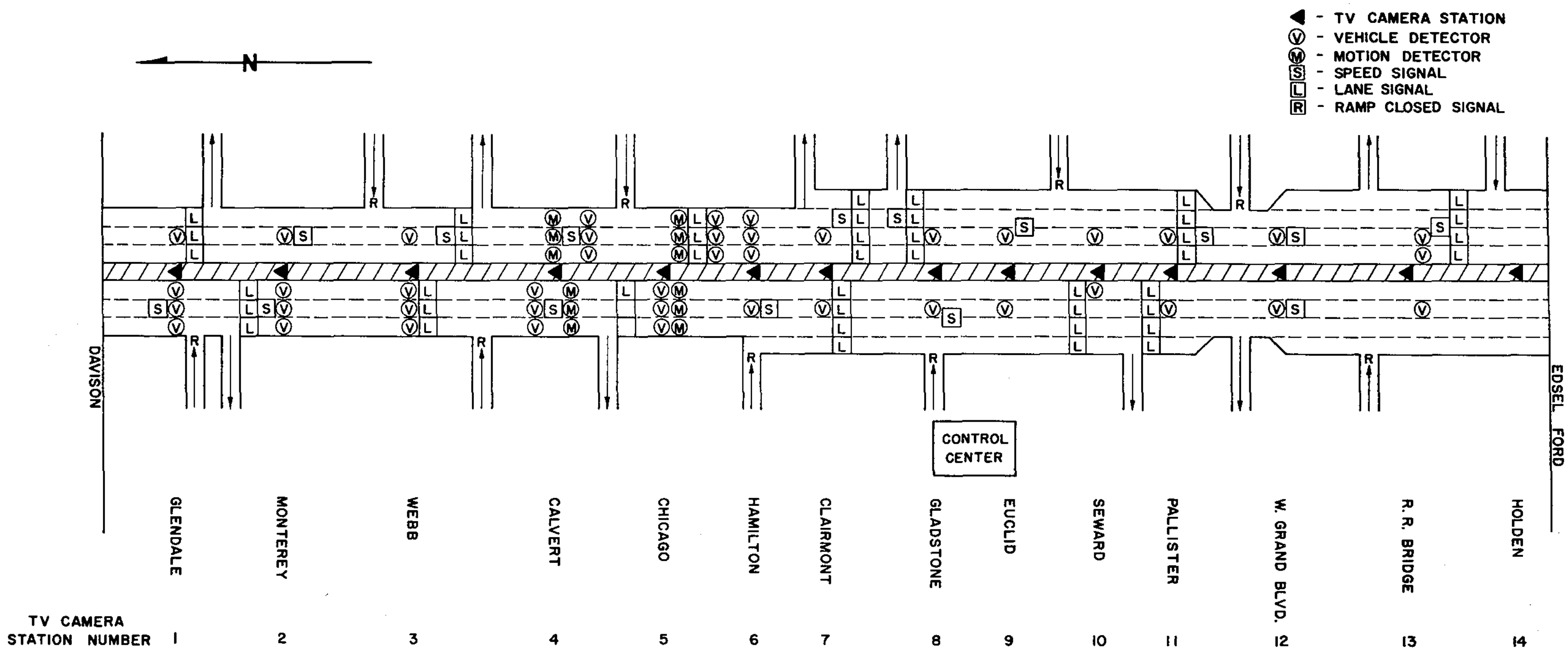


Figure 3. Schematic Diagram of National Proving Ground Equipment Locations.

III. LODGE FREEWAY TRAFFIC ANALYSIS

One of the first analyses that was performed by the staff of NCHRP Project 20-3 was an examination of the adequacy of the control and surveillance area of the National Proving Ground for the research objectives of the Project as well as for the primary control function of the NPG Traffic Control System. In attempting to determine the proper area of surveillance, the following criteria were used:

1) The surveillance and control area on the freeway must include all major bottlenecks;

2) The surveillance and control area must extend far enough upstream of all bottlenecks to include the entire queuing area; and,

3) The surveillance area must extend a sufficient distance downstream of all bottlenecks that the traffic flow would have returned to normal.

Satisfying these criteria assures that the entire area of influence of the NPG Traffic Control System on the Lodge Freeway is included in the analysis. With these criteria in mind, both the inbound (southbound) freeway subsystem in the morning and the outbound (northbound) freeway subsystem in the afternoon were analyzed to determine the proper area of surveillance for each of these subsystems.

ANALYSIS OF THE OUTBOUND FREEWAY SUBSYSTEM

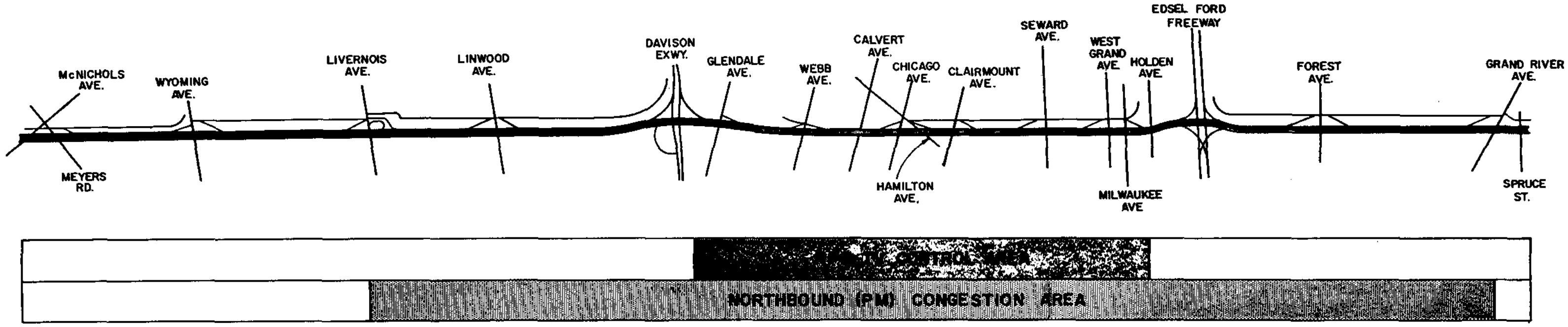
There are two major bottleneck areas on the northbound John Lodge Freeway in the afternoon peak period. The first of these is in the present NPG Control Area and is located in the area of the Chicago and Webb entrance ramps. This bottleneck is caused by two conditions, the first of which is the reduction in the number of lanes from four to three at the Hamilton exit ramp. The second is the influence of traffic entering on the Chicago and Webb entrance ramps which enter downstream of the Hamilton exit. The combination of the end of the auxiliary lane and the added traffic in the three lane section (along with the other geometric features such as curvature and grade) produces this bottleneck area.

In addition, a similar situation exists in the vicinity of the Livernois and Linwood interchanges. An auxiliary lane is added at the Davison entrance ramp and it is terminated at the Linwood exit ramp. After the reduction in the number of lanes, traffic is added at the Linwood entrance ramp and further downstream at the Livernois interchange more traffic enters the Freeway than exits during part of the peak period. This combination of operational and geometric characteristics makes the Linwood and Livernois area on the Lodge Freeway another bottleneck location.

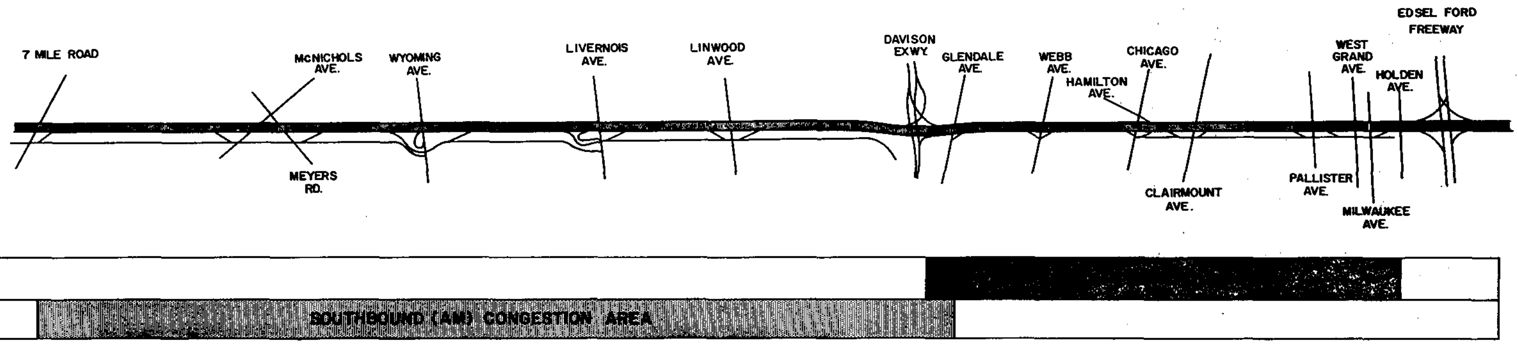
Congestion develops independently at these two bottlenecks. However, late in the peak period the queue on the Freeway at the downstream bottleneck (Linwood and Livernois area) is propagated into the Chicago-Webb bottleneck. At the height of the peak period, congestion normally extends from the Livernois interchange upstream for a distance of approximately 6.5 miles to the Grand River Avenue overpass.

For these reasons, the northbound Lodge Freeway between the Spruce Pedestrian Overpass (near Grand River) and the Meyers Overpass was chosen for analysis. This is a distance of 8.3 miles and extends on both sides of the present 3.2 mile control area of the National Proving Ground.

Figure 4 shows the relationship between the NPG TV Control Area and the maximum areas of congestion described above. Much of the peak-period evaluation of the NPG Traffic Control System was concentrated in the northbound direction due to the installation of a computer-detector surveillance system in this direction; however, some significant research was conducted on the southbound direction as well.



NORTHBOUND JOHN C. LODGE FREEWAY – SCHEMATIC



SOUTHBOUND JOHN C. LODGE FREEWAY – SCHEMATIC

Figure 4. National Proving Ground TV Control Area and Congestion Areas of the John C. Lodge Freeway.

IV. MOTORISTS' RESPONSES TO THE NPG TRAFFIC CONTROL SYSTEM DURING OFF-PEAK PERIODS

Two control studies were conducted during the off-peak periods in a test section from Glendale to Webb Avenue on the inbound Lodge Freeway shown in Figure 5. The two studies were evaluations of drivers' responses to a) the lane control signs and b) the variable speed control signs. No such controlled study of the ramp closure signs was made since adequate research had been performed previously by others (2) and continuing research by the Texas Transportation Institute on NCHRP Project 20-3 involves control of a similar nature, ramp metering, which is evaluated in detail in another report (3). Advantage was taken, however, of one situation which developed and required the use of the ramp closure signs. The results of studies during this incident are reported herein.

Any beneficial effects of the traffic control signs depends upon three factors, namely:

1) The sign conveys the proper message;
2) The motorists comprehend the message; and
3) The motorists choose to respond to the message in the proper fashion.

The following two sections relate the study techniques, findings, and conclusions of the off-peak control sign studies and a summary of the results of previous research.

OVERHEAD LANE CONTROL SIGN STUDY

This type of control is used to inform the Freeway motorists whether the lanes ahead are open or closed. A green arrow over a lane means that lane is clear, while a red 'X' indication means the lane is blocked ahead. The intent is, of course, to give the motorists advance warning so they can move out of the blocked lane as soon as they can safely do so.

Past Research

Previous research on the effectiveness of the signs has been documented by Clinton (4) (summarized by Gervais (5)) and Forbes (6). These studies revealed the effectiveness of the signals during periods of light to moderate demand. As a result of the first study at two locations, 1) Gladstone in the southbound direction and 2) Webb in the northbound direction, the following conclusions on the effectiveness of the lane controls were made in a previous report (5) and are stated below:

1) Lane changing is initiated further in advance of the obstruction;

2) Traffic volumes past the obstruction increase significantly if demand is high;

3) When traffic demand is moderate, speed past the incident remains near optimum while stoppages are minimized or eliminated; and,

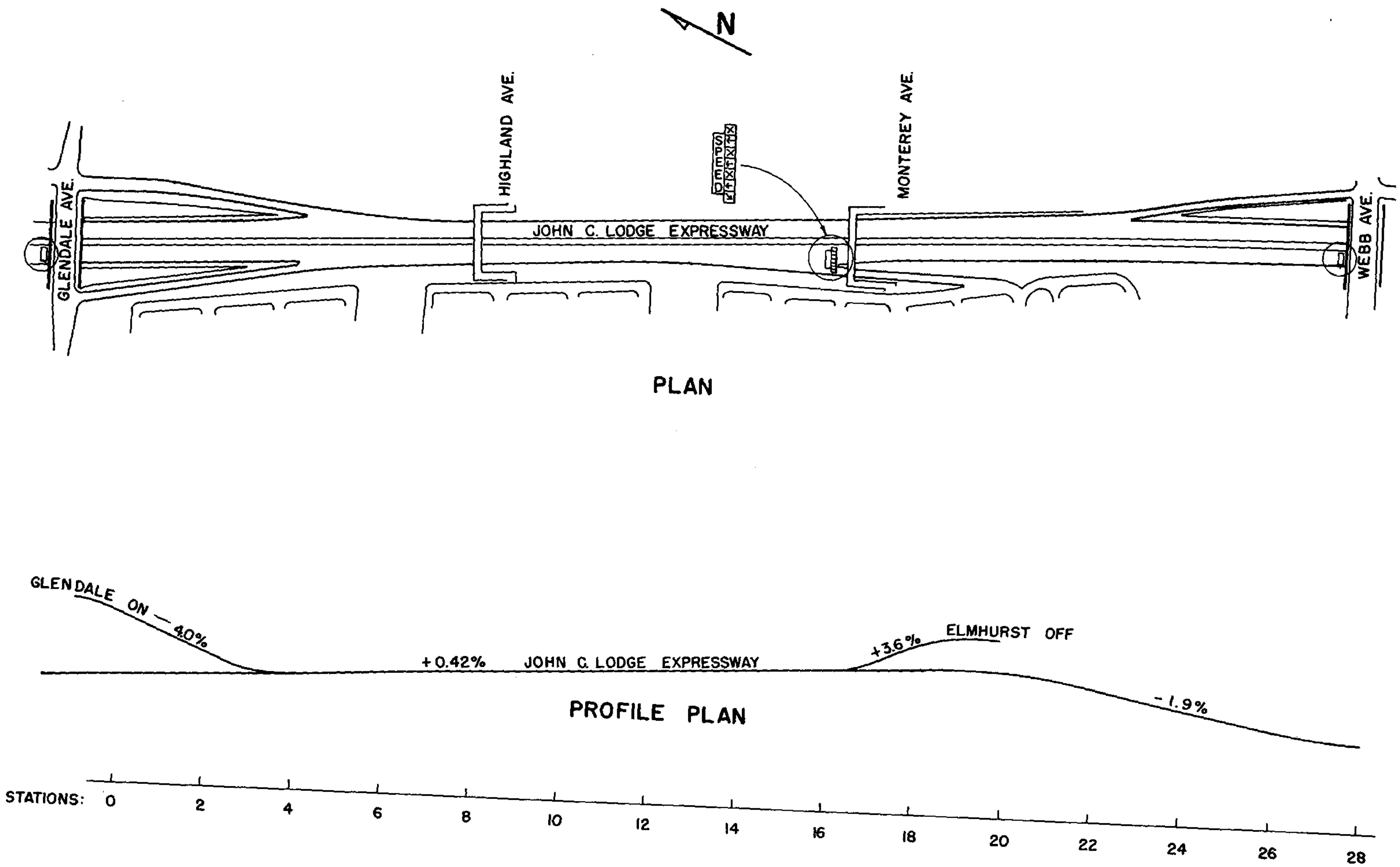


Figure 5. Study Section - Evaluation of Motorist Responses.

4) The number of vehicles trapped behind the obstruction, for a given time period, is reduced.

The staff of NCHRP Project 20-3 felt that these conclusions were applicable in the case of light demand but that the case of heavy flow during off-peak periods needed further investigation. This attitude was due partially to the lack of statistical support for the second conclusion noted above. Also, during the normal daylight hours on the Lodge Freeway, light demand is exceedingly rare and this fact added emphasis to the need for further investigation of the heavier demand situations.

Present Research

In order to study the effectiveness of the lane control signals the median lane (lane one) was closed for normal maintenance operations at the same location on two successive days using two advance warning schemes, one of which included the overhead lane control signals. The study periods (1:00 - 1:45 p.m.) were influenced by operational policies on freeway lane closures of the local agencies. The studies were conducted during the early afternoon because traffic flow was lightest during this daytime off-peak period in the study section.

On one day the lane was closed normally, using advance warning signs "This Lane Closed 1 Mile Ahead" at one mile upstream and "Left Lane Closed" placed about 500 feet upstream and a large flasher board mounted on the back of a truck protecting the maintenance crew. The flasher board was positioned at the crest of a vertical curve at station 18 of the test section where it was visible to motorists from a point at about station 9. (Station locations are shown in Figure 5.)

On the following day the lane closure was imposed at the same location with the flasher located slightly further downstream (station 20). At this position the flasher was on a down grade, thereby making it less visible to the approaching motorists. A red 'X' over lane one at station 15 replaced the "Left Lane Closed" sign and was visible to motorists at station 7. In this manner the motorists were presented nearly the same conditions ahead in the two cases but with different advance warnings provided.

Although traffic volume was lower (4200 vph) during the time period studied than during the peak period in that direction, congestion developed immediately when the lane closure was invoked because traffic demand exceeded the capacity of the remaining open lanes.

Data were collected on a third day during the same period under normal conditions (no lane closure) to establish a base for travel time and delay studies. The experiment consisted of three days under three conditions, namely:

1) Normal operation;
2) Lane closure - conventional advance warning procedure; and,
3) Lane closure - overhead signals operating.

The two latter conditions could be directly compared using several measures of effectiveness. The study techniques for obtaining the various measures were as follows:

a. Input-Output Study (7, 8) - This technique was used to determine 1) output volume, 2) total travel, 3) total travel time, 4) delay, 5) average speed, and 6) kinetic energy through the study area. It should be noted that the total travel time and delay was not complete since it did not include that time spent in the queue upstream of the study section input point at Glendale; however, the length of the queue was observed to be approximately the same in both control situations.

Figures 6b and 6c show the total output (i.e., Elmhurst off ramp and the Freeway at Webb) from the system for half an hour of control while Figure 6a shows corresponding data during normal operation. By restricting the analysis to the final half-hour of the 45-minute lane closure period, the traffic conditions were allowed to stabilize (in a state of congestion) before any comparative analysis was made. Based on statistical tests, using the 't' statistic and a 95% significance level, it could not be concluded that the operation of the lane control signals increased the flow past the lane closure under the volume conditions studied. It should be noted that the sample sizes used in this analysis are quite small.

Other results of the input-output studies are presented in Table 1 and show only slight improvement in operational characteristics when the overhead lane control signal was used in place of the conventional advanced warning. The total travel time was 4.17 veh-hr lower and total travel was 31.78 veh-mi higher, which means flow was smoother and somewhat faster (1.4 mph) during the overhead lane control. The total kinetic energy of the traffic stream was 1699 veh-mi/hr^2 higher when the overhead lane signals were used. This increase in kinetic energy means (assuming the total kinetic energy during normal operation nearly equal to the total energy of the system during this time period) a reduction of internal energy or stream turbulence (9). These differences in operational characteristics are small and are of the same order of magnitude as the possible errors in the input-output technique.

b. Lane Change Study - The study section was divided into four sub-sections (stations 0-9, 9-13, 13-17, and 17 to the lane closure) and counts of lane changes were made in each subsection. Figure 7 shows the subsections, the location of the lane closure, and the average volumes during the two lane closures. Figure 8 presents the effect of the overhead lane control signals on lane changes from the closed lane upstream of the closure. It indicates that, when the overhead lane controls were used, the vehicles moved from lane one (the closed lane) farther in advance of station 18* than when a conventional advanced warning was used. This finding substantiates earlier work on evaluation of these signals (5).

*A fixed reference point was used since the effect of the overhead signals is being tested and they are in a fixed location.

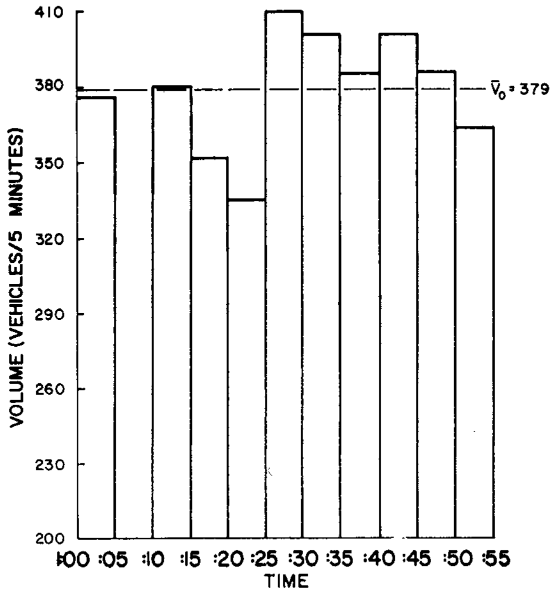
TABLE 1

INPUT-OUTPUT STUDY - OVERHEAD LANE CONTROL STUDY
STUDY PERIOD - 1:15-1:45 p.m.

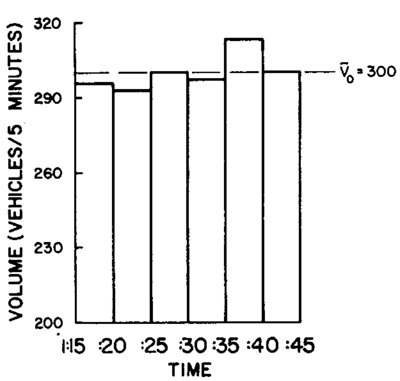
Control Condition	Date	Total Travel Time TTT(veh-hr)	Total Travel TT(veh-mi)	Delay D(veh-hr)	Av. Speed $\bar{U}$ (mph)	Kinetic Energy KE (veh-mi/hr^2)
Normal, n	4/7/67	20.55	1162.67	---	56.6	65,782
Conventional, c	4/11/67	67.59	904.52	47.04*	13.4	12,121
Red 'X', x	4/12/67	63.42	936.30	42.87**	14.8	13,820

* Delay = $TTT_c - TTT_n$

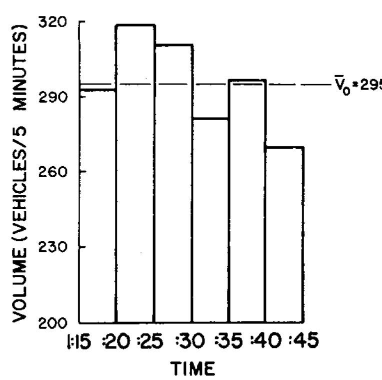
** Delay = $TTT_x - TTT_n$



a. TOTAL OUTPUT - NO CLOSURE

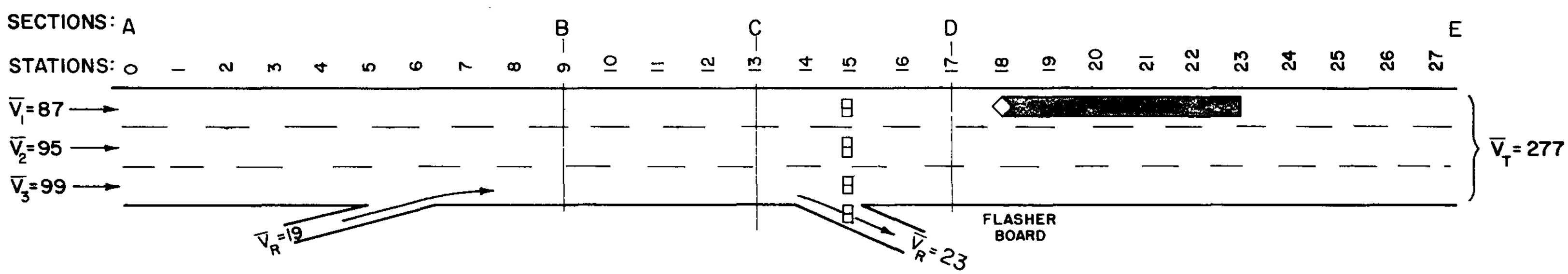


b. TOTAL OUTPUT-LANE CLOSURE CONVENTIONAL WARNING

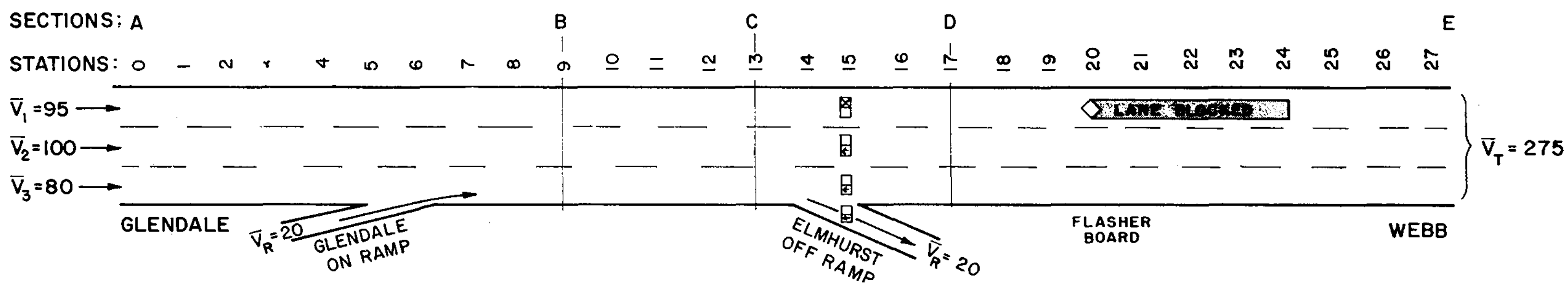


c. TOTAL OUTPUT-LANE CLOSURE LANE CONTROL, RED "X"

Figure 6. Effect of Lane Closure and Advanced Warning Technique on Volume Past the Closure



a. SUMMARY OF CONDITIONS DURING LANE CLOSURE WITH CONVENTIONAL ADVANCED WARNING (VOLUMES IN VEHICLES PER 5 MINUTES)



b. SUMMARY OF CONDITIONS DURING CLOSURE WITH OVERHEAD LANE CONTROL WARNING (VOLUMES IN VEHICLES PER 5 MINUTES)

Figure 7. Schematics Showing Lane Closure Conditions.

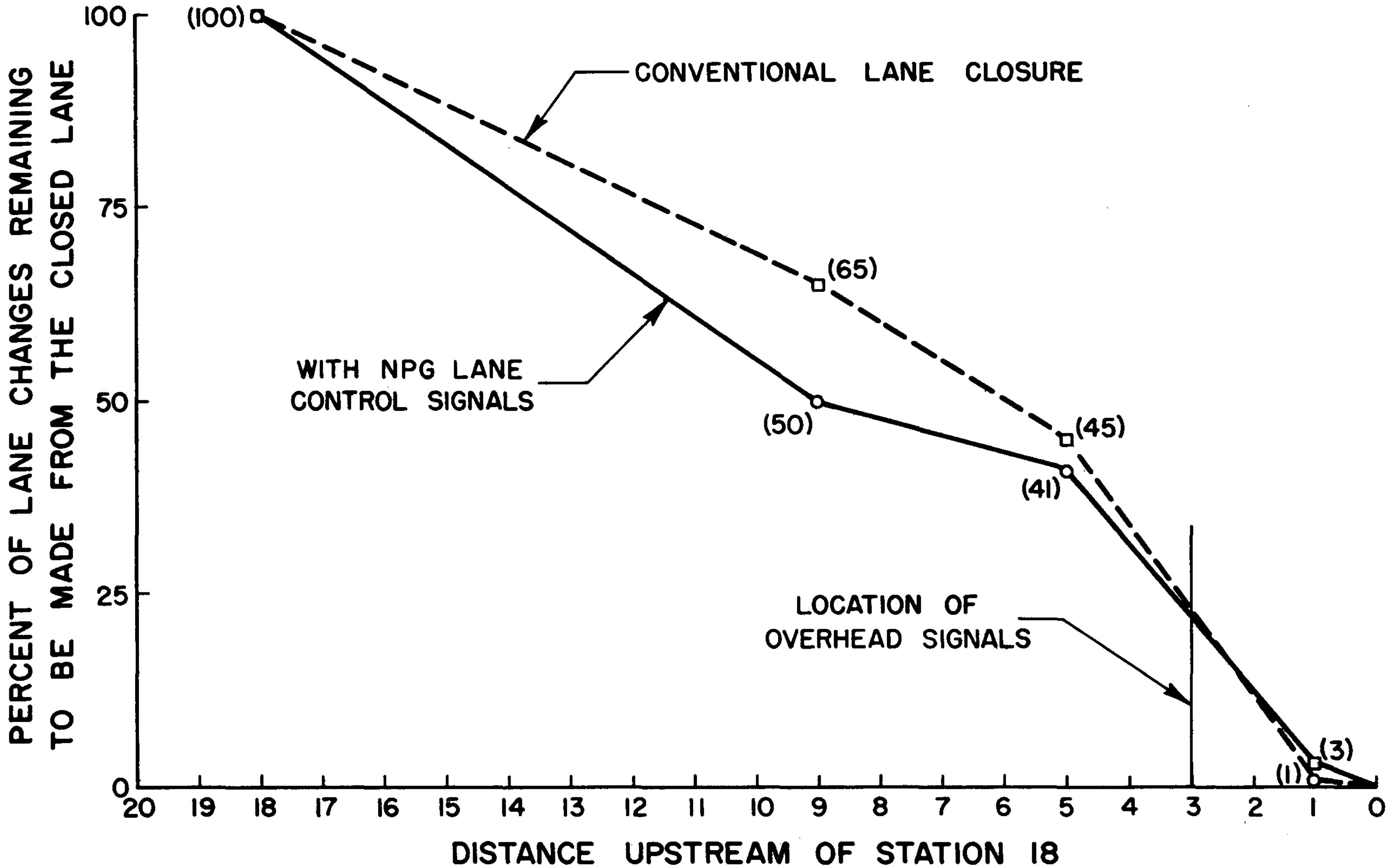


Figure 8. Effect of NPG Overhead Lane Control Signals on Lane Changes (from the Closed Lane) in Advance of a Freeway Lane Closure.

OVERHEAD VARIABLE SPEED CONTROL SIGNS

The subsystem of overhead variable speed control signs has two primary purposes: 1) to warn motorists on the Freeway of a shock wave ahead so that they can begin to decelerate before actually reaching the congested areas and 2) to indicate to motorists leaving a congested area to increase their speed to help disperse the congestion. One of three speeds (25, 40 or 55 mph) can be displayed on the matrix-type signs. The television surveillance and, to a very limited extent, the oscilloscope display provide the information required for the operators to select the proper speed setting for each of the speed control signs.

The benefits of the speed control signs are quite subtle and difficult to measure. For this reason, the bulk of the research to determine the motorists' benefits will come from the more comprehensive peak period study which is described later. The purpose of this study was to detect motorists' responses to the speed control signs during off-peak period conditions.

The conceptual design of the off-peak study involved six operational conditions (three control situations and two environmental conditions) and is shown in Table 2.

TABLE 2

CONCEPTUAL DESIGN, OVERHEAD SPEED CONTROL SIGN STUDY

			Control Condition		
			j=1	j=2	j=3
Speed Sign Locations	Glendale	i=1	55	55	40
and	Monterey	i=2	55	40	25
Speed Indication	Webb	i=3	55	40	25
Environmental Condition k=1	No Distraction		1 hr.	1 hr.	1 hr.
Environmental Condition k=2	Roadside Distraction		1 hr.	1 hr.	1 hr.

These six conditions were imposed on six days. The roadside distraction was a Wayne County Road Commission rubbish truck performing regular duties during the hours of study. The same control section that was used for the lane control study was used in this study. The speed signs are located at Glendale, Monterey, and Webb as shown in Figure 5.

A spot-speed study was used to obtain accurate speed data at selected points in the control section. The locations selected for the spot-speed studies were Glendale, Monterey, and Webb. Vehicles were timed through speed traps and the data were recorded in five-minute groups and at least one speed sample was obtained from each lane each minute. The sample sizes used in the analyses ranged from 90 to 373. The spot-speed samples were used for five purposes, namely:

1) To compare observed speed with posted speed at each location;
2) to compare observed speeds at each location under different speed control conditions;
3) to compare observed speeds at different locations for each speed control condition;
4) to compare observed speeds at each location under the two conditions of distraction; and,
5) to combine observed speeds with volume data to determine changes in the speed-flow characteristics.

All tests of hypotheses to follow were based on the 't' statistic (10).

Comparison of Observed Speeds With Posted Speeds

The time mean speeds (TMS) for one hour were tested statistically to determine if the drivers considered the speed signs either as a speed limit or a guide by comparing the observed speeds with the posted speeds. The TMS was significantly different from the posted speed in all but one case (U_{11}^{1}) and Appendix Table A-1 presents the time mean speed and the statistical acceptance region for each condition. It can be seen that the observed speeds correspond closely to the posted speeds only at Glendale when a 55 mph speed is posted. Apparently, this is because the 55 mph posted speed is quite close to the desired speed of traffic at Glendale. At the lower posted speeds (25 and 40 mph), the observed speeds were quite different from the posted speeds (from 4.5 to 18.9 mph with no distraction and from 3.9 to 19.9 mph with the roadside distraction).

Comparison of Observed Speeds at Each Location Under Different Speed Controls

The most significant comparison is the comparison of TMS at each location and condition for different speed sign settings. The average speed corresponding to the higher speed sign indication is $\overline{U}_H$ and with the lower speed indication is $\overline{U}_L$. Table 3 shows the results of these comparisons. The values shown in the table under the heading "Difference" represents $\overline{U}_H - \overline{U}_L$. The null hypothesis was that the TMS during the higher posted speed was less than or equal to the corresponding TMS during the lower posted speed. An asterisk indicates that the hypothesis was rejected. Because of the large sample sizes, some small speed differences were found to be significant. The speed differences corresponding to a 15 mph decrease in posted speed ranged from -4.5 mph to 5.6 mph - not nearly equal to the 15 mph posted speed reduction. At Monterey the reduction in posted speeds from 55 mph to 25 mph had a corresponding decrease in observed speeds of 7.7 mph with no distraction and this was the largest speed decrease.

TABLE 3

COMPARISONS OF DIFFERENCES IN TIME MEAN SPEEDS BETWEEN SIGN INDICATIONS AT EACH LOCATION

Environmental Condition	Location	Posted Speeds		Difference	Posted Speeds		Difference
		S_H	S_L	$\bar{U}_H - \bar{U}_L$ (mph)	S_H	S_L	(mph)
No Distraction	Glendale	55	55	0.4	55	40	-2.1
	Monterey	55	40	2.1*	40	25	5.6*
	Webb	55	40	0.7	40	25	0.6
With Distraction	Glendale	55	55	4.8	55	40	-4.5
	Monterey	55	40	0.0	40	25	2.5*
	Webb	55	40	0.2	20	25	1.3*

*Hypothesis rejected - $H: \bar{U}_H \leq \bar{U}_L$ ($\alpha = 0.05$)

Comparison of Speed Profiles Under Different Control Conditions

The speed profiles under the three different speed control conditions are shown in Figure 9 (no roadside distraction) and Figure 10 (with roadside distraction). In Figure 9 the speed profiles are quite similar under the three speed controls. At Monterey and Webb the speed profile for the 25 mph posted speed is the lowest and the speed profile corresponding to the 55 mph posted speed is the highest. There is little difference between the profiles, however.

The same pattern exists at Monterey and Webb when a roadside distraction was present at Monterey (Figure 10). Again, there is little difference between the profiles. It is interesting to note that none of the mean observed speeds was below 40 mph even when a 25 mph speed was posted.

Effect of Roadside Distraction on Speed Profiles

For the three cases in which no roadside distraction was present, stream speeds generally decreased at about the same rate between Glendale and Webb as seen in Figure 9. But when a flasher board on a rubbish truck was placed in view on the shoulder downstream and downgrade from Monterey, traffic speeds decreased from Glendale to Monterey and then increased from Monterey to Webb as seen in Figure 10. This suggested that when the motorists could evaluate the source of distraction and realize it offered no hazard, they disregarded the information on the signs and began to resume normal speed. When the roadside distraction was present at Monterey, the average speeds were about 3 mph lower than without the distraction.

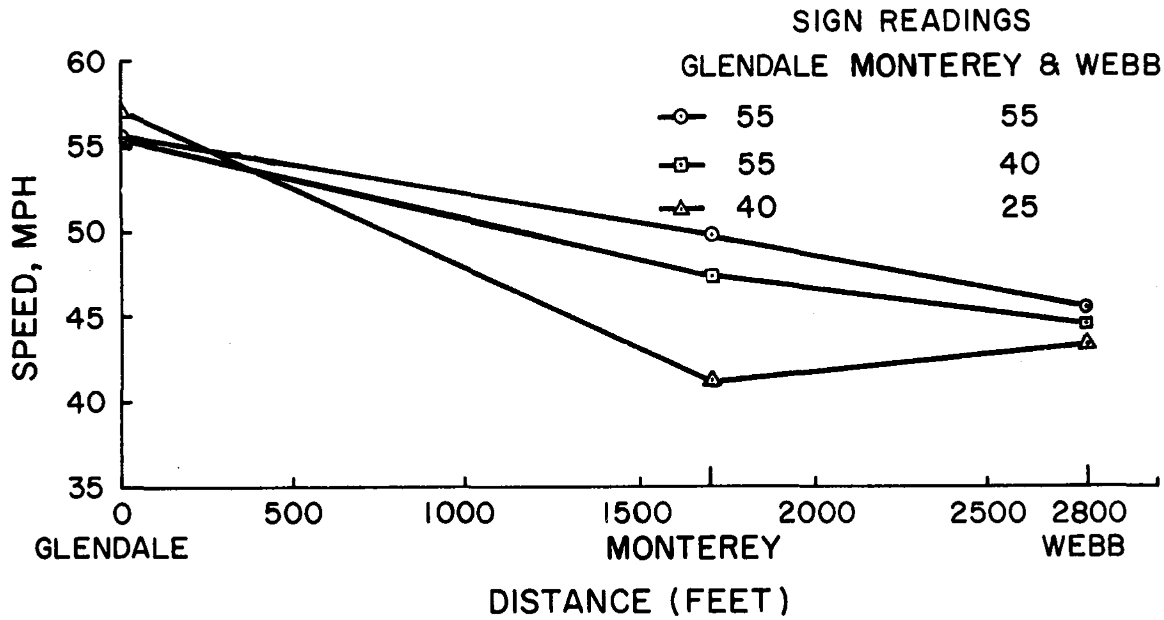


Figure 9. Speed Profiles Under Three Speed Control Conditions With No Distraction (One Hour).

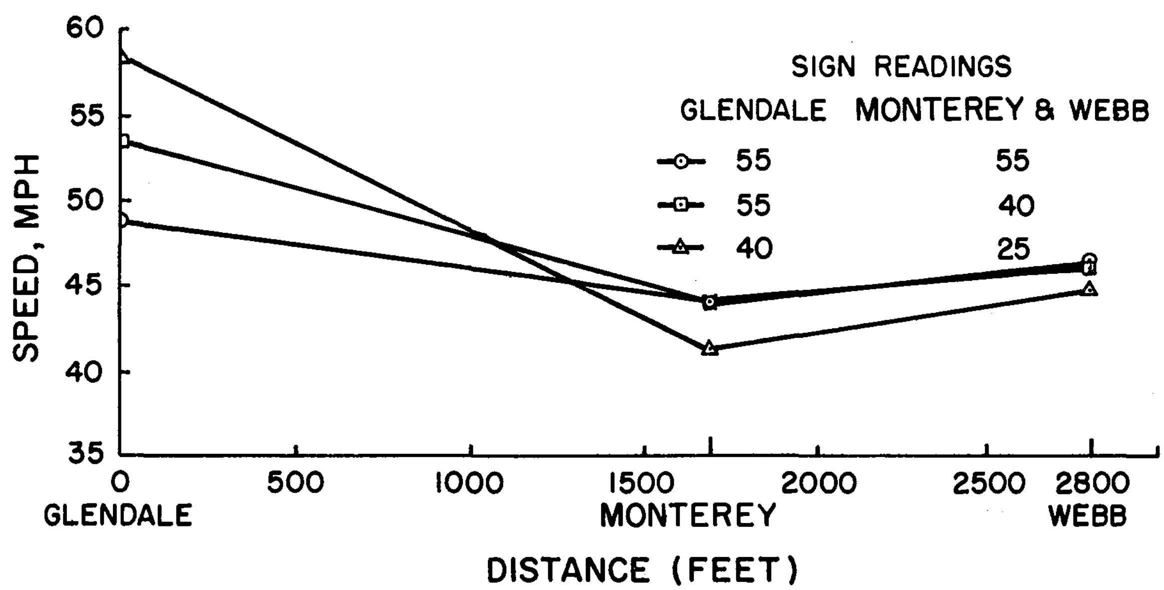


Figure 10. Speed Profiles Under Three Speed Control Conditions With a Roadside Distraction at Monterey (One Hour).

Effect of Speed Controls on Flow and Density

Another point of interest using data from the spot-speed study is the effect of the speed control signs on flow. It had been contended by some* 1) that by reducing the speed indication on the overhead speed control signs, flow toward a congested area could be decreased and 2) that by increasing posted speeds downstream, motorists were encouraged to depart from the congestion faster, thereby increasing flow out of the area. Table 4 presents the hourly space mean speeds and corresponding flow rates for the six situations at the Webb location, which might be considered representative of a location upstream of a congested area which is out of view of the motorist.

TABLE 4

SPEED AND FLOW COMPARISONS AT WEBB

	Speed Indication					
	Without Distraction			With Distraction		
	55	40	25	55	40	25
SMS, hourly average	44.3*	43.5*	43.1*	45.9**	44.8**	44.2**
Av. Volume Veh/5 min.	373	373	366	382	375	377
Density = Volume/SMS	84.5	85.5	85.0	84.0	82.0	85.0

* No statistically significant differences in speeds with no distraction

** Only one speed difference is statistically significant. The differences of 1.7 mph between the 55 mph speed indication and the 25 mph indication is significant.

As seen there was little decrease in stream speeds or volume at this location when lower posted speeds were displayed. The density remained nearly constant as well, indicating the speed signs did not substantially influence these characteristics.

DISCUSSION OF RESULTS OF OFF-PEAK STUDIES

The studies which were conducted with the overhead lane control signals indicated that motorists leave a closed lane farther upstream of the closure when the overhead lane control signals were used. This did not lead to any particular motorists' benefits in terms of reduction in travel time and delay during this study because of the queueing which was present upstream of the lane closure. The operation of the lane control signals did not increase the output rate past the lane closure under the queueing situation which prevailed during the studies.

Earlier studies (5) have demonstrated similar results under lower volume conditions and indicated that a much smoother operation prevailed at the

* The source of this information is Appendix A3 of Reference 1.

lane closure and fewer vehicles became "trapped" upstream of the lane closure when the overhead lane control signals were used. Thus, lower delay and greater safety would be associated with the operation of the overhead lane control signals during low volume conditions.

The critical condition which must be met for the overhead lane control signals to produce tangible benefits (in terms of reduced travel time) for the motorists is that the volume on the Freeway must be less than the capacity which would remain with the lane or lanes closed. The present hours of operation of the overhead lane signals on the Lodge Freeway are 6 a.m. to 8 p.m. on week days and, during these hours, the volume is rarely below the capacity of the Freeway with one lane closed. This would suggest that during the present hours of operation, the motorists' benefits of the lane control signals are small and that some potential benefits during other hours of operation are not being realized. The operation of the lane control signals at night may produce a sizable improvement in safety due to the high closure rates and the reduced attentiveness and visual acuity of drivers at night.

The changeable speed signs were able to reduce slightly the speeds of the traffic stream when the posted speed was reduced by a large amount. The reduction in stream speeds was not nearly equal to the amount of the posted speed reduction. During the off-peak periods very little motorist benefits of the operation of these signs was determined. The value of these signs as an advanced warning of slower speed ahead is open to conjecture. The signs may produce a safety benefit if the advance warning intent is realized by the motorists. Human factors techniques would be required to evaluate the amount of advanced warning provided by the speed control signs.

V. RAMP CLOSURE SIGNS

The ramp closure signs (illuminated "Don't Enter" sign with the painted word "Ramp") are used during unusually critical freeway conditions when it is preferable to deny access to the Freeway. These are located on all approaches to all entrance ramps in the NPG TV Control Area. Figure 11 shows an installation of a "Don't Enter Ramp" sign.

No controlled studies had been planned to evaluate these signs. However, on June 13, 1967, a situation necessitated their use (their normal use was quite infrequent). This was an extremely hot day and a large pavement eruption occurred just north of the Davison Interchange on the northbound Lodge. Lanes 2 and 3 were closed by maintenance crews from 4:00 to 5:01 p.m., leaving only the median lane and the auxiliary (right) lane open for traffic. Since this was during the afternoon peak period, very heavy congestion developed and extended upstream in all lanes for a distance of more than eight miles.

The "Don't Enter Ramp" signs in the northbound direction were activated at the following entrance ramps:

1) West Grand Boulevard,
2) Seward Avenue,
3) Chicago Boulevard, and
4) Webb Avenue.

Since the electronic detectors were in operation on the ramps, data were collected throughout the incident. Table 5 presents the one hour ramp volumes (4:00-5:00 p.m.) obtained during the ramp closure as well as the average ramp volumes during the same time period.

TABLE 5

COMPARISON OF RAMP VOLUMES DURING NORMAL CONDITIONS AND ONE HOUR OF "RAMP CLOSURE"

Location	Average Normal Volume			Observed Volume			% Reduction
	4:00-4:30	4:30-5:00	4:00-5:00	4:00-4:30	4:30-5:00	4:00-5:00	4:00-5:00
W. Grand Blvd.	547	616	1163	413	433	846	22.2
Seward Avenue	197	234	431	124	227	351	18.6
Chicago Blvd.	188	221	409	117	180	297	27.4
Webb Avenue	80	102	182	76	101	177	2.7
TOTAL	1012	1173	2185	730	941	1671	23.5

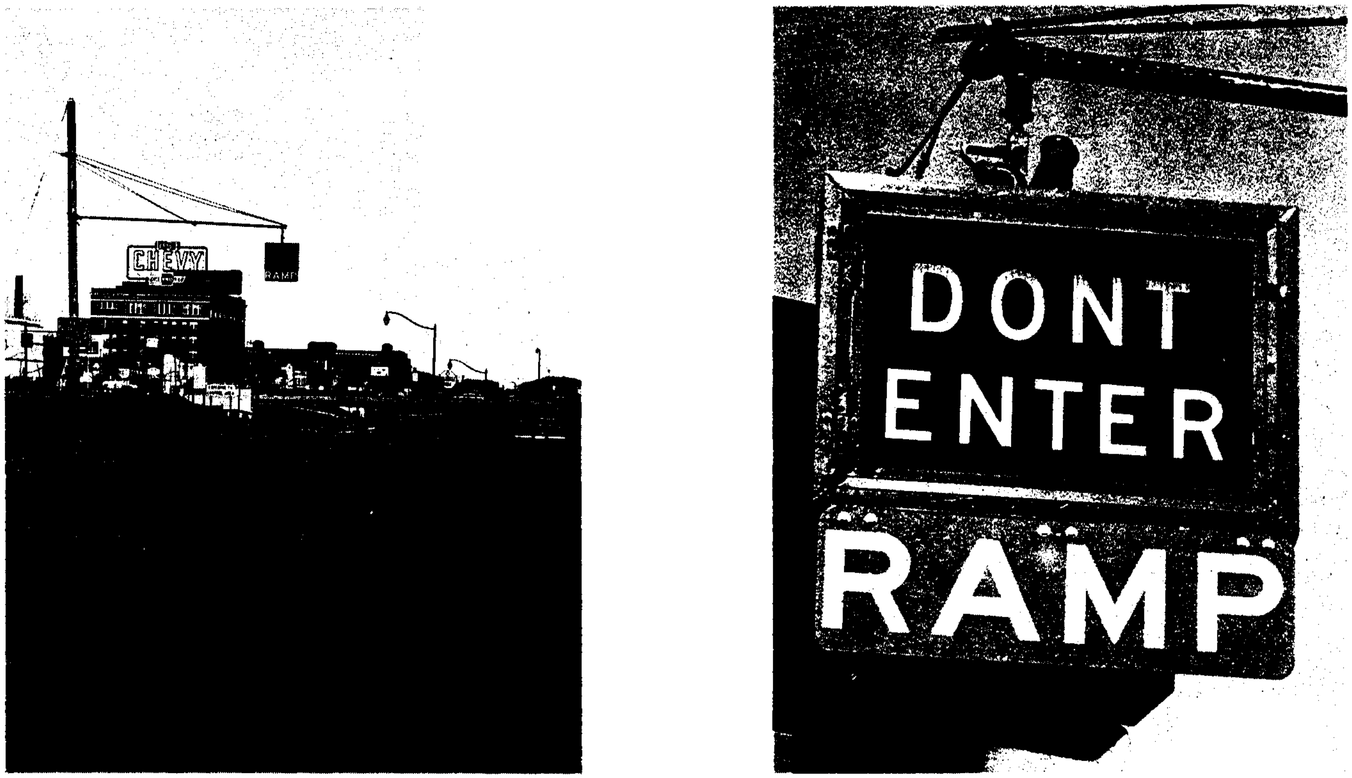


Figure 11. Field Installations of Ramp Closure Signs.

The intention of ramp closure is that the ramp will be used by no vehicles. However, these signs are not completely positive because they do not physically close the ramp. By reducing the input to the Freeway, they did, in a broad sense, function in a manner similar to ramp metering. The compliance (of about 23.5%) was concentrated at the three southern ramps where excellent alternate routes are available. The reduction of volume at Webb, on the other hand, was so slight it may well have been normal variation, and the small magnitude of the reduction may well have been caused by the lack of an easily accessible alternate route at this location.

The results suggest that use of the ramp closure signs during periods of congestion - either normal congestion caused by maintenance activities or accidents - will normally be able to improve freeway corridor operation by redistributing some demand to noncongested portions of the system (see Section VIII). It also suggests that the operation of a ramp metering system during the same conditions could produce essentially the same results.

VI. EFFECT OF THE ON-FREEWAY CONTROL SYSTEM ON PEAK PERIOD TRAFFIC OPERATION

The nature of traffic movement in urban areas is such that the worst problems normally develop during the two peak periods and during these times congestion frequently occurs on a regular basis. Because the quality of traffic flow is lowest during the peak periods, the primary benefits of a traffic control system would logically be made during these peak periods. The National Proving Ground Control System is no exception. It was designed and installed primarily to aid traffic on the Lodge Freeway during the peak periods. This section of the report presents several studies which were designed and conducted to evaluate the effectiveness of the NPG Traffic Control System in the improvement of traffic flow on the Lodge Freeway. In this evaluation, primary emphasis was placed on the "on freeway" portion of the control system, i.e., the speed control signs and the lane control signals.

STUDY PROCEDURES

Studies were conducted during both peak periods in order to evaluate as completely as possible the benefits of the NPG Traffic Control System. The NPG Traffic Control System was operated on alternate two-week periods from April to September, 1967. The "two week on-two week off" operation allowed a comparison of traffic operation on the Lodge Freeway with and without benefit of this control system.

In the southbound direction the volumes at Monterey and the travel time on the inbound Freeway were used to measure the performance of the control system. The volumes at Monterey are important since Monterey is just downstream of the last major bottleneck (Davison-Glendale area) and the volumes there reflect the ability of the on-freeway control system to increase the output at a bottleneck, which has been suggested as one of the features of the NPG Traffic Control System. It is necessary for a peak period freeway control system either to increase the flow rate at bottlenecks or to alter the demand of the freeway. Since the NPG Traffic Control System does not alter the demand on the Freeway (except for rare uses of the ramp closure signs), it must increase the flow rates at the bottlenecks to reduce delay to the motorists on the Freeway.

The travel times over the 9.8 mile distance from Seven Mile to Grand River are used to evaluate the effect of the NPG Traffic Control System on individual motorists during both peak periods.

In the afternoon peak period, input-output studies (7, 8) were conducted on the 8.3 mile section of the Lodge Freeway between Grand River and Meyers. From Holden to Meyers an electronic detector-computer system* was used to perform the input-output studies from 2:30 to 6:30 p.m. In the section from Grand River to Holden manual input-output studies were conducted

* Additional information on this electronic surveillance system can be found in Reference 3.

from 3:00 to 6:30 p.m. The input-output studies provided several important measures of effectiveness of the operation of the northbound Lodge Freeway.

PRESENTATION OF RESULTS - SOUTHBOUND FREEWAY

Freeway Volumes at Monterey

In the morning peak period the critical bottleneck in the southbound direction is in the Davison-Glendale area and is due to the high merging volumes. Queueing from this bottleneck extends upstream to Seven Mile Road, a distance of about four and a half miles. An overhead speed control sign is located at Glendale - at the extreme downstream end of the queueing - and another is located at Monterey which is just downstream of the queueing area (see Figure 2).

If the NPG Traffic Control System is successful in reducing travel time for motorists on the southbound Lodge, it must increase the volumes out of the queueing area. The Freeway volumes at Monterey are a measure of the volumes leaving the bottleneck area.

Figure 12 is a graph of the average cumulative volumes at Monterey from 6:30 to 9:30 a.m. both with the on-freeway control system in operation (n = 25 days) and with it not in operation (n = 19 days). Table 6 presents the individual volumes for each fifteen-minute period and the results of the statistical tests. Based on one-sided 't' tests, none of the differences in the fifteen-minute volumes was significant at the 95% level of significance. Therefore, it is <u>not</u> possible to conclude that the operation of the NPG Traffic Control System increased the volumes through the critical bottleneck area. This is primarily a reflection of the overhead speed signs since the lane control signals were little used during the peak periods studies.

TABLE 6

COMPARISON OF VOLUMES AT MONTEREY, SB LODGE FREEWAY
TIME PERIOD 6:30 - 9:30 A.M.

Time Ending	15 Minute Volumes and Standard Deviations				Difference	Cumulative Difference
	Signals ON n=25 days		Signals OFF n=19 days			
	$\bar{X}$	S_x	$\bar{Y}$	S_y	$\bar{X}-\bar{Y}$	
6:45	1335	61.2	1347.	40.67	-12*	-12
7:00	1363	113.1	1379.	101.0	-16*	-28
7:15	1361	139.0	1397.	139.9	-36*	-64
7:30	1352	147.0	1339.	175.3	13*	-51
7:45	1341	180.2	1324.	174.4	17*	-34
8:00	1299	188.7	1273.	152.3	26*	- 8
8:15	1283	202.3	1267.	222.7	16*	+ 8
8:30	1278	186.4	1258.	235.7	20*	+28
8:45	1258	190.0	1252.	274.9	6*	+34
9:00	1254	237.2	1229.	292.1	25*	+59
9:15	1221	220.6	1196.	258.0	25*	+84
9:30	1195	197.5	1209.	304.2	-14*	+70
TOTAL	15540	624.9	15470	735.3	70*	

*Cannot reject the hypothesis $H:V_{on} \leq V_{off}$ at 95% level of significance

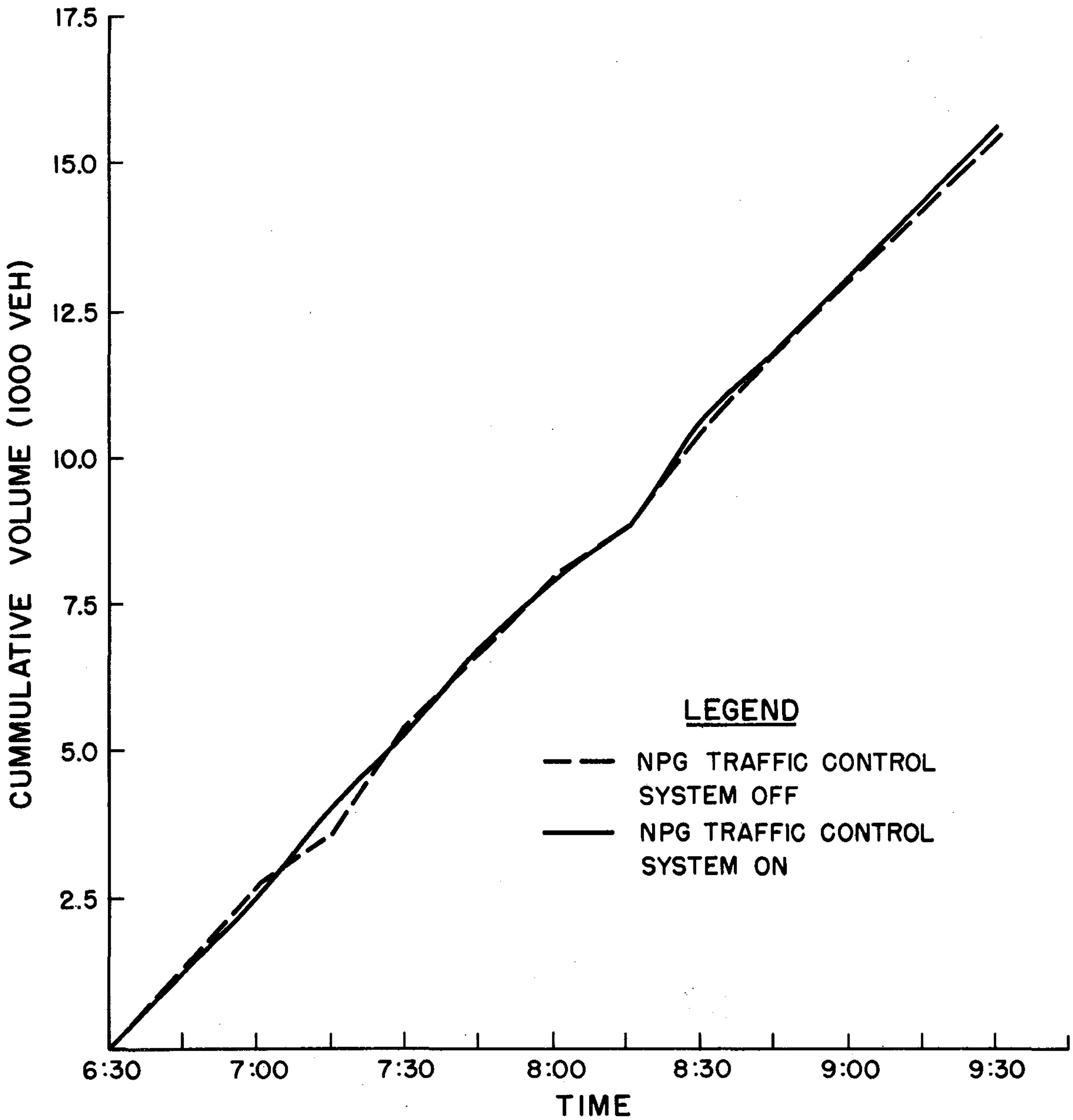


Figure 12. Average Cumulative Volumes on the Southbound Lodge Freeway at Monterey With and Without the NPG Traffic Control System in Operation

TRAVEL TIMES

Table 7 contains a summary of the travel time data for vehicles traveling the 9.8 miles from Seven Mile Road to Grand River. The data were obtained from the moving vehicle studies. In four of the six half-hour periods, the average travel time with the NPG Control System on was higher than the average travel time with the system off and all of the differences are small. For the remaining two periods, the average travel times with the NPG Control System on were lower and the differences were relatively large (3.1 and 4.1 minutes). The average difference in travel time was 0.8 minutes for the 9.8 mile trip. None of the differences were statistically significant and the sample sizes are small.

TABLE 7

SOUTHBOUND TRAVEL TIME DATA
SEVEN MILE TO GRAND RIVER

Time Period	NPG Controls On			NPG Control Off			Difference
	$\bar{X}$	S_x	n_x	$\bar{Y}$	S_y	n_y	$\bar{X}-\bar{Y}$
6:30-7:00	16.1 min.	4.8	4	15.7 min.	4.3	9	0.4 min.
7:00-7:30	19.7	3.2	4	23.8	4.9	5	-4.1
7:30-8:00	24.1	1.6	3	24.0	9.9	3	0.1
8:00-8:30	26.0	2.9	3	24.8	5.4	3	1.2
8:30-9:00	17.4	3.0	5	20.5	5.8	8	-3.1
9:00-9:30	12.3	1.4	4	11.5	---	1	0.8
				AVERAGE DIFFERENCE			0.8 min.

Note: None of the differences is statistically significant.

Assuming the average travel time savings of 0.8 minutes/9.8 mile trip to be accurate, it is possible, with some other reasonable assumptions, to estimate the net travel time savings due to the use of the NPG Traffic Control System during a typical morning peak period. The average volume at Monterey during the three-hour peak period was about 15,500 vehicles (Table 6). Assuming the average three-hour volume over the entire 9.8 mile section is 15,500 vehicles, the average travel in the section is 9.8 x 15,500 vehicle miles. The average travel time savings is (0.8/9.8) minutes/vehicle mile. Thus, on this basis, the average total travel time savings each morning peak period is about 200 vehicle hours.

Summary

The two studies which were conducted in the morning peak period provided a range of possible motorists' benefits due to the operation of the NPG Traffic Control System. Based on the study of the volumes at Monterey, the operation of the NPG Control System had no effect on the traffic stream. Based on the moving vehicle studies (and accepting differences which are not statistically significant) the savings in total travel time is 200 vehicle hours during a morning peak period when the NPG Traffic Control System is used. Thus, the actual savings in travel time is probably between 0 and 200 vehicle hours.

PRESENTATION OF RESULTS - NORTHBOUND FREEWAY

Input-Output Studies

The input-output studies (3, 7, 8) were conducted daily on the northbound Lodge Freeway between Grand River (Spruce) and Meyers (8.3 miles) from 2:30 to 6:30 p.m. (see Figure 4). These studies produced a great deal of valuable data on the operation of the entire 8.3 mile length of Freeway during the afternoon peak periods. The samples include 12 days with the NPG Control System in operation and 15 days without it in operation. The following sections contain the measures of effectiveness which were obtained from these studies.

1) Total Input

The total input to the Freeway (sum of all entrance ramp volumes and the volume on the Freeway at Grand River) represents the volume processed in the section being considered and also represents a measure of demand on the Freeway. Figure 13 presents the cumulative input volume and Table 8 presents the half-hour input volumes. None of the differences in input volumes was statistically significant but the total input was about 1000 vehicles less on the days in which the NPG Traffic Control System was in operation.

TABLE 8

COMPARISON OF TOTAL INPUTS TO THE SYSTEM
FROM SPRUCE TO MEYERS
TIME PERIOD 2:30-6:30 p.m.

Time	30 Minute Volumes and Standard Deviations						Difference
	Signals ON			Signals OFF			
	n	$\bar{X}$	S_x	n	$\bar{Y}$	S_y	
2:30-3:00[a]	2	4527	41.7	3	4317	295.9	210*
3:00-3:30	3	5547	201.8	6	5737	170.9	-190*
3:30-4:00	12	5851	875.4	13	5778	153.2	73*
4:00-4:30	12	5327	501.9	15	5604	196.1	-277*
4:30-5:00	12	5624	317.0	15	6024	205.1	-400*
5:00-5:30	12	5570	204.5	15	5790	166.2	-220*
5:30-6:00	12	5082	255.9	15	5044	206.2	38*
6:00-6:30	12	4587	176.7	14	4823	154.9	-236*

[a] Includes Holden to Meyers only.

* None of the differences is statistically significant.

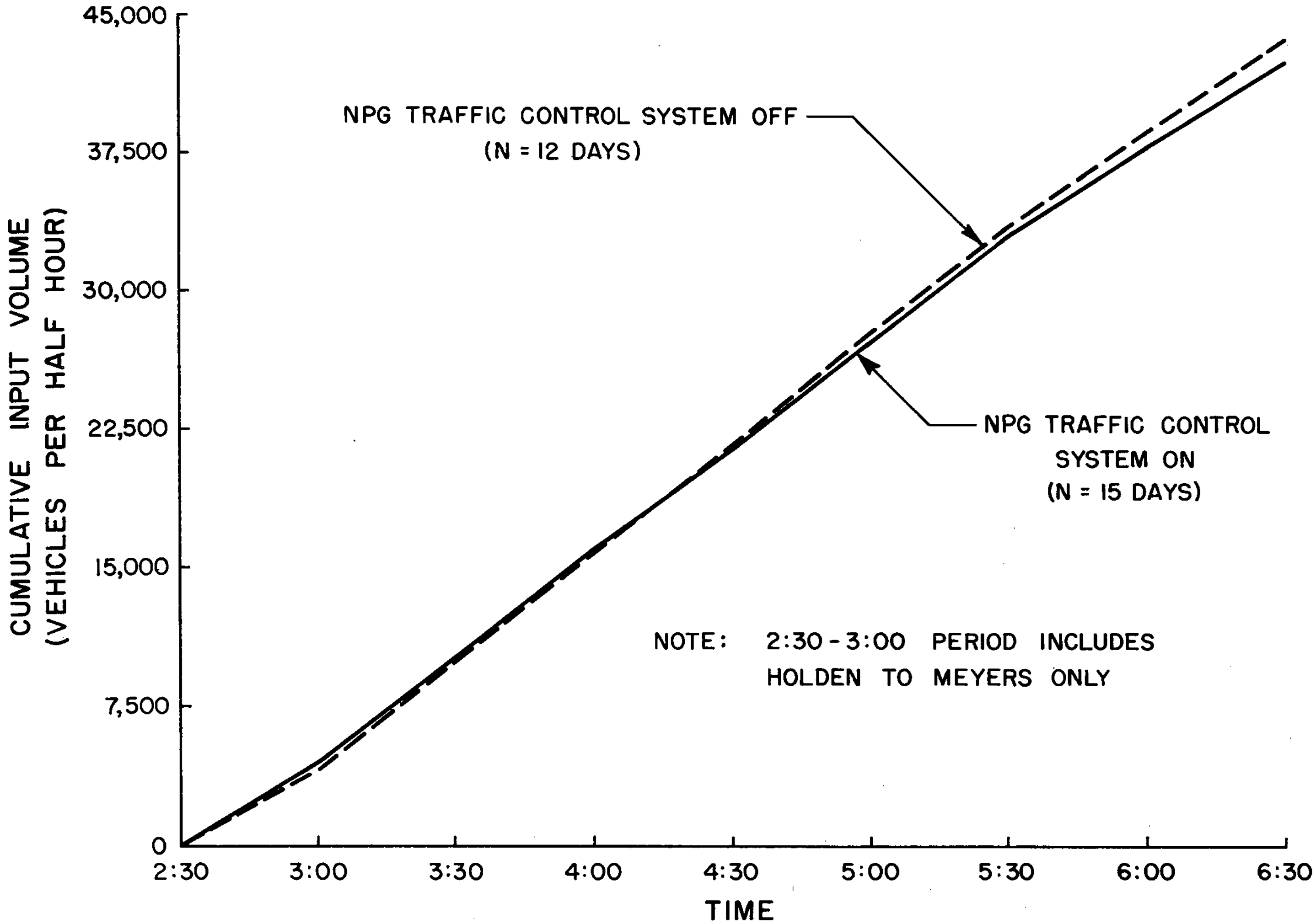


Figure 13. Average Cumulative Input to the Northbound Lodge Freeway During the Afternoon Peak Period With and Without the NPG Traffic Control System in Operation

2) Total Travel (TT)

The total travel in terms of vehicle miles is also a measure of the performance of a traffic system and to a certain extent reflects the demand on the system and the efficiency of the system. Figure 14 presents the total travel on the northbound Lodge Freeway during the afternoon peak period under two control conditions - with and without the NPG Traffic Control System in operation. The total travel was slightly less during the times in which NPG Control System was in operation.

3) Storage in the Freeway

The number of vehicles on the Freeway can easily be converted to density by dividing by the length of the section. Thus, the number of vehicles on the Freeway as a function of time is a means of describing the development, dissipation and severity of congestion.

4) Total Travel Time (TTT)

The total travel time of all vehicles on the Freeway can easily be determined from the storage-time function (14). The bar charts in Figure 15 show the total travel time on the northbound Lodge Freeway for each half-hour period. In the bar chart on the left each half hour is the total travel time without control, and the right bar chart is the total travel time on the days with the NPG Traffic Control System in operation. For most of the time periods the total travel time was slightly lower with no control.

5) Delay

The delay on the Freeway was also obtained from the input-output studies. It was assumed that delay was incurred by the traffic stream when the average speed was less than 40 mph. Thus, the delay of the traffic stream in a time period equals the total travel time minus the total travel time if the average stream speed had been 40 mph, if this is greater than zero. Stated mathematically:

$$D = TTT - TT/40 \text{ or } 0, \text{ whichever is greater}$$

where D is the delay in a time period,
TTT is the total travel time in the period
and TT is the total travel in the period.

The delay during each half-hour period is also shown on Figure 15. The delay is a portion of the total travel time and is shown as a bar chart which is part of the TTT bar chart. In each half-hour period, the left delay bar chart is the delay with the NPG Control System in operation and the right delay bar chart represents the delay with no control. For most time periods the delay is lower with no control.

6) Average Speed

If the total travel (TT) and the total travel time (TTT) in any time period is known for a traffic system, the average speed in the system in the same time period U = TT/TTT (8). Figure 16 shows the average speed on the northbound Lodge Freeway from Grand River (Spruce) to Meyers. During most of the afternoon peak period, the average speed was higher with no controls in effect.

7) Kinetic Energy

Another measure of effectiveness of value is the system kinetic

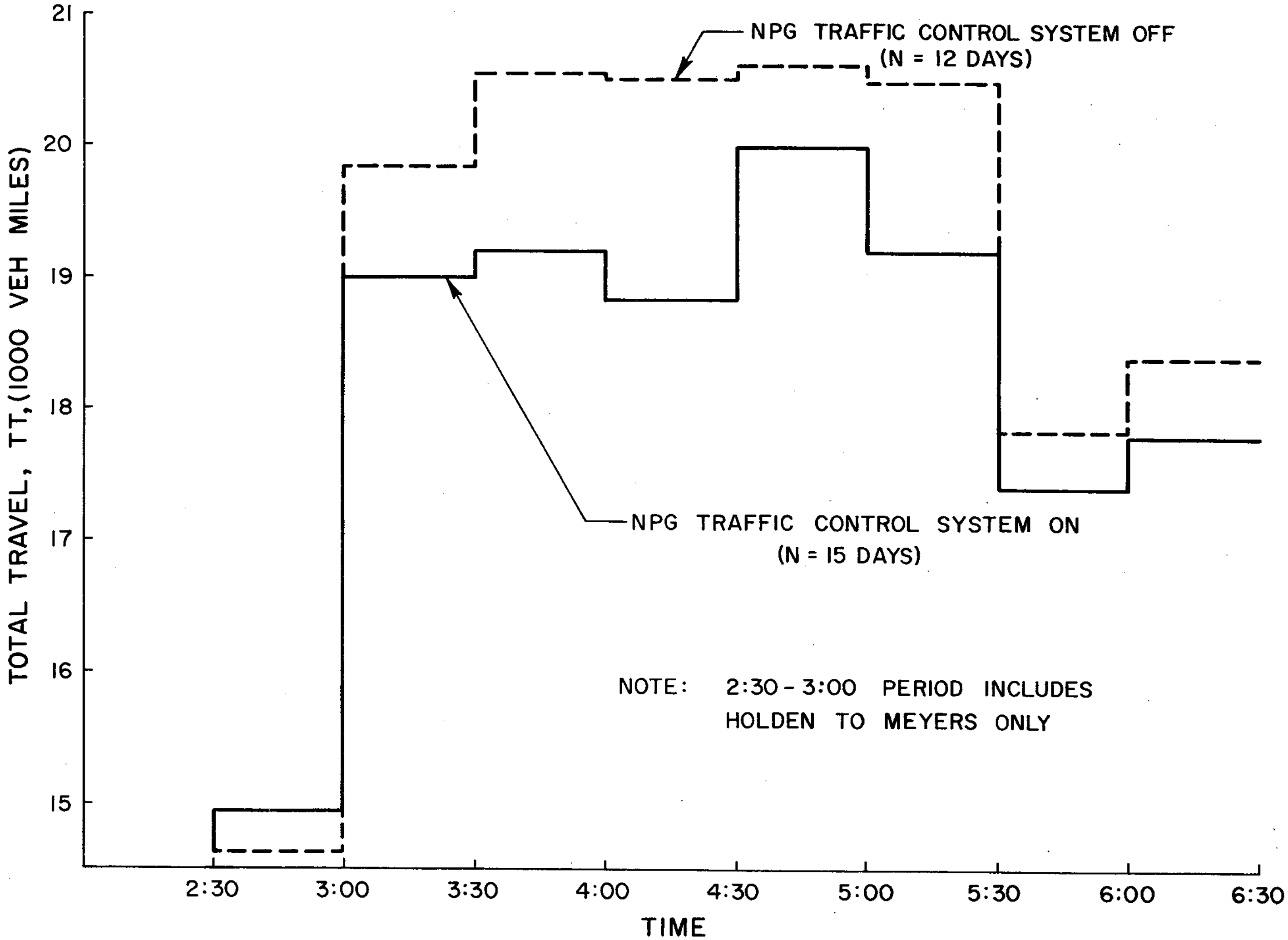


Figure 14. Total Travel on the Northbound Lodge Freeway During the Afternoon Peak Period With and Without the NPG Traffic Control System in Operation

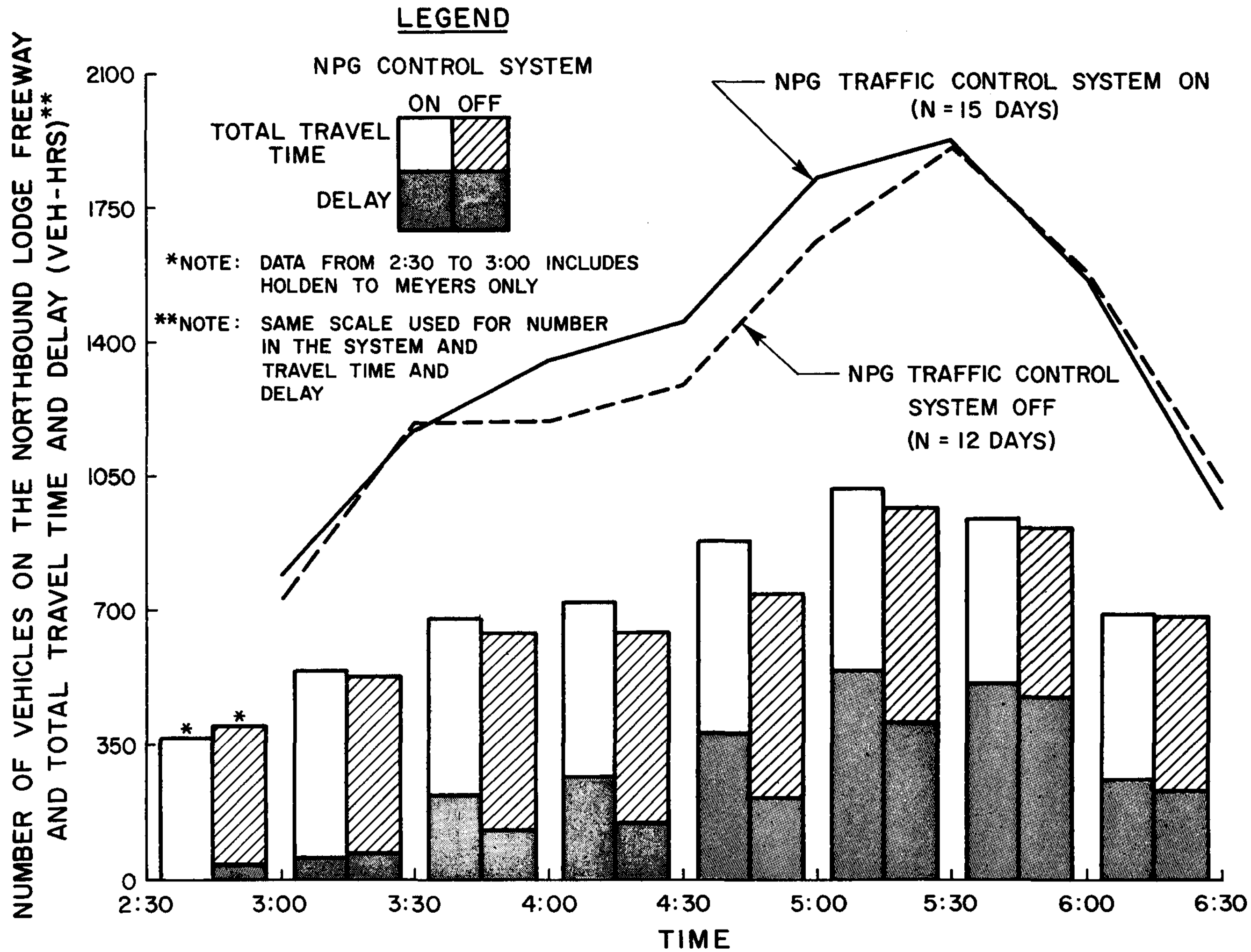


Figure 15. Storage, Total Travel Time and Delay on the Northbound Lodge Freeway During the Afternoon Peak Period With and Without the NPG Traffic Control System in Operation

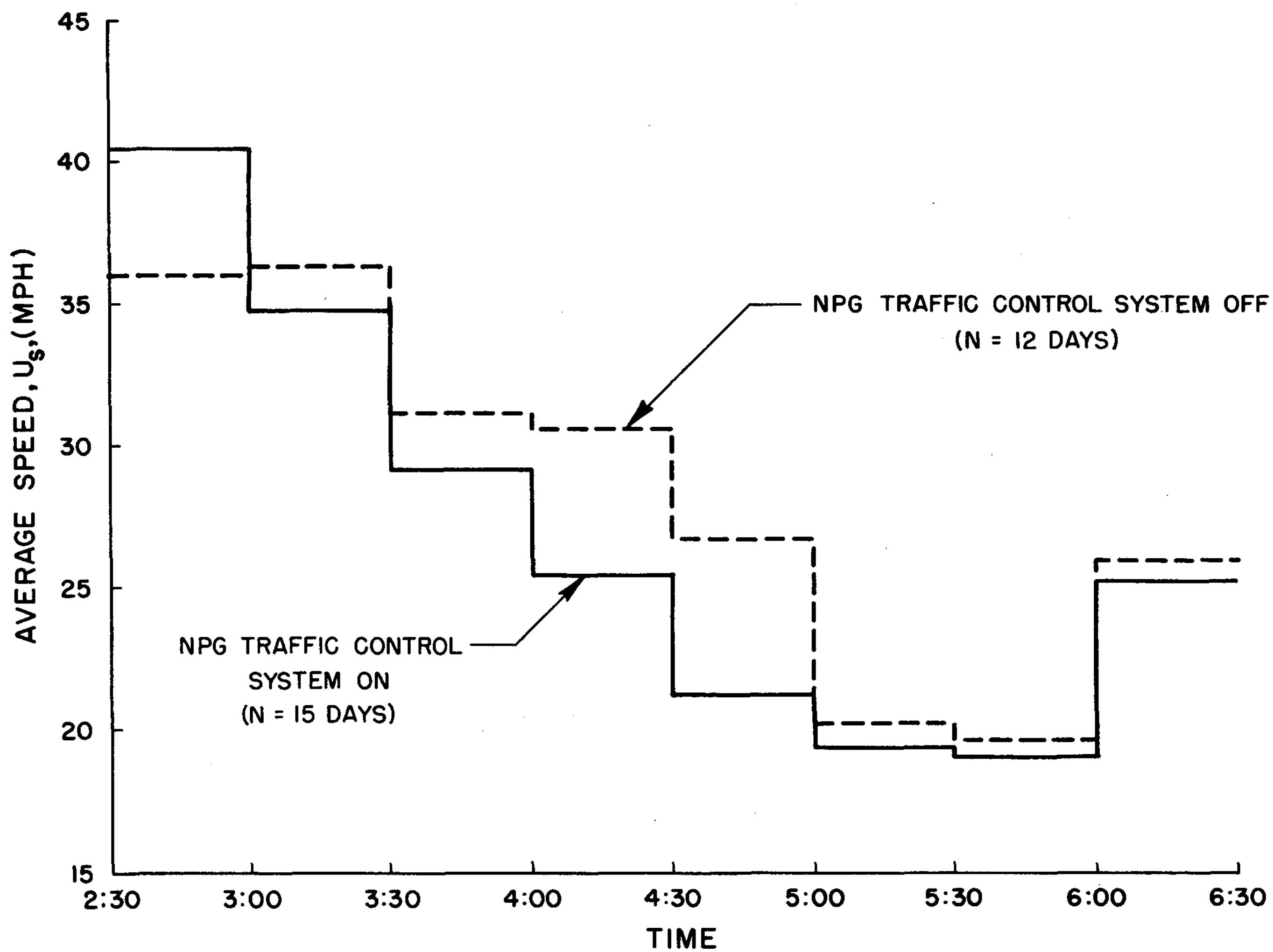


Figure 16. Average Speed on the Northbound Lodge Freeway During the Afternoon Peak Period With and Without the NPG Traffic Control System In Operation

energy, KE, which is a measure of the energy expended by the traffic stream. It is based on a fluid flow analogy (9, 11) where KE = qu, where q is volume and u is speed. The system analog of this relationship is $KE = TT^2/TTT$ or $\bar{U}_s \times TT$ (8) for a given time period of interest.

The kinetic energy for the two conditions studied are shown in Figure 17. Except for the 2:30-3:30 p.m. period, the kinetic energy is higher with no control, indicating that operation was better with no controls.

SUMMARY OF INPUT-OUTPUT STUDIES

Table 9 presents a summary of the most pertinent measures of effectiveness which were obtained from the input-output studies and a summary of statistical analyses which were performed on these data. Three differences were statistically significant. The total travel time with the NPG Traffic Control System in operation was 323 vehicle hours lower than with no control and this difference was significant. Similarly, the total travel was less and the delay was greater when the controls were in effect.

The average travel time per vehicle mile (60 TTT/TT) was calculated as well. With no control the average travel time per vehicle mile was 2.16 minutes, and 2.42 minutes with the controls in effect.

Travel Times

Table 10 contains a summary of the travel times for vehicles traveling the entire 8.3 miles from Grand River to Meyers Road. In five of the eight half-hour periods the average travel times with the NPG Control System operating were lower than those obtained with no freeway control. Two of these differences were quite large (-3.1 and -3.8 minutes) although not statistically significant. In two of the half-hour periods the average travel times were lower with no control and one difference was large - 3.2 minutes. Because of the small sample sizes, none of the differences was significant.

Assuming the average difference of -0.55/8.3 mile trip to be accurate and representative of conditions through the peak periods, the average travel time saving per vehicle mile is 0.066 minutes. Since the total travel in an average peak period is about 150,000 vehicle miles (Table 9), the total travel time savings is about 165 vehicle hours per afternoon peak period, estimated from the moving vehicle data.

DISCUSSION OF RESULTS OF PEAK PERIOD STUDIES

The peak period studies which were conducted present means of estimating the possible range within which falls the benefit to the motorists of the operation of the NPG Traffic Control System during the morning and afternoon peak periods. Different measures of effectiveness provided somewhat different estimates of the benefits and with different statistical significance, hence the range of benefits.

For the morning peak period, the benefits were estimated from the volume studies at Monterey and from the moving vehicle studies. From the volume studies it would be concluded that the on-freeway control system had no effect

TABLE 9

COMPARISONS OF PEAK PERIOD OPERATIONS WITH AND WITHOUT THE NPG TRAFFIC CONTROL SYSTEM (N.B. System-Spruce to Meyers)

Measure of Effectiveness	Time Period	Statistical Hypothesis ($\alpha = 0.05$)	NPG Control System ON n = 12 days		NPG Control System OFF n = 25 days		Difference
			$\bar{X}$	S_x	$\bar{Y}$	S_y	$\bar{X}-\bar{Y}$
N.B. Total Input-Vehicles........	3:00-6:30	$H: \bar{I}_{on} = \bar{I}_{off}$	58,589.0	3903.4	60,323.0	415.8	-1734.0
N.B. Total Travel Time - Veh.Hrs..	2:30-6:30	$H: TTT_{on} = TTT_{off}$	5,827.0	215.0	5,504.6	188.5	323.0*
N.B. Total Travel-Vehicle Miles...	2:30-6:30	$H: TT_{on} = TT_{off}$	146,706.0	3532.1	153,011.7	2143.3	-6305.7*
N.B. Total Delay-Vehicle Hours...	2:30-6:30	$H: D_{on} = D_{off}$	2,215.1	329.7	1,695.4	157.1	520.0*
Average Travel Time-Minutes Per Veh.Miles...	2:30-6:30	None	2.42		2.16		0.26

*Significant Differences

TABLE 10

NORTHBOUND TRAVEL TIME DATA
GRAND RIVER TO MEYERS ROAD

Time Period	NPG Controls ON			NPG Controls OFF			Difference
	$\bar{X}$	S_x	n_x	$\bar{Y}$	S_y	n_y	$\bar{X}-\bar{Y}$
2:30-3:00	11.7 min.	---	1	14.8 min.	4.2	4	-3.1
3:00-3:30	13.8	1.9	7	13.9	1.3	6	-0.1
3:30-4:00	19.0	8.5	4	15.8	1.8	9	3.2
4:00-4:30	17.2	2.3	7	16.3	3.6	10	0.9
4:30-5:00	18.9	2.4	4	19.0	3.6	10	-0.1
5:00-5:30	24.3	4.2	3	24.3	4.5	6	0.0
5:30-6:00	18.4	3.9	4	22.2	4.7	5	-3.8
6:00-6:30	---	---	0	---	---	0	---
6:30-7:00	9.4	0.9	3	9.9	1.6	8	-0.5
				AVERAGE DIFFERENCE			-0.55 minutes

Note: None of the differences is statistically significant.

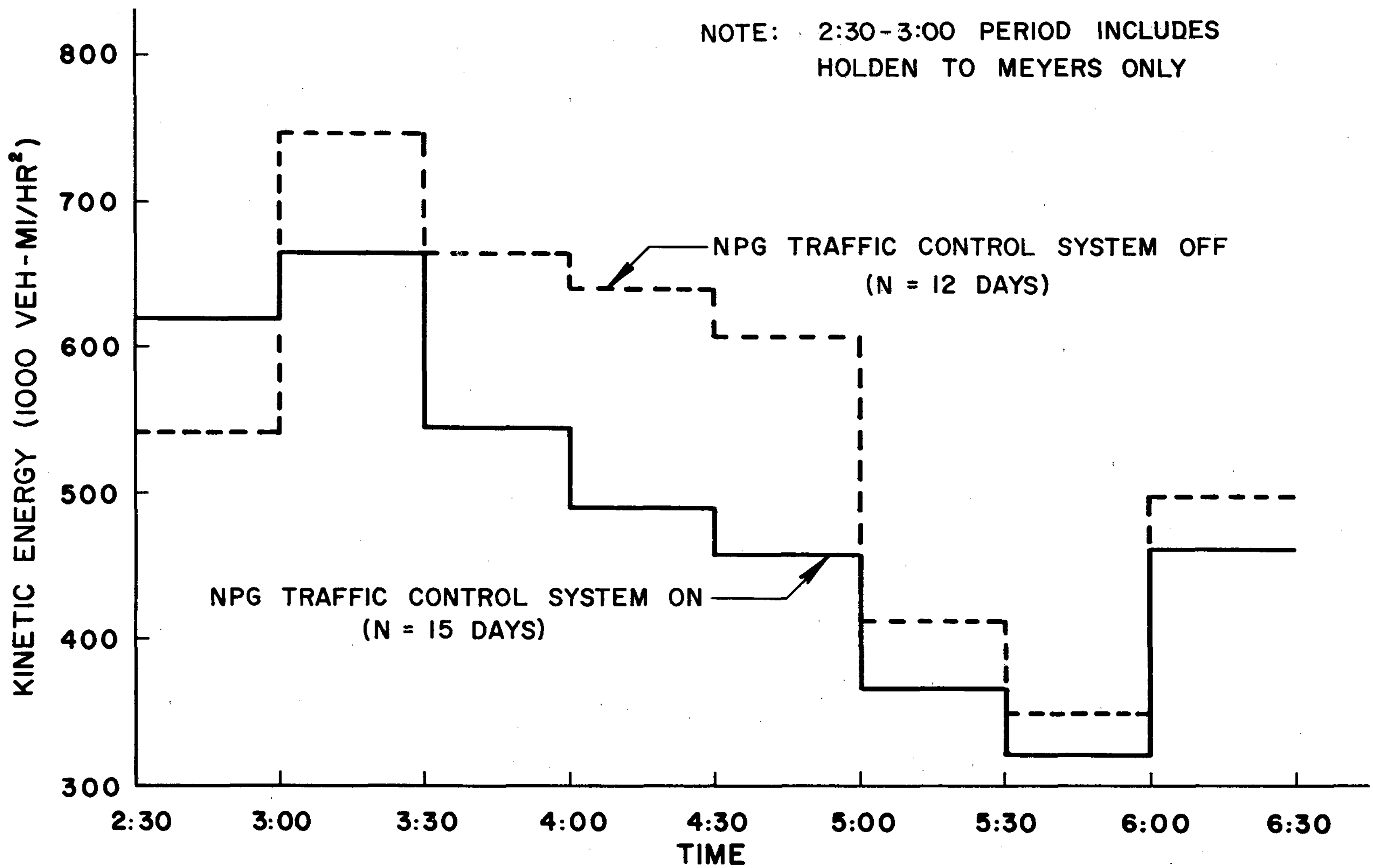


Figure 17. Average Kinetic Energy on the Northbound Lodge Freeway During the Afternoon Peak Period With and Without the NPG Traffic Control System in Operation

on the inbound traffic stream. If one views the travel time data with statistical rigor, the conclusion would be that the NPG Control System had no effect since none of the travel time differences were significant. If one is willing to accept the travel time differences which are not significant, the estimated total travel time savings is 200 vehicle hours per peak period. Weighting the results of the volume studies by 0.50, the statistically significant results of the travel time studies by 0.25, and the results of the travel time studies based on non-significant differences by 0.25, the weighted estimate of total travel time savings is:

$$0.50(0) + 0.25(0) + 0.25(200) = 50 \text{ vehicle hours per morning peak period.}$$

In the afternoon peak period, the input-output studies and the travel time studies were used to estimate the total travel time savings due to the operation of the NPG Traffic Control System. From the input-output studies, it would be concluded that the total travel time was 323 vehicle hours lower (statistically significant) during an average peak period with no control. Again, in the afternoon peak period, the unit travel times indicated a slight improvement with control but none of the differences was statistically significant. Thus, the rigorous statistical conclusion would be that there was no improvement, while a more liberal view would be that there was an average reduction in total travel time of 165 vehicle hours due to control in an average afternoon peak period. Weighting the results of the input-output studies 0.50 and weighting the results of the travel time studies as before, the weighted estimate of total travel time savings due to control is:

$$0.50(-323) + 0.25(0) + 0.25(165) = -120 \text{ vehicle hours per afternoon peak period.}$$

The following table summarizes the estimates of travel time savings due to the NPG Traffic Control System during the two peak periods.

TABLE 11

ESTIMATED SAVINGS IN TOTAL TRAVEL TIME
DURING PEAK PERIODS DUE TO THE OPERATION
OF THE ON-FREEWAY TRAFFIC CONTROL SYSTEM

	Estimate of Total Travel Time Savings Per Peak Period		
Peak Period	High Estimate	Low Estimate	Weighted Estimate
Morning	200 veh. hrs.	0	50 veh. hrs.
Afternoon	164 veh. hrs.	-323 veh. hrs.	-120 veh. hrs.
Total	365 veh. hrs.	-323 veh. hrs.	- 70 veh. hrs.

Probably a reasonable conclusion would be that the NPG Traffic Control System had no effect on peak period traffic flow.

VII. EFFECT OF TELEVISION SURVEILLANCE ON FREEWAY OPERATION

With a closed-circuit television surveillance system on a freeway, the response time of official aid to obstructions can be reduced by prompt detection and reporting of the obstructions. This section presents an estimate of the annual reduction in total travel time due to the television surveillance system. The estimate is based on an analytical model rather than on operational studies.

EFFECT OF TELEVISION SURVEILLANCE ON FREEWAY OPERATIONS DURING PEAK PERIODS

The model which is developed in Appendix B can be used to estimate the reduction in total travel time which can be attributed to the closed circuit television surveillance system. There can be little doubt that a closed circuit television system can be useful in reducing the response time of official aid to obstructions on a freeway. If this earlier arrival of aid is translated to an earlier removal of the obstruction which blocks one or more freeway lanes, a reduction in travel time on the freeway will result. An improvement in safety, in the form of reduction in the frequency of minor accidents, would probably also be realized but this is not considered here.

In calculating the average travel time savings due to the television surveillance system, several assumptions must be made. First, it is assumed that the average reduction in response time for official aid at an accident is 2.5 minutes and 1.0 minutes at an incident. The reduction in police response time to an accident was determined in a previous NPG report (15) and this same report indicated that no savings in average response times to an incident was effected by the TV surveillance system. In the analysis presented here a more liberal value of 1.0 minutes was used for the reduction in response time to an incident during peak periods. The lane blockage under analysis was assumed to take place at the mid-point of the peak period. Another NPG report (16) presented the distribution of the length of time during which accidents and incidents blocked one or more Freeway lanes. The average time of lane blockage was 4.94 minutes for incidents and 6.14 minutes for accidents. Only 20% of the incidents and 30% of the accidents remained on the roadway for more than 6 minutes. In the calculation of the average savings of travel time due to more prompt removal of the blockage, a normal occupancy time of 15 minutes is used for both accidents and incidents. Later, when the frequency of incidents which require official aid, only those incidents lasting more than 6 minutes are considered.

Table 12 presents the complete peak period analysis, including all assumptions, of the average travel time savings for each incident due to the earlier arrival of official aid. For accidents, the total travel time savings (A in Table 12) range from 300 vehicle hours for the three-lane section outbound to 180 vehicle hours for the four-lane section inbound, and for incidents the range is 72 to 120 vehicle hours. All parameters refer to those defined in Appendix B.

TABLE 12

ANALYSIS OF TOTAL TRAVEL TIME SAVINGS
DUE TO EARLIER REMOVAL OF AN OBSTRUCTION
FROM THE FREEWAY DURING PEAK PERIODS

	Outbound Peak Period		Inbound Peak Period	
	3-Lane Section	4-Lane Section	3-Lane Section	4-Lane Section
t=0	2:00 p.m.	2:00 p.m.	6:00 a.m.	6:00 a.m.
t_b	2:30 p.m. (0.5 hrs)	2:30 p.m. (0.5 hrs)	6:30 a.m. (0.5 hrs)	6:30 a.m. (0.5 hrs)
t_e	6:30 p.m. (4.5 hrs)	6:30 p.m. (4.5 hrs)	9:30 a.m. (3.5 hrs)	9:30 a.m. (3.5 hrs)
C	6000 vph	7000 vph	6000 vph	7000 vph
γ	3500 vph	4500 vph	3500 vph	4500 vph
α	5500 vph	7500 vph	5500 vph	7500 vph
B	4500 vph	4500 vph	4500 vph	4500 vph
t_i	4:15 p.m. (2.25 hrs)	4:15 p.m. (2.25 hrs)	7:45 a.m. (1.75 hrs)	7:45 a.m. (1.75 hrs)
A (accident)	300 veh.hrs.	235 veh.hrs.	240 veh.hrs.	180 veh.hrs.
A (incident)	120 veh.hrs.	94 veh.hrs.	96 veh.hrs.	72 veh.hrs.

In estimating the total effect of the television surveillance system in reducing travel time due to incidents, the average travel time saving per incident must be combined with the number of incidents in a one year period. Table 13 contains the data used in the analysis and these data were largely obtained from information in Reference 16. A 10% increase in the number of occurrences was assumed since the 1962-63 data were obtained. The average savings in travel time in Table 12 refer only to the incidents which received official aid. It was assumed that only incidents remaining on the Freeway more than six minutes received official aid and this represents 30% of the total accidents and 20% of the total incidents. Reference 16 also indicates that about 60% of the accidents and incidents occur in the three-lane section.

TABLE 13

NUMBER OF OBSTRUCTIONS PER YEAR - LODGE FREEWAY

	Accidents	Incidents
June 1, 1962 - June 1, 1963 Data*		
Outbound - 2:00-6:30 p.m.	83	355
Inbound - 6:00-9:30 a.m.	51	191
Used in Analysis**		
Outbound - 2:00-6:30 p.m.	27	78
Inbound - 6:00-9:30 a.m.	17	63

* From Figure 4, Reference 16

** Assumes a 10% total increase in accidents and incidents over the 1962-63 data. Assumes only vehicles with more than a six-minute duration on the Freeway receive official aid. This is 30% of the accidents and 20% of the incidents.

The annual travel time savings due to the reduced occupancy time of the freeway because of television surveillance during the peak period is:

$$\begin{aligned}\text{Travel Time Savings} &= (0.60)(27)(300) + (0.40)(27)(235)\\ &+ (0.60)(17)(240) + (0.40)(17)(180)\\ &+ (0.60)(78)(120) + (0.40)(78)(94)\\ &+ (0.60)(63)(96) + (0.40)(63)(72)\\ &= 25{,}000 \text{ vehicle hours per year}\end{aligned}$$

EFFECT OF TELEVISION SURVEILLANCE ON FREEWAY OPERATION DURING OFF-PEAK PERIODS

Since queueing occurs when one or more Freeway lanes are closed during the off-peak periods and in the off-peak direction during the peak periods, the more rapid removal of the cause of the lane closure can effect benefits to the motorists during these periods. May (18) derived a delay model for the condition in which the capacity of a freeway is reduced for a period and then allowed to return to normal during off-peak periods. Converting May's model to the terminology used in Appendix B we have

$$D = \frac{c\gamma}{2\alpha}\left[\frac{\gamma - \alpha}{c - \alpha}\right] t_o^2$$

where the terms are defined in Appendix B. The time t_o is the time during which the freeway capacity is reduced. If television surveillance can reduce t_o by an amount t_r, the delay is:

$$D = \frac{c\gamma}{2\alpha}\left[\frac{\gamma - \alpha}{c - \alpha}\right]\left[t_o - t_r^2\right]$$

and the reduction in delay or travel time is:

$$\text{Travel time reduction} = \frac{c\gamma}{2\alpha}\left[\frac{\gamma - \alpha}{c - \alpha}\right]\left[2t_o t_r - t_r^2\right].$$

Table 14 presents the assumed values for each parameter and the savings in total travel time due to the earlier removal of an obstruction during off-peak periods and in the off-peak direction during the peak period. The assumed reduction in response time to an accident is 2.5 minutes and no reduction in response time to incidents is assumed in the off-peak periods and is in agreement with the findings of Reference 15. A one-minute reduction in time to aid an incident during the peak period in the off-peak direction is assumed.

TABLE 14

ANALYSIS OF TOTAL TRAVEL TIME SAVINGS DUE TO EARLIER REMOVAL OF AN OBSTRUCTION FROM THE FREEWAY DURING OFF-PEAK PERIODS AND OFF-PEAK DIRECTION DURING PEAK PERIODS

	3-Lane Section	4-Lane Section
C	4500 vph	5000 vph
γ	3500 vph	4500 vph
α	5500 vph	7500 vph
A (accident)	55 veh.hrs.	34 veh.hrs.
A (incident)	23 veh.hrs.	14 veh.hrs.

Assuming 105* accidents during the off-peak period and assuming that 60% occur in the three-lane section and that 30% receive official aid, the total travel time savings due to earlier removal of accidents is

$$(105)(0.30)\left[(0.60)(55) + (0.40)(34)\right] = 1480 \text{ vehicle hours}$$

If 200 incidents** occur in the off-peak direction during the peak period and if 20% receive official aid, the total travel time savings is

$$(200)(0.20)\left[(0.60)23 + (0.40)(14)\right] = 780 \text{ vehicle hours}$$

Thus, the total annual savings in travel time during the off-peak periods and in the off-peak direction during the peak periods due to the reduction of response time to obstructions is 2260 vehicle hours per year.

The total effect, then, of the television surveillance system in reducing travel time on the Freeway by reducing response time to obstructions is 27,260 vehicle hours per year.

* In Reference 16 the total number of accidents in a year was 229 (Table 1) and 134 were previously considered in the peak period (in the peak direction). Thus, 95 remain during the off-peak periods or in the off-peak direction in the peak period. A 10% increase was assumed.

**In Figure 4 of Reference 16 a total of 175 incidents occured in the off-peak direction during the peak period.

VIII. EFFECT OF THE "DON'T ENTER RAMP" SIGNS

The "Don't Enter Ramp" signs are intended to close the entrance ramps when the need arises. The effect, however, is to divert about 25% of the ramp traffic while the remaining 75% uses the ramp in violation of (the intent of) the signs. There are circumstances in which even the diversion of 25% of the traffic on certain ramps can improve the overall traffic operation. Such circumstances would include lane closure due to maintenance operations and other traffic incidents which cause queueing on the Freeway.

Presently these signs are infrequently used. The NPG staff does not maintain records of the use of these signs but an estimate was made that they are used about 50 times per year in conjunction with incidents on the Freeway. Based on observation, this is probably not a low estimate.

The May model (18) can be used to estimate the effect of these signals in a typical occurrence on the Freeway. In this model the following parameters were assumed: t_o = 45 minutes, γ = 3500 vph, α = 550 vph, without the ramp signals c = 4900 vph and with the ramp signals c' = 4500 vph. The effect of the "Don't Enter Ramp" signs was assumed to be the diversion of 400 vehicles per hour around the queueing situation.

Without the operation of the signs, the delay is 2930 vehicle hours and with signs in operation the delay is 2680 vehicle hours. Thus, for an "average obstruction" the operation of the "Don't Enter Ramp" signs would be 250 vehicle hours based on the assumed parameters. Thus, the total annual savings in travel time due to the operation of the ramp control signs is 12,500 vehicle hours based on 50 uses per year, which is approximately the present level of usage.

IX. NATIONAL PROVING GROUND TRAFFIC CONTROL SYSTEM ANALYSES

This section contains two analyses which were performed on the NPG Traffic Control System. The first is a functional analysis and the second is a cost/effectiveness analysis.

FUNCTIONAL ANALYSIS

General

The system analysis procedure is basically one of comparing a system's performance to its intended performance by means of various measures of effectiveness. The first step is to define the mission of the system or its intended performance. The second step is to select the appropriate measures of effectiveness by which to evaluate the system's performance and the third is actually to perform the analysis.

Statement of Missions

Broadly stated, the three missions or objectives of the NPG Traffic Control System are 1) to optimize flow on the Freeway, 2) to increase the efficiency of the roadway, and 3) to provide necessary information to the drivers. The first mission refers to flow during normal conditions and the second mission refers to the minimizing of the effects of reduced-capacity situations. These missions were obtained from NPG personnel and a more complete discussion is contained in Appendix A3 of Reference 1.

Measures of Effectiveness

The measures of effectiveness of traffic system operation which were used to evaluate the NPG Traffic Control System are traditional ones - total travel time, total travel, average speed, delay, volume processed and kinetic energy. In addition, travel time of an individual vehicle and the volumes at a bottleneck were used. One important measure of effectiveness, contribution to safety, was not considered since it is not readily subject to measurement. Any reflections on possible contributions to safety would be little more than conjecture.

Analysis

1. Mission 1

The first mission is to optimize flow on the Freeway (during normal conditions). During off-peak periods when normal conditions prevail, the NPG Control System does not improve flow since no problem generally exists and, thus, the NPG Control System is not used during such periods.

Several comments can be made regarding peak period operation under normal conditions. First, the cause of normal peak period operational problems (congestion) is that the demand exceeds the capacity of the Freeway and the NPG Traffic Control System cannot resolve the demand/capacity relationship. Only in rare instances (reduced-capacity operation) are the "Don't Enter Ramp" signs used. The NPG Control System was found to be unsuccessful in increasing the flow at a critical bottleneck (Davison-Glendale southbound). Thus, the concept of accepting all of the demand on a (congested) freeway and then "optimizing" flow must be assigned a low probability of success.

As shown in Figure 2, the NPG Traffic Control System has an adaptive element in the control loop. This adaptive element is the NPG control operator. With the control operator in the control loop this control system is "responsive" or "reactive" control system rather than a "preventive" control system. The control system with the human observer can only respond to a given situation and attempt to correct it rather than to try to prevent the occurrence of an undesired situation, such as congestion.

The "Don't Enter Ramp" signs on the entrance ramps appear to have little or no role to play in normal peak period operation. These signs were intended for use in closing completely an entrance ramp on a temporary basis to reduce demand on the Freeway. They have been found ineffective for complete closure (Reference 2 and Section V of this report) as only about 25% of the motorists obeyed the signs (Section V). One could argue, perhaps, that the daily use of these signs at all ramps in the NPG Control Area during the peak periods would reduce the demand by 25% of the ramp volumes. It is more likely, however, that the compliance would approach zero after repeated use in this manner. For normal peak period application the signs must be made to function as intended or should not be operated.

2. Mission 2

The second mission of the NPG Traffic Control System is to increase the efficiency of the roadway (under reduced-capacity conditions) and in this mission it is more successful. The closed circuit television surveillance system is particularly well suited to providing the operator with the necessary qualitative information on traffic incidents, including information needed to respond properly to an emergency situation. The TV system uniquely provides the operator with information on which to decide whether a police vehicle, a wrecker, or an ambulance is required. Based on normal police patroling procedures, there can be little question that the use of a television surveillance system can reduce the police response time to an incident.

The "Don't Enter Ramp" signs do not function as intended, but during off-peak periods can still provide a useful function. When queueing occurs at an incident on the Freeway, the operation of the ramp signs as advisory displays can decrease the demand rate on the Freeway at the incident (by 25% of the ramp volume). In fact, it appears at the present time that traffic flow could be benefited from increased use of the "Don't Enter Ramp" signs in the off-peak periods during reduced-capacity conditions when queueing has occurred.

The benefits of the lane control signals depends on the volume conditions and they can be useful under lower volumes. During most of the present hours of operation the volumes are too high to realize benefits from these signals.

The speed signs during the peak periods function 1) to warn motorists of congestion ahead and 2) to indicate to the motorists that the problem has been passed and to increase speed. The use of speed in the present form to convey these messages is somewhat indirect. The advance warning function is possibly confused with the speed limit function by some motorists and this could decrease the effectiveness. It would appear that the use of the speed signs for one purpose or the other would enhance their utility.

The results of the input-output studies in the northbound peak period raised the possibility that the "on freeway" controls may actually have worsened traffic operation. This was not a conclusive result but two possible reasons for this arise. First, the control operators may have been displaying the wrong message due to inability to adequately assess the traffic situation. Secondly, under capacity conditions the displays may provide competition for the drivers' attention from other necessary stimuli and this may reduce slightly the capacity at critical locations (through a slight increase in average headways). A human factors analysis would be advised to clarify this point.

3. Mission 3

The third mission of the NPG Traffic Control System is to provide necessary information to the motorists. There can be little question that it provides useful information to the Freeway motorists. Questions remain, however, of whether this is necessary information or whether the <u>most</u> useful information is being provided.

COST/EFFECTIVENESS ANALYSIS

The sixteen candidate systems which are considered in the cost/effectiveness analysis are composed of all combinations of the four NPG Traffic Control System surveillance and control elements - 1) the closed circuit TV system, 2) the overhead speed signals, 3) the lane control signals and 4) the "Don't Enter Ramp" signs. The candidate systems are those which would be fairly easily formed from the present NPG Control System, which is Candidate System #16. Only the present hours of operation are considered.

The first eight candidate systems do not employ closed circuit television and, therefore, represent a fairly major departure from present NPG operation. Candidate System #2 involves only the "Don't Enter Ramp" signs and, in this system, an operator would provide the necessary control commands on receipt of a telephone or radio message and telephone lines would be used for transmission of control signals. Candidate System #3 involves the lane control signals operated in a similar manner except the NPG transmission cable would be used. In Candidate System #5 the overhead speed signals are the only control display and these would be operated by the computer-detector system.

Candidate Systems 4, 6, 7, and 8 are combinations of these systems. In the effectiveness analysis, the estimate of effectiveness of each control component was changed from the effectiveness based on present operation to account for the modified operation.

Cost Analysis

Table 15 is a summary of the cost analysis and contains the annual cost of each candidate system. Included in the costs are the fixed cost of the Control Center and a supervisor, annual maintenance and operation costs, annual lease price of leased items and an annual amortization cost of purchased

TABLE 15

COST ANALYSIS OF CANDIDATE SYSTEMS
(ANNUAL COSTS IN DOLLARS)

Candidate System	Elements Included				Annual Costs					
	TV	Speed Signs	Lane Signals	Ramp Signs	TV	Computer & Detectors	Cable	Speed Signals	Lane Signals	Ramp Signals
1					--	--	--	--	--	--
2				XX			500			1,100
3			XX				22,500		4,150	
4			XX	XX			22,500		4,150	1,100
5		XX				51,750	22,500	4,350		
6		XX		XX		51,750	22,500	4,350		1,100
7		XX	XX			51,750	22,500	4,350	4,150	
8		XX	XX	XX		51,750	22,500	4,350	4,150	1,100
9	XX				34,100		22,500			
10	XX			XX	34,100		22,500			1,100
11	XX		XX		34,100		22,500		4,150	
12	XX		XX	XX	34,100		22,500		4,150	1,100
13	XX	XX			34,100		22,500	4,350		
14	XX	XX		XX	34,100		22,500	4,350		1,100
15	XX	XX	XX		34,100		22,500	4,350	4,150	
16	XX	XX	XX	XX	34,100		22,500	4,350	4,150	1,100

TABLE 15 - Continued

Candidate System	Annual Costs: Control Panel	Maintenance Facility	Operators	Administration	Total Annual Cost
1	--	--	--	--	0
2		1,000	12,000		$14,600
3	6,140	15,600	12,000	17,500	77,890
4	6,140	15,600	12,000	17,500	78,990
5	6,140	15,600	12,000	17,500	129,840
6	6,140	15,600	12,000	17,500	130,940
7	6,140	15,600	12,000	17,500	133,990
8	6,140	15,600	12,000	17,500	135,090
9	6,140	15,600	12,000	17,500	107,840
10	6,140	15,600	12,000	17,500	108,940
11	6,140	15,600	12,000	17,500	111,990
12	6,140	15,600	12,000	17,500	113,090
13	6,140	15,600	12,000	17,500	112,190
14	6,140	15,600	12,000	17,500	113,290
15	6,140	15,600	24,000	17,500	128,340
16	6,140	15,600	24,000	17,500	129,440

items. These costs are based on the present equipment design and do not necessarily reflect the costs which would be incurred if the system were to be redesigned. The annual amortization cost of purchased equipment assumes a 10-year life and a $4\frac{1}{2}\%$ interest rate.

Effectiveness Analysis

The effectiveness of each surveillance and control component and each candidate system has been estimated in terms of the annual amount of travel time reduction in vehicle hours. There may be other benefits of these systems, such as an increase in safety, which are not considered. These are not included in the analysis because of the difficulty in making reasonable estimates of their importance and because it is believed that their inclusion would not substantially change the results of the analysis.

Table 16 presents the effectiveness of each of the surveillance and control elements (closed circuit television, overhead speed signs, overhead lane control signals and the "Don't Enter Ramp" signs). The effectiveness of the ramp signals in Candidate Systems 2, 4, 6 and 8 was assumed to be 6,250 vehicle hours of travel time savings per year. This is half of the effectiveness of this element in Candidate Systems 10, 12, 14 and 16 because the television is not a part of Candidate Systems 1-8.

Table 17 presents the vehicle hours of travel time savings per year which is assiciated with the operation of each of the sixteen candidate systems. The effectivenesses of the four surveillance and control elements are essentially independent and are treated as such in this analysis.

TABLE 16

EFFECTIVENESS OF SURVEILLANCE AND CONTROL COMPONENTS WHICH WERE USED IN THE EFFECTIVENESS ANALYSIS (ANNUAL MOTORIST BENEFITS STATED IN VEHICLE HOURS OF TRAVEL TIME SAVINGS)

Elements	Candidate Systems 1-8	Candidate System 9-16
Closed Circuit TV	Not Used	27,260
Speed Signs		
1. High Estimate	91,250	91,250
2. Low Estimate	-80,750	-80,750
3. Estimate Used in Analysis	0	0
Lane Control Signals	0	0
"Don't Enter Ramp" Signs	6,250	12,500

TABLE 17

EFFECTIVENESS ANALYSIS OF CANDIDATE SYSTEMS (ANNUAL MOTORIST BENEFITS STATED IN VEHICLE HOURS OF TRAVEL TIME SAVINGS)

Candidate System	Surveillance and Control Elements				Effectiveness		
	TV	Speed Signs	Lane Signals	Ramp Signs	High Estimate	Low Estimate	Estimate Used in Analysis
1							0
2				XX			6,250
3			XX				0
4			XX	XX			6,250
5		XX			91,250	-80,750	0
6		XX		XX	97,500	-74,500	6,250
7		XX	XX		91,250	-80,750	0
8		XX	XX	XX	97,500	-74,500	6,250
9	XX						27,260
10	XX			XX			39,760
11	XX		XX				27,260
12	XX		XX	XX			39,760
13	XX	XX			118,510	-53,490	27,260
14	XX	XX		XX	131,010	-40,990	39,760
15	XX	XX	XX		118,510	-53,490	27,260
16	XX	XX	XX	XX	131,010	-40,990	39,760

Cost/Effectiveness Analysis of the Candidate System

Table 18 summarizes the annual cost and effectiveness for each of the candidate systems and also presents the cost/effectiveness ratio of each. This same information is presented graphically in the cost-effectiveness plane in Figure 18. The interpretation of the cost/effectiveness ratio for each candidate system is that it is the minimum cost value which could be assigned to a vehicle hour of travel time savings in order for the system to have a benefit/cost ratio of one. It is, in fact, the expended cost for each vehicle hour of travel time saved by this system; hence, if the cost of a vehicle hour is considered worth less, the system is not cost/effective.

If E is the effectiveness of a system in annual vehicle hours of travel time savings, K is the value assigned to a vehicle hour of travel time savings in dollars per vehicle hour, B is the annual benefit of the system in terms of dollars, and C is the annual cost of the system, some relationship can be derived. The benefit B = KE. The cost/effectiveness ratio is C/E and the benefit/cost ratio is B/C. Therefore, B/C = K(E/C) = K/(C/E). If a minimum B/C* is required to justify a system and if a K value is assigned

$$\text{min.}(B/C) = K/(C/E)$$

and therefore $$\text{max.}(C/E) = K/\text{min.}(B/C)$$

is the maximum cost/effectiveness ratio for which the system would provide the minimum required benefit/cost ratio. In order for a system with a known C/E ratio to be cost/effective, the following relationship must hold true $K \geq (C/E)\ \text{min.}\ (B/C)$. This does not mean that the system is the <u>most</u> cost/effective since an analysis of alternate systems is required before this conclusion can be reached.

In Table 18, the most favorable cost/effectiveness ratio belongs to Candidate System #2 which is merely the operation of the "Don't Enter Ramp" signs. Since C/E = \$2.34 per vehicle hour, $K \geq \$2.34\ \text{min.}(B/C)$ must hold for this system to be justified. If min.(B/C) = 1, K must be \$2.34 or larger; if min.(B/C) = 3, K must be \$6.84 or larger. Candidate Systems 2-8 are clearly not cost/effective based on present evaluations of travel time costs.

Candidate System #10, which includes only the television surveillance and ramp signal elements, has a cost/effectiveness ratio of \$2.74. A recently completed research report (19) indicates that a value of travel time of \$2.82 <u>per person per hour</u> is reasonable. Thus, a value of \$3.00 per vehicle hour of travel time would not be excessive. If a benefit/cost ratio of one is required to justify installation of a traffic control system, Candidate System #10 would be cost/effective.

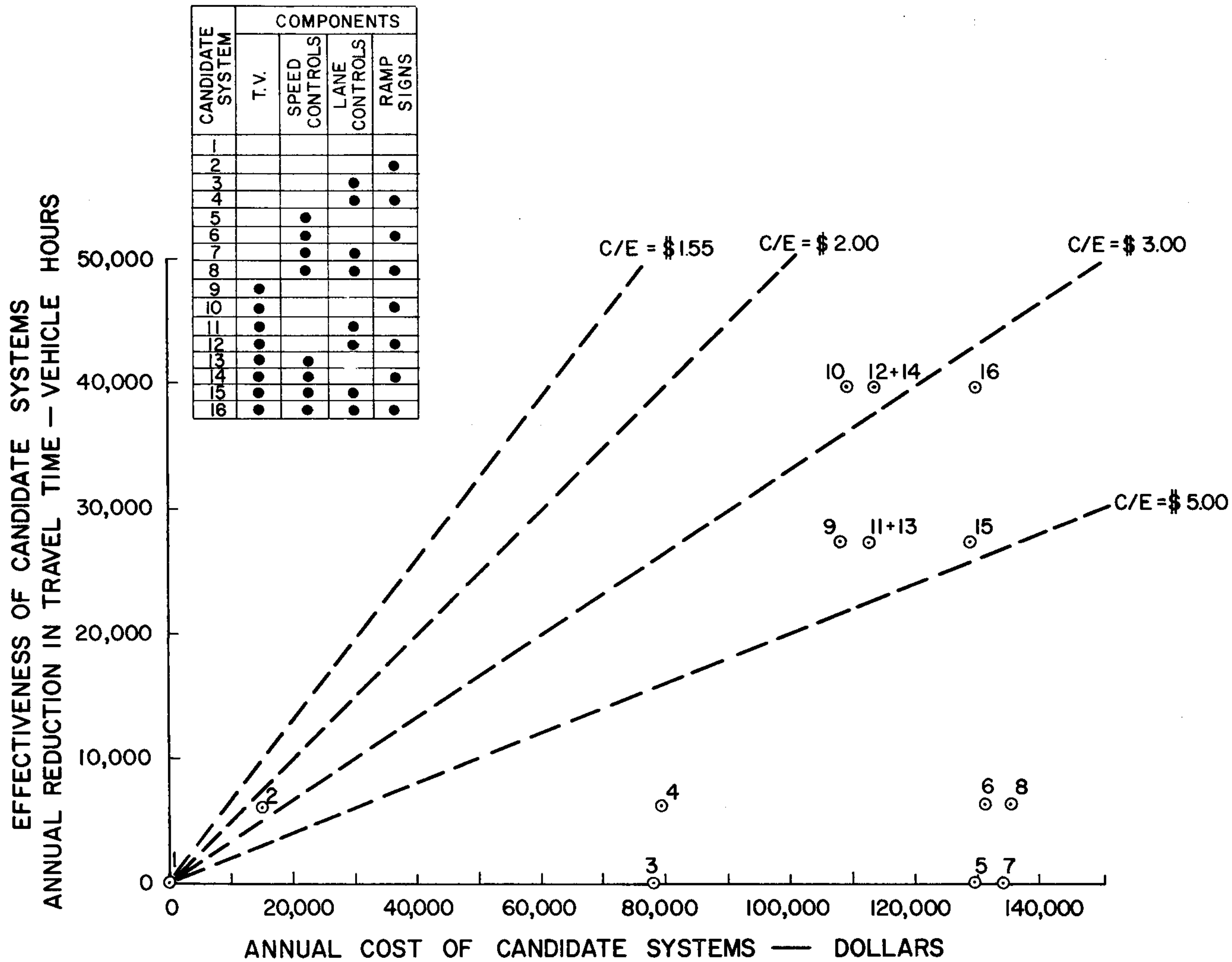
Based on the \$3.00 per vehicle hour of travel time, Candidate System #9 would not be cost/effective since for this system C/E = \$3.92. Candidate

* Perhaps a benefit/cost ratio of 3.0 is required to justify road construction so the same benefit/cost ratio may then be required to justify investing in a traffic control system.

TABLE 18

COST/EFFECTIVENESS ANALYSIS

Candidate Systems	Elements: TV	Elements: Speed Signs	Elements: Lane Signals	Elements: Ramp Signs	Annual Cost	Effectiveness- Annual Travel Time Savings- Vehicle Hours	Cost/Effectiveness- Dollars per Vehicle Hour Saved
1					0	0	--
2				XX	$ 14,600	6,250	$ 2.34
3			XX		77,900	0	0
4			XX	XX	79,000	6,250	12.65
5		XX			129,800	0	0
6		XX		XX	130,900	6,250	20.90
7		XX	XX		134,000	0	0
8		XX	XX	XX	135,100	6,250	21.70
9	XX				107,800	27,260	3.92
10	XX			XX	108,900	39,760	2.74
11	XX		XX		112,000	27,260	4.11
12	XX		XX	XX	113,100	39,760	2.85
13	XX	XX			112,200	27,260	4.12
14	XX	XX		XX	113,300	39,760	2.86
15	XX	XX	XX		128,300	27,260	4.72
16	XX	XX	XX	XX	129,400	39,760	3.26



CANDIDATE SYSTEM	COMPONENTS: T.V.	SPEED CONTROLS	LANE CONTROLS	RAMP SIGNS
1				
2				●
3			●	
4			●	●
5		●		
6		●		●
7		●	●	
8		●	●	●
9	●			
10	●			●
11	●		●	
12	●		●	●
13	●	●		
14	●	●		●
15	●	●	●	
16	●	●	●	●

Figure 18. Costs and Effectivenesses of the Candidate Systems (Based on the Components of the NPG Traffic Control System)

Systems 11-16 are not cost/effective since they all cost more than Candidate System #10 and none provides an increased effectiveness.

In conclusion, Candidate Systems 2 and 10 are cost/effective if a $3.00 value is assigned to a vehicle hour of travel time and if a minimum benefit/cost ratio of 1.0 is used to justify a control system. Since a higher minimum benefit/cost ratio would probably be required, the cost/effectiveness of even Candidate Systems 2 and 10 must be considered questionable unless other effectiveness measures can be proved (such as increased safety).

X. CONCLUSIONS

This report contains the results of several studies and analyses which have been made for the purpose of evaluating the effectiveness of the "on-freeway" traffic control system on the John C. Lodge Freeway. The conclusions are offered with some reservations. The off-peak studies were of limited scope and in none of these studies were the sample sizes extremely large.

The studies were conducted on only one particular traffic control system on one particular freeway and the results should not necessarily be translated directly to other systems. The conclusion should also not be viewed necessarily as applying to the general concept of "on-freeway" controls.

The traffic control system which was evaluated was not located ideally to provide the greatest benefits to the motorists and this should be borne in mind when considering the conclusions. Due to the extension of the Lodge Freeway to the north, the traffic pattern on the Lodge Freeway has changed drastically since the National Proving Ground Traffic Control System was installed. Consequently, the congestion limits do not presently coincide with the Control Area and this fact naturally has an effect on the results of the evaluation.

Within the limitations of these factors, the following specific conclusions are offered:

1. The motorists do not decrease their speeds to coincide with the posted speed unless there is an apparent reason to do so. This would suggest that the motorists do not consider the changeable speeds as regulatory.

2. The variable speed signs were not successful in increasing the flow rate at a critical bottleneck when there was adequate demand to do so (congestion upstream of the bottleneck).

3. The effectiveness of the overhead lane control signals appears to be a function of the Freeway demand.

   a. Based on previous research (4, 5), when Freeway demand is less than the Freeway capacity remaining during the lane closure (no queueing upstream), vehicles appear to obey the red "X" indications and leave the closed lane farther in advance of the closure than with conventional advance warning.

   b. Based on the "off-peak" period studies, when Freeway demand is greater than the Freeway capacity remaining during the lane closure (queueing upstream), the effectiveness of the red "X" indication appeared to be much less. Vehicles left the closed lane sooner with no overhead lane controls than under normal advance warning but this was not translated to reduced travel time because (for these demand conditions) the use of the red "X" indication did not increase the throughput at the lane closure (over that using normal lane closure techniques).

c. For the present hours of operation, the benefits of the lane control signals are very small since during this time period the demand on Freeway is nearly always greater than the remaining capacity if a lane is closed.

4. In periods of high demand and congestion, the NPG Traffic Control System is incapable of balancing demand and capacity and consequently is not effective in improving traffic operation under normal peak period conditions.

5. On the one day in which the "Don't Enter Ramp" signs were used, the volume on the four ramps which were "closed" was 23% below the normal volume. The compliance to this type of control was greater on the ramps at which a good alternate route is available.

6. The usefulness of the speed control signs as advanced warning devices could not be fully evaluated from the traffic operational studies which were conducted and a human factors approach would be required for this analysis. It would appear that other messages might provide a more direct advance warning to the motorists.

7. Based on the cost/effectiveness analysis which was conducted,

   a. the present NPG Traffic Control System as it is now operating is not cost/effective,

   b. the computer and detectors contributed little to this system and are, therefore, not cost/effective (this refers to its part in the NPG Traffic Control System only),

   c. the Preferred Systems from a cost/effectiveness point of view were Candidate Systems 2 and 10. Candidate System 2 includes only the "Don't Enter Ramp" signs and Candidate System 10 includes only the TV surveillance system and the "Don't Enter Ramp" signs. The cost/effectivenss of these systems was marginal and was based on a required benefit/cost ratio of one.

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APPENDICES

APPENDIX TABLE A-1

TIME MEAN SPEED FOR DIFFERENT CONDITIONS

Locations		Posted Speeds S_{ij}^{k}					
		Without Distraction, k=1			With Distraction, k=2		
		i=1	i=2	i=3	i=1	i=2	i=3
Glendale	j = 1	55	55	40	55	55	40
Monterey	j = 2	55	40	25	55	40	25
Webb	j = 3	55	40	25	55	40	25

APPENDIX B

EFFECT OF REDUCING THE TIME PERIOD DURING WHICH AN INCIDENT BLOCKS A FREEWAY

An incident which blocks one or more freeway lanes during a peak period will almost certainly increase the total travel time in the Freeway. (It will certainly increase the total travel time if it reduces the volume past the incident below the normal volume there.) Consequently, a reduction in the amount of time during which an incident blocks the Freeway will decrease the total travel time on the Freeway. The model which is developed is similar in many respects to models which have been developed previously (14, 17, 18).

Appendix Figure B-1 shows the time and flow rate parameters which affect the amount of the time savings. The definitions are presented below this figure. It is assumed that any incident occurring during the peak period or within a time t_b before the peak period can be described by this model.

The line $Q_5^n(t)$ represents the cumulative output under normal conditions while $Q_5^i(t)$ represents the cumulative input when affected by an incident. The line between these curves represent the cumulative output if the incident is removed more quickly.

The time at which congestion would clear when an incident blocks the Freeway temporarily is called t_c and an analytical expression for this time can be derived from the output curved relationships. The lines $Q_5^n(t)$ and $Q_t^i(t)$ intersect a t_c. The equation of $Q_5^n(t)$ after t_e is:

$$Q_5^n(t) = ct_e + \beta(t-t_e) \text{ for } t \geqslant t_e$$

Similarly $Q_5^i(t) = ct_i + \gamma(t_m - t_i) + \alpha(t - t_m)$ for $t \geqslant t_m$

Thus at $t = t_c,\ Q_5^n(t_c) = Q_5^i(t_c)$

and $ct_e + \beta(t_c - t_e) = ct_i + \gamma(t_m - t_i) = \alpha(t_c - t_m)$

and $t_c = \left[\frac{1}{\alpha - B}\right]\left[(c-\beta)t_e + (\gamma - c)t_i + (\alpha - \gamma)t_m\right]$

If the length of time during which the incident blocks the Freeway can be reduced by a time t_r, the net reduction in total travel time can be seen as area A in Appendix Figure B-1. The area A can be found by the approximate relationship:

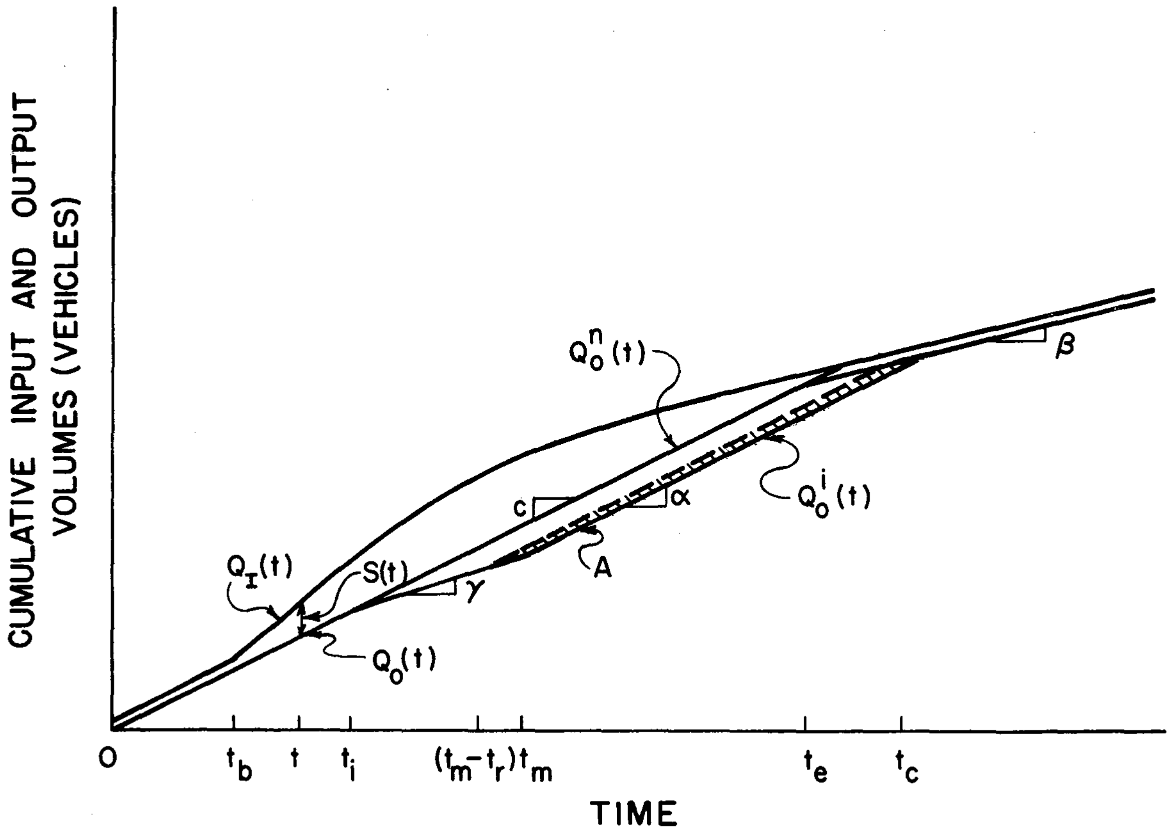
$$A \cong (t_c - t_m)(t_r)(\alpha - \gamma)$$

By substituting for t_c,

$$A \cong (t_r)\left(\frac{\alpha - \gamma}{\alpha - \beta}\right)\left[(c-\beta)t_e + (\gamma - c)t_i + (\beta - \gamma)t_m\right]$$

Now let $t_m = t_i + t_o$, where t_o is the length of time the incident blocks the freeway (without the reduction time t_r).

Then, $A \cong (t_r)\left(\frac{\alpha - \gamma}{\alpha - \beta}\right)\left[(c - \beta)t_e + (\beta - c)t_i + (\beta - \gamma)t_o\right]$



Appendix Figure B-1. Effect of Reducing the Time During Which an Incident Blocks a Freeway.

<u>Definitions</u>

$Q_I(t)$	=	Cumulative input volume - vehicles
$Q_o(t)$	=	Cumulative output volume - vehicles
$S(t)$	=	Storage (number stored in the queue) - vehicles
$Q_o^n(t)$	=	Normal cumulative output volume - vehicles
$Q_o^i(t)$	=	Cumulative output volume when affected by an incident - vehicles
$q_o(t)$	=	$\frac{dQ_o(t)}{dt}$ = output rate - vehciles per hour
t_b	=	Normal beginning time of congestion
t_e	=	Normal ending time of congestion
t_i	=	Time at which an incident blocks one or more freeway lanes
t_r	=	Reduced freeway blockage time
c	=	Normal output rate during the peak period - vehicles per hour
γ	=	Output rate while incident is blocking the freeway
α	=	Output rate when incident is moved to shoulder
β	=	Demand rate and output rate after t_c.
A	=	Reduction in total travel time due to reduced time of freeway blockage