Experimentation with Manual and Automatic Ramp Control

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This paper describes the planning, conduct and evaluation of a series of experiments with freeway ramp control undertaken for the purpose of improving network operations.

The development of the control plan included the identification of the critical section, determination of the period of time and degree of control, estimation of the redistribution of traffic, and re-evaluation of system operations. A comprehensive set of measurements was obtained for the network, including expressway and major arterials, for three weeks without control and for three weeks with freeway ramp control. The ramp control consisted of partially closing one on-ramp and metering traffic at a second on-ramp. The effect on the network of the freeway ramp control was evaluated on the basis of vehicle-minutes and vehicle-miles of travel for each link, route, and for the total network. The results indicate that travel time on a network basis was reduced by freeway ramp control.

•AN EXPRESSWAY Surveillance Project was established in April 1961 as a part of the research program of the Illinois Division of Highways, under the supervision of the Bureau of Research and Planning. The project is being financed with Highway Planning Survey funds made available through the Federal-Aid Highway Acts, with the State of Illinois, Cook County, and the City of Chicago contributing the necessary matching funds. An Advisory Committee, consisting of representatives of the four cooperating agencies, was appointed and meets frequently to review the progress of the project and to review and to advise on steps recommended for future experimental work.

The immediate objective of the project is to develop, operate and evaluate a pilot network information and control system to reduce travel time and to increase traffic flow. Successful progress could lead eventually to a centralized information and control system for the entire Chicago Metropolitan Expressway and major street network system.

The approach being used in accomplishing this objective is frequently referred to as a case study or pilot study approach. A typical portion of the Metropolitan Chicago highway network system was selected as the laboratory or demonstration area, and a pilot detection system is being used to measure the existing traffic patterns from which control plans can be developed. Through experimentation with control, the pilot detection system gradually will be converted to a pilot network information and control system. When complete, the system will be evaluated in terms of road user benefits and system costs. Administrative decisions can then be made as to the possible extension of the system.

The first major phase of the project, development of a pilot detection system, consisted of operational studies, surveillance equipment evaluation, system design, and installation. The pilot detection system became operational in October 1962 and the work leading to this development was described by May et al. (1).

This paper describes the planning, conduct and evaluation of a series of experiments

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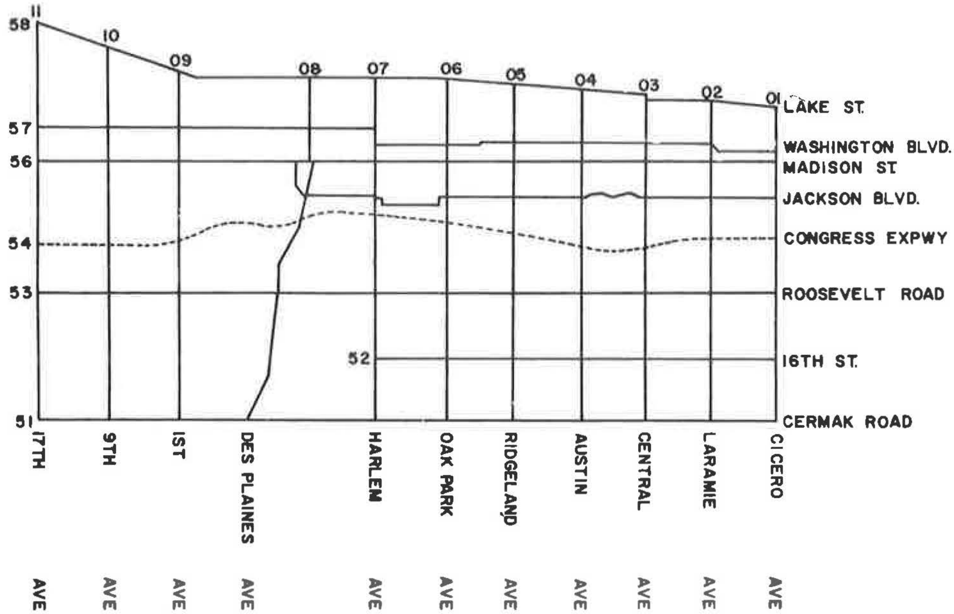

Figure 1. Network study area and inventory coding system.

with freeway ramp control which were undertaken for the purpose of improving network operations following development of the pilot detection system.

INITIAL EXPERIMENTATION WITH MANUAL CONTROL

The first step toward experimentation with control was the comprehensive collection and analysis of traffic volume and travel time data under uncontrolled conditions on the expressway and the major arterial streets. This knowledge permitted evaluation of the effectiveness of various devised control schemes, and resulted in the selection of the control plan with the least estimated total travel time and one which was feasible under actual traffic conditions. The conduct of the experiment was designed so that the plan could be evaluated on a network basis by field measurements, and so that it could be carried out with a minimum of additional equipment. The final stage of this initial experimentation with control was to evaluate the effectiveness of the control plan and to determine means for future improvement with control.

Network System Inventory

A comprehensive collection of traffic volume and travel time data was obtained for the network study area during a three-week study period (October 4 to October 24, 1962) under uncontrolled conditions. Each major arterial between intersecting major arterials was defined as a link, and volume and travel time data were summarized on a link basis. The network study area and the link coding system are shown in Figure 1. In this manner the vehicle-miles and vehicle-minutes of travel, as well as traffic volume and speeds, were computed for each link and for various periods of time. In addition to volume and travel time data, aerial observations were made during daylight hours to record any unusual events such as accidents, disabled vehicles, or other special events. An origin-and-destination study of vehicles entering the expressway within the study area was conducted in order to evaluate later the effect of various diversion schemes. Numerous secondary studies were conducted simultaneously such as an aerial density study, transit use study, persons per vehicle study, and expressway shoulder usage study.

Following the traffic data collection phase, a physical inventory was completed for the expressway and major arterials and all data were summarized on a link basis. The physical inventory included the number of moving lanes, parking conditions, width of streets, surface conditions, pavement markings and signs, and details pertaining to traffic signal equipment and existing settings.

Developing the Control Plan

The tasks performed in developing the control plan included the identification of bottlenecks, determination of period of time and degree of control, estimation of the redistribution of diverted traffic, re-evaluation of surface street system, and final evaluation of control plan on expressway, ramp and surface street traffic.

Identification of Bottleneck. —There are essentially two bottlenecks on the outbound Congress Expressway within the study area and each weekday afternoon congestion exists from approximately 4 to 6 PM. The one farthest upstream is caused by a reduction from 4 to 3 lanes without a corresponding reduction in traffic demand. The second bottleneck farther downstream and the last bottleneck on the outbound expressways are caused by fairly heavy on-ramp traffic (600 veh/hr) which has short periods of very heavy flow (20 to 25 veh/min) and is located at the top of an approximate 1,000-ft, 3 percent upgrade. The upgrade three-lane section is preceded by a reverse curve over which three, wide, closely spaced overhead structures appear to present a "tunneling effect" to the expressway motorists.

The initial experimentation with control was limited to the downstream portion of the study area which includes the bottleneck caused by the upgrade and on-ramp, and downstream from which free-flow conditions exist for the remaining portion of the outbound expressway. The reasons for this were to simplify the initial experimentation and to evaluate closely the effect of a particular controlled action. Further, if the expressway flow can be increased through control, it is apparent that the bottleneck farthest downstream should be placed under control first, and at later stages the control extended upstream.

Period of Time and Degree of Control. —Essentially the degree of control was determined by comparing the expressway free-flow capacity downstream of the on-ramp with the traffic demand prior to the on-ramp. The difference indicated the approximate maximum allowable ramp volume which could enter without resulting in congestion. A comparison of the computed maximum allowable ramp volume with the ramp demand indicated the approximate time interval when controls might be required and gave the first approximation of the amount of ramp traffic which might require diversion.

These analyses were performed using data collected in the October study, and are presented in graphical form in Figures 2 and 3. The bottleneck output (Fig. 2) for the 30-min period preceding congestion varied between hourly rates of 6,000 to 6,150 veh/hr and a free-flow bottleneck capacity of 6,000 veh/hr was assumed and is indicated. The traffic demand approaching the bottleneck on the expressway was obtained from volume measurements in advance of the bottleneck and modified to take into consideration the storage of vehicles which occurred once congestion developed. The lightweight line indicates the approach volumes, and the heavier line indicates the expressway traffic demand approaching the bottleneck. The shaded area indicates the approximate maximum allowable ramp volume for the various periods of the afternoon.

The comparison of present ramp demand with the foregoing estimated maximum allowable ramp volume is shown in Figure 3. The present ramp demand is either northbound traffic making a left into the ramp, southbound traffic making a right into the ramp, or traffic originating in the adjacent parking lot serving the transit station. This demand is depicted by the three curves across the lower portion of Figure 3. The shaded area indicates the allowable ramp volume, and it can be noted that the demand exceeds the allowable volume from 4:30 to 6:00 PM. Limiting the control at the ramp to metering without diversion was considered, but it was not deemed appropriate because the demand considerably exceeded the allowable ramp volume. A technique for handling such a situation by advanced displays on the surface streets is considered later in this paper.

Inasmuch as a portion of the diverted ramp traffic would enter the expressway at a

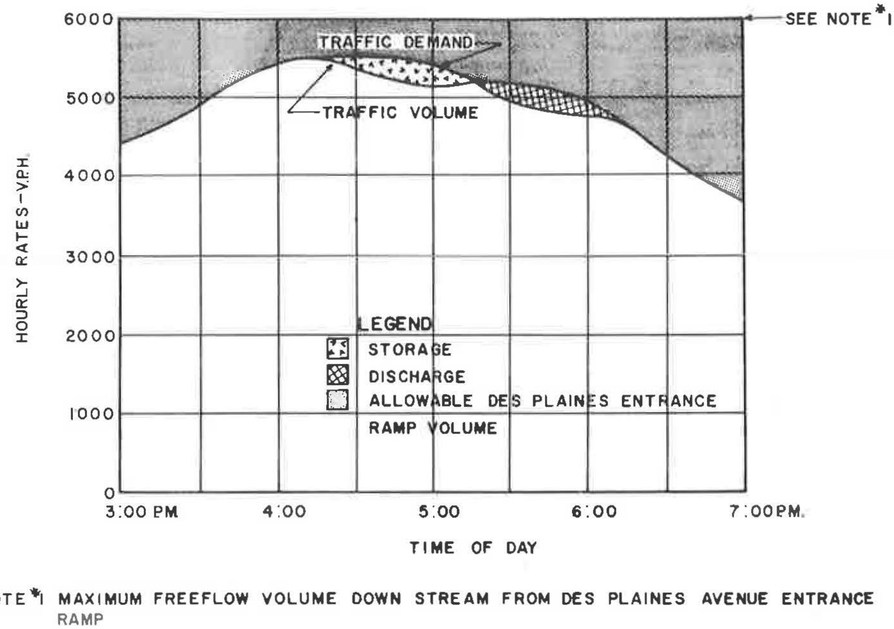

Figure 2. Traffic volume and demand—westbound Congress Street Expressway at Des Plaines Avenue.

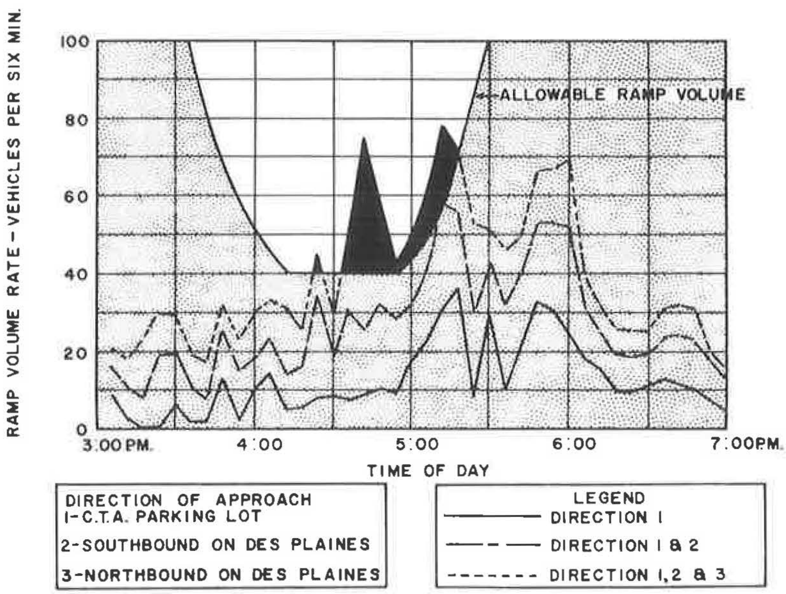

Figure 3. Estimation of period of time and degree of ramp control.

ramp upstream of the bottleneck, this would further reduce the allowable ramp volume at the bottleneck. Therefore a rather conservative action was initially proposed permitting only the traffic originating in the adjacent parking lot serving the transit station, to use the ramp. Also, if the ramp were closed to part of the ramp traffic at a specified time, some traffic might advance the time of their trip in order to enter the ramp before ramp closure. This possible increase in ramp flow might cause congestion to occur earlier and so the period of time initially proposed for partial ramp closure was changed from 4:30 to 6 PM to 4 to 6 PM.

Estimated Redistribution of Traffic. —The origin-and-destination data for the diverted ramp traffic combined with the travel time study results were employed to estimate the redistribution of the approximate 700 vehicles which would be diverted between 4 and 6 PM. The travel patterns for the ramp traffic under uncontrolled conditions (Fig. 4) indicate that approximately 80 percent of the traffic from the north originates on or north of the major arterial (Madison Street) located ½ mi north of the expressway and that 60 percent of the traffic from the south originates on or south of the major arterial (Roosevelt Road) located ½ mi south of the expressway. This traffic could proceed to the next ramp downstream without adverse distance.

The reason for selecting the traffic from the parking area as the traffic which could continue to use the ramp during control can be seen in Figure 4. Each of these vehicles would encounter an adverse distance of 1 mi. Approximately one-third of the ramp traffic from the north originates east of the on-ramp upstream and therefore would logically enter the expressway at that point and could actually save time without adverse distance. In fact, this illustrates that the traffic recognizing the normal expressway congestion postpones entering the expressway until it is downstream from the bottleneck.

The estimated redistribution of the proposed diverted traffic is shown in Figure 5. Of the 700 ramp vehicles being diverted between 4 to 6 PM, it was estimated that approximately 300 vehicles would divert to the upstream on-ramp, 300 vehicles to the downstream on-ramp and 100 vehicles would abandon the use of the expressway primarily because of the short length of trip.

Re-Evaluation of System Operation. —The redistribution of traffic discussed in the preceding section might well change the operation on the major arterials as well as on the expressway. Therefore the next task was to evaluate the effect of this change and, if necessary, to provide for additional modifications and/or controls.

In regard to the major arterials, the estimated change in traffic volumes varied from -10 percent to +5 percent. It was reasoned that this relatively small volume change on major arterials would, at most, adversely affect the traffic at signalized intersections of major arterials. This position was reinforced further by the fact that the two parallel major arterials carried a substantial portion of the expressway traffic before the opening of the expressway in 1960.

Some 30 signalized intersections which might be affected were reviewed and from these, eight signalized intersections were selected for detailed study. Intersection delays, queue lengths, turning movements under controlled conditions and estimated changes in turning movements in the event of diversion were analyzed. These studies indicated that the traffic demand would exceed substantially the capacity at only one intersection because of an estimated increase of 160 left-turn movements in the 2-hr period. A second capacity study indicated that the addition of a left-turn phase would result in below capacity conditions and satisfactory operations. The detailed study also revealed that two other intersections, the intersections of major arterials at the mouth of the on-ramps immediately upstream and downstream from the ramp in question, would operate near or slightly above capacity. However, no changes were made at these two locations. All calculations indicated that the other intersections would operate satisfactorily, although some increase in delay could be anticipated. These signals were inspected and adjusted for best operations for normal traffic conditions before control.

The estimated redistribution of traffic did require a re-evaluation of the anticipated expressway operations at the on-ramp location immediately upstream, at the upgrade near the bottleneck, at the on-ramp near the top of the grade, and at the next on-ramp downstream.

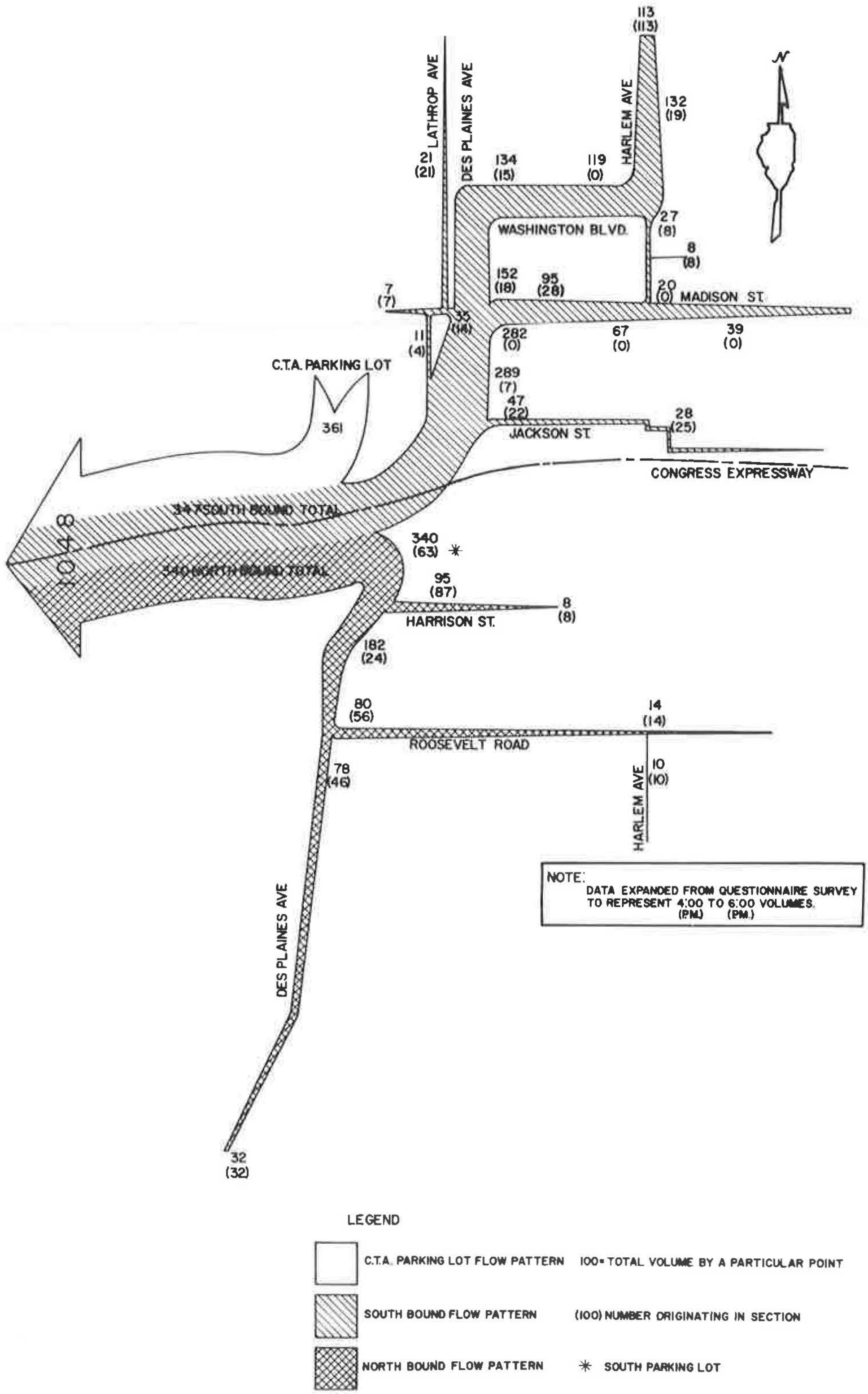

Figure 4. Present flow pattern of Des Plaines ramp traffic.

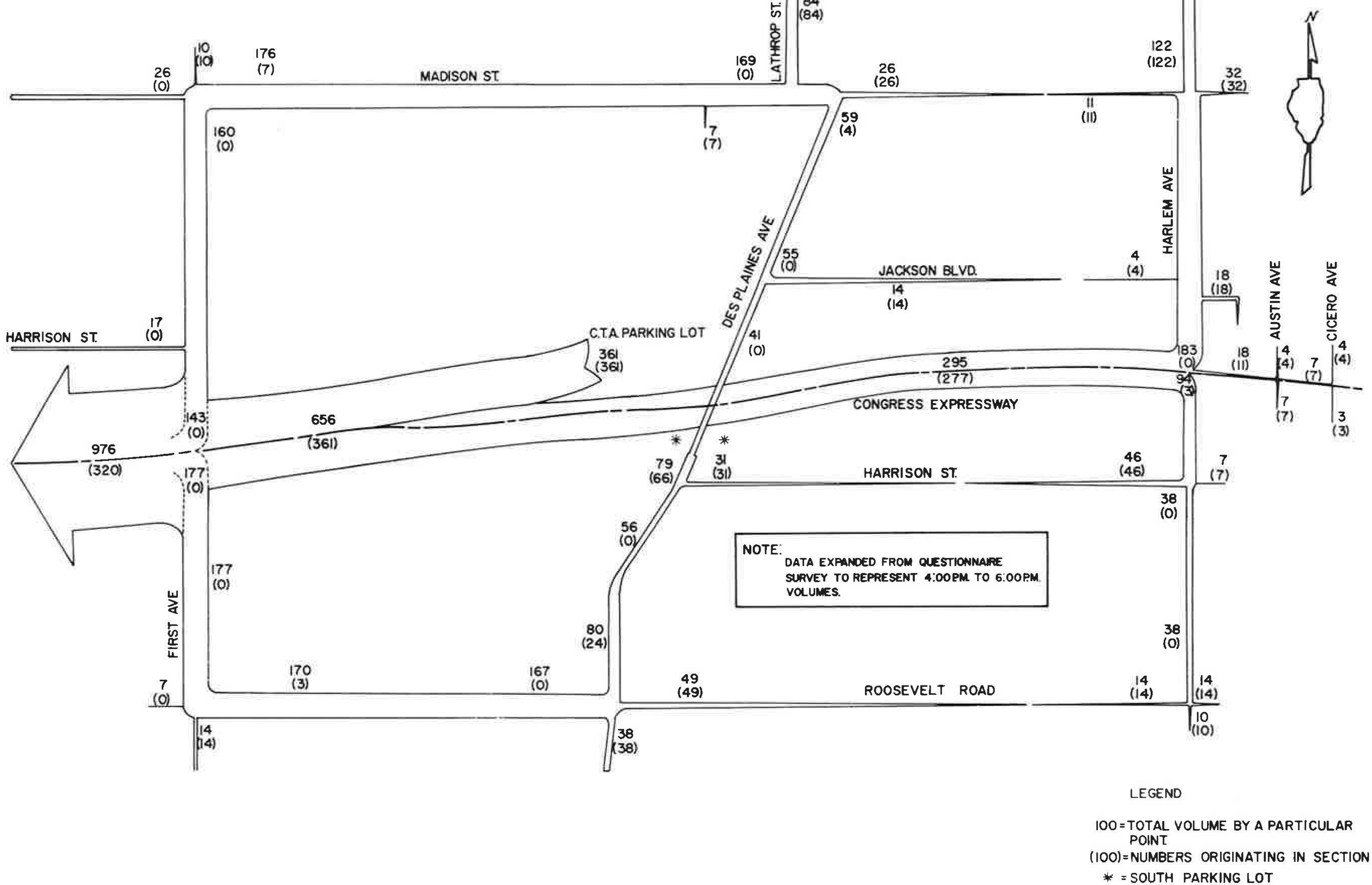

Figure 5. Estimated flow pattern of Des Plaines ramp traffic with partial diversion.

At the on-ramp location immediately upstream the anticipated increase in ramp traffic was of some concern. It was estimated that the merging volumes (5,300 veh/hr on the mainline and 400 veh/hr on the ramp) would not result in congestion, and it was decided that metering would be the most severe control required. In analyzing the expressway upgrade conditions (5,700 veh/hr), it was decided that if the merging free-flow capacity immediately downstream was 6,000 veh/hr and provided free flow could be maintained on the grade, the upgrade should not produce a capacity restraint.

The diversion of 700 vehicles from the ramp located near the top of the grade appeared to be more than adequate to maintain free-flow conditions. Estimates were made which indicated that diverting as few as 400 vehicles during the 2-hr period would be sufficient to maintain free-flow conditions. However, there did not appear to be any practical means of permitting any other vehicles on the ramp in addition to the traffic from the transit parking lot on a time-clock basis.

The location of greatest concern was the next on-ramp downstream where it was estimated that 300 additional vehicles would be diverted. The estimated merging (5,500 veh/hr and 600 veh/hr) indicated that congestion might exist and considerable thought was given to means of alleviating this potential problem. Fortunately, a 3-lane, one-way frontage road originated at this ramp and continued beyond two off-ramps, and terminated at the next on-ramp further downstream. It was concluded that ramp metering might be required, and a metering plan was developed which is described in the section pertaining to conduct of field experimentation. In the event that metering resulted in a sufficiently long queue causing undue delay to the motorists and hazard at the nearby intersection, the traffic would be directed to use the frontage road and the next on-ramp. An estimated 200 veh/hr could be directed to the next ramp without creating a merging problem on the expressway.

With the completion of this final operational re-evaluation, the next and last step before conducting the field experimentation was to estimate the effect of the total control plan on the motorists in terms of travel time and vehicle-miles of travel.

Evaluation of Control Plan. —The three groups of motorists affected by the control plan were the diverted ramp traffic, expressway traffic and the major arterial traffic. The effect on each is described in the following paragraphs.

The 700 vehicles which were diverted from the ramp were classified into origin-and-destination groups and their individual trip distances and trip travel times under normal conditions and under the proposed control plan were determined. The determination of travel time under normal conditions and trip distances under both conditions were obtained easily. However, estimation of travel time under controlled conditions had to take into account the increased travel time, particularly at two or three of the more critical signalized intersections, due to increased flow on major arterials. These additional delays due to increased flow were considered as time penalties for vehicles making a particular turning movement at an intersection which was affected by the control plan. The estimated effect on travel time and distance for each origin-and-destination group is shown in Figure 6. From the figure it can be seen that the 111 trips originating in zone 6 would have an increased trip travel time of 4.5 min and an increased trip travel distance of 0.7 mi; also, some of the diverted ramp traffic would be benefited. For example, it was estimated that the 130 trips originating in zone 15 would have a reduced trip travel time of 1.5 min, and a reduced trip travel distance of 0.1 mi. The estimated over-all effect on the diverted ramp traffic for the 2-hr period was an increase of 300 veh-min and an increase of 11 veh-mi.

The approach used to evaluate the effect of the proposed control plan on expressway traffic was to estimate the flow rate under control conditions for various locations along the expressway study section, and then from previously determined flow-speed curves, to calculate the travel time. The difference between the calculated travel time and measured travel time under normal conditions multiplied by the number of expressway vehicles served, resulted in a reduced travel time of 13,900 veh-min.

The effect of the proposed control plan on major arterial traffic was determined by comparing the results of previously conducted travel-time studies with estimates of travel time with control. The estimates of travel time with control were based on the previously obtained travel-time data modified to include additional delays for particular

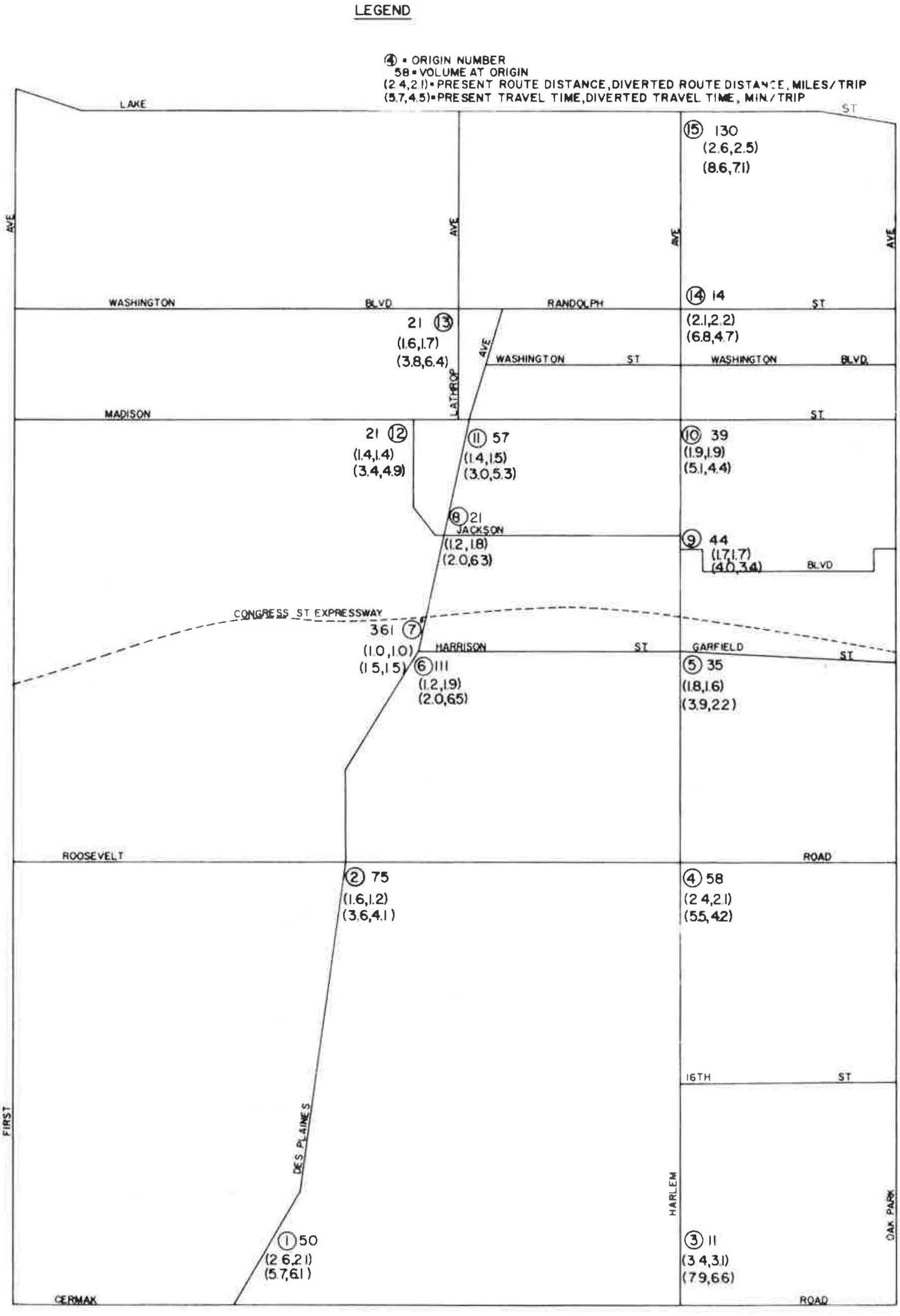

Figure 6. Ramp traffic travel time and mileage as affected by Des Plaines ramp control (4-6 PM travel time and volume).

TABLE 1

Traffic Type	Travel Time (veh-min)		
	Normal Conditions	Controlled Conditions	Effect on Travel Time
Diverted ramp	3,900	4,200	+ 300
Expressway	44,600	30,700	-13,900
Major arterial	35,100	37,600	+ 2,500
Total	83,600	72,500	-11,100

turning movements at selected intersections. The estimated amount of increased travel time to the major arterial traffic was 2,500 veh-min.

Table 1 gives a summary of the travel-time investigations discussed in the preceding paragraphs.

In April 1963, the Project Advisory Committee approved the recommendation of the staff that final plans be made to conduct the proposed experimentation with control.

Conduct of Control Experimentation

The general plan developed for control experimentation is shown in Figure 7 and consists of three parts: before measurements, publicity and coordination, and control with measurements. The before-measurement phase was designed to provide the standard or basis which the operations with control could be compared and evaluated. The publicity and coordination activity consisted of informing the public, particularly the motorists, and representatives of several governmental agencies of the plans for control experimentation. The final phase of the plan was the application of control and operational measurements.

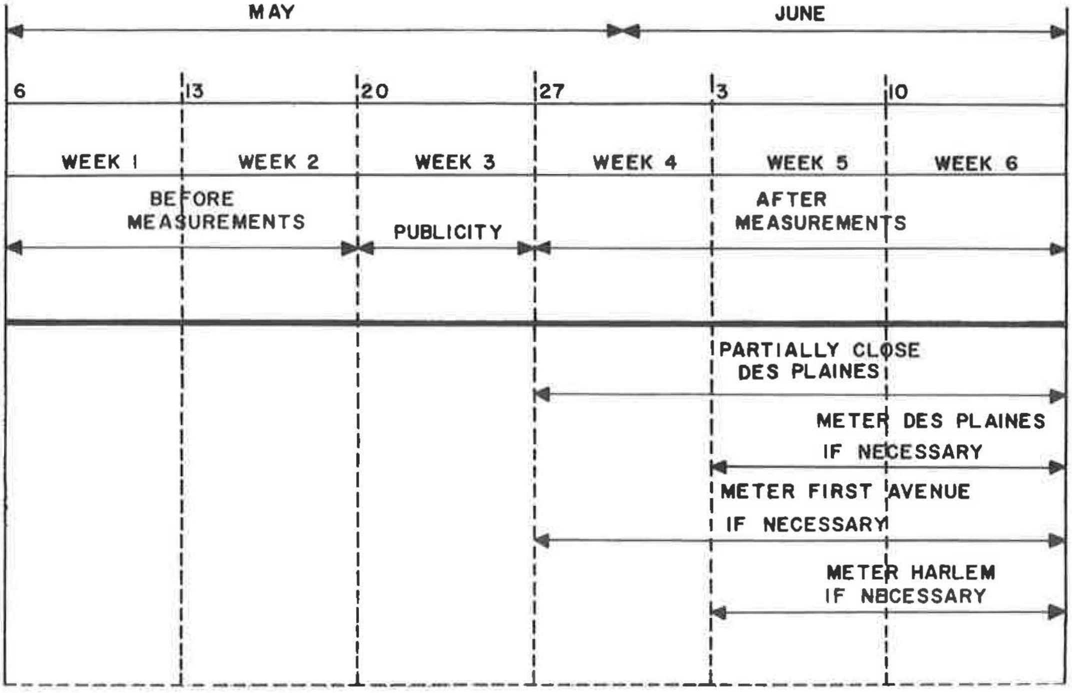

Figure 7. Study calendar.

Before Measurements. —It was planned that the measurements obtained during the 2-week-before study would be identical to measurements obtained during the following 3-week study with control. The period of time for control was 4 to 6 PM and the period of time selected for measurement was 3 to 7 PM.

On the expressway the pilot detection system recorded on punched tape the minute volume and occupancy or speed for the seven mainline stations and for each off- and on-ramp. Arrangements were made with the U. S. Bureau of Public Roads for the use of its impedance vehicle which is a specially equipped vehicle for recording individual vehicle performance. An emergency patrol vehicle was assigned to the expressway study section to inform the project office by radio of unusual conditions and to remove any hazards as quickly as possible.

On the surface streets approximately 25 portable 15-min traffic recorders were installed for purposes of obtaining volume and vehicle-miles of travel on the various links of network system. A license plate travel-time study was made on the major arterials for purposes of obtaining vehicle-minutes of travel on the various links of the network system. Plans were made for obtaining turning movements at selected intersections and for general evaluation of intersection performance.

In addition to the specific measurements planned for the expressway and major arterials, ten afternoons of aerial photography were planned for the before study and the study with the control. The purpose of the aerial photography was to record permanently the conditions with and without control, to permit the determination of queue lengths at intersections and ramps, and most important, to investigate a proposed technique for estimating total travel time in a network. The simplicity of measurement and the importance of network travel time have created considerable interest in this particular activity. Essentially, time lapse photographs were taken throughout the afternoon period from an airplane which flew back and forth over the network study area. The photographs are analyzed by counting the number of vehicles in each directional link, and travel time was obtained by multiplying the number of vehicles by the time interval between photographs. Average travel time can be obtained by dividing the travel time in vehicle-minutes by the vehicle-miles computed from the traffic counts.

Publicity and Coordination. —The publicity phase consisted of preparing news releases for newspapers, radio stations and television stations, placement of temporary roadway signs in advance of the ramp to be partially closed, and traffic bulletins handed to the motorists using the ramp which was to be partially closed. In addition, the office address and phone number were included with the news releases and traffic bulletins and arrangements were made for communicating additional information in response to phone calls.

An important function of this advance planning included the coordination with representatives of governmental agencies. Arrangements were made for meetings with several of the villages which might be affected by the control plan, with State and local police, with transit authority representatives and with the various agencies sponsoring the project. Providing advance information to those agencies and obtaining ideas and comments from them proved valuable.

It should be stressed that in accordance with the control plan shown in Figure 7, the before measurements were completed before the publicity began and discussions held with governmental agencies were of a confidential nature until the completion of the before measurements. There was some concern that otherwise the publicity and coordination might have affected the before measurements.

Control with Measurement. —During the last three weeks of the experimentation it was planned that control would be exerted and measurements taken. The first week of control was generally thought of as a transitional period for the changing traffic pattern and as a period for fine tuning the metering technique. This first week included a national holiday which may have affected the normal traffic pattern. The last two weeks were planned to be used for evaluational purposes.

The partial ramp closure was handled by placing a barricade across the major entrance to the ramp at 4 PM each weekday afternoon and removing the barricade at 6 PM. Arrangements were made for a State Police officer to be present during the period the ramp was closed. Signs were posted well in advance of the ramp reminding the motorists of the ramp closure.

Two metering techniques were developed for the on-ramp immediately downstream if it was found that such action was required. One technique utilized an occupancy measurement on the mainline just upstream of the on-ramp; the other utilized a volume measurement on the mainline about ½ mi in advance of the on-ramp, and an off-ramp volume between the mainline volume measurement and the on-ramp. After further study the former technique based on occupancy was selected.

From previous measurements a relation was established between the mainline occupancy in the middle lane (in advance of the on-ramp) and the maximum safe ramp volume provided that free flow existed further downstream. From this information a metering rate was established for various levels of occupancy. The rules of the game for ramp metering were developed and the essential elements are, as follows:

1. Metering commenced as soon as the mainline lane two occupancy equaled or exceeded 15 percent (yellow indication on map display) and provided it was after 4 PM.

2. The metering rate was set based on the 1-min digital percent occupancy of the mainline lane two. The permitted metering rate for various levels of occupancy is

% of Occupancy	Metering Rate
15-16	13 vpm
17-18	10 vpm
19-20-21	8 vpm
22-23-24	6 vpm

3. The ramp entrance was closed as soon as the mainline lane two occupancy equaled or exceeded 25 percent (red indication on ramp display) and provided it was after 4 PM. The queue already on the ramp was to be discharged at a metering rate of not more than 6 veh/min.

4. The metering rate was never to exceed the metering rates previously stated, but could have been reduced under the following specific circumstances: (a) ramp demand less than metering rate, (b) ramp occupancy equal to or greater than 25 percent (red indication on map display), and (c) ramp was closed and queue was small.

5. Metering operation was to be terminated as soon as the mainline lane two occupancy was less than 15 percent (green indication on map display) and provided it was after 6 PM.

To implement this metering technique, the metering decision was made in the central office and transmitted by phone to the field station. The field personnel then set a timer which, at regular intervals, sounded a bell and indicated to the State Police officer directing ramp traffic that a vehicle could enter the expressway. For example, if a metering rate of 10 veh/min was selected, the bell would ring every 6 sec. This use of simplified equipment was in keeping with the thought that more sophisticated equipment should not be developed until the possible benefits of metering could be evaluated.

Evaluation of Control Experimentation

The experimentation with control was conducted essentially as described in the previous section. Of the four possible control actions indicated in Figure 7, partially closing the Des Plaines ramp and metering the First Avenue ramp was the only control that was necessary. Inasmuch as the required action only affected a portion of the total pilot network, a revised study area was selected. The locations of ramp control and the revised study area are shown in Figure 8.

Unpredictable traffic and weather events occurred during the 10 days of before measurements and the 14 days of after measurements which affected the traffic flow on the expressway to varying degrees and for various durations of time. The time and occurrence of these unpredictable events such as accidents, vehicle disabilities, foreign objects on the pavement, pedestrians on the roadway, emergency maintenance, and adverse weather are summarized in Figure 9. To directly relate the differences between the before and after measurements to the ramp control experimentation, it was necessary to select days which were free of the unpredictable traffic and weather events. Therefore three consecutive event-free midweek days (Tuesday, Wednesday, Thursday) were selected from the before study and the after study, and the comparison of the two sets of data served as a basis for evaluating the control experimentation.

It is unfortunate that there is not a similar direct method of evaluating the effect of the ramp control experimentation during periods which included the unpredictable events. Obviously similar events did not occur at the same location and at the same time in both the before and after studies and therefore an objective evaluation was not possible. However an unpredictable event occurred on two days during the period when controls were being applied which permit some subjective observations. On Friday, May 31 at 4:58 PM and on Monday, June 3 at 4:47 PM, an incident occurred on the expressway lanes between the First Avenue on-ramp and the Seventeenth Avenue on-ramp (see Fig. 8 for ramp locations). These incidents caused a severe reduction in expressway capacity and resulted in congestion extending upstream. Before congestion reached the First Avenue on-ramp, the metering rate was reduced and soon afterwards the ramp was closed. The traffic normally enter ing at this ramp was diverted along the frontage road and entered the expressway by the Seventeenth Avenue on-ramp which was downstream of the incident location. This controlled action benefited the diverted ramp traffic as well as the expressway traffic. Because of the large numbers of such events occurring on the expressway, and because of the serious consequences that often result, the control of entering traffic during periods when these events do occur will most likely result in benefits greater than during periods of time when unpredictable events do not occur.

Effect on Traffic Volumes. — Changes in traffic volumes on the various links of the study area were

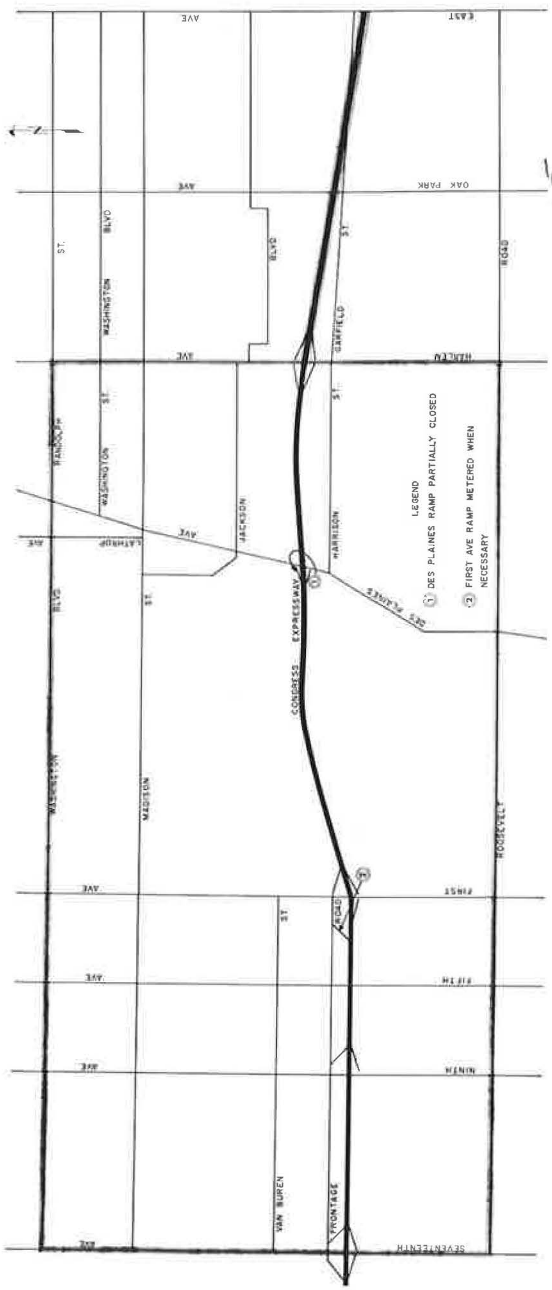

Figure 8. Location of ramp control and revised study area.

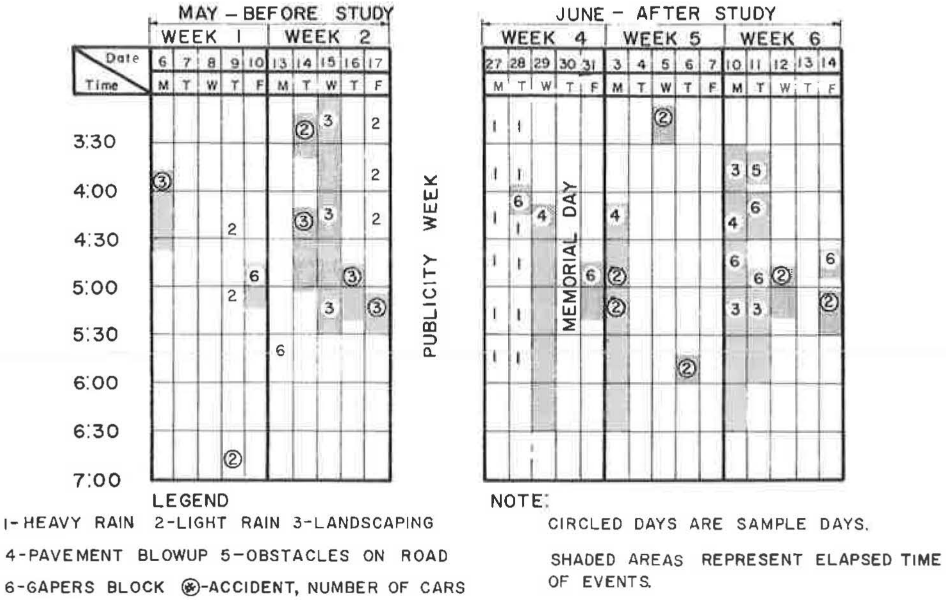

Figure 9. Traffic and weather conditions during, before and after measurements.

obtained for 4 to 5 PM, 5 to 6 PM, and for the total 2-hr period, and are graphically presented in Figures 10, 11, and 12, respectively.

Between 4 and 5 PM, the expressway volume upstream of the Des Plaines ramp was only slightly increased while the expressway volume downstream of the Des Plaines ramp was reduced by approximately 250 vehicles. The volumes on the surface streets increased, except for Des Plaines Avenue between Roosevelt and Madison, and for several streets parallel to the expressway between Harlem and Des Plaines. The total westbound corridor volume between Des Plaines and First Avenue was only slightly increased.

Between 5 and 6 PM the expressway volume upstream of the Des Plaines ramp was increased by 280 vehicles while the expressway volume downstream of the Des Plaines ramp was reduced by 60 to 110 vehicles. The volumes on the surface streets increased except for Des Plaines between Roosevelt and Madison, and for the several streets parallel to the expressway between Harlem and Des Plaines. The total westbound corridor volume between Des Plaines and First Avenue was increased by approximately 90 vehicles.

The measured changes in traffic volumes for the total 2-hr period (Fig. 12) indicate that the westbound volume through the critical corridor (Des Plaines to First Avenue) was increased by 120 vehicles during the 2-hr period. The original estimated change in flow pattern (Fig. 5) compares favorably with the measured change in traffic volumes for the 2-hr period. On the expressway the volume change immediately upstream of Des Plaines ramp was estimated to be an increase of 295 vehicles, while the measured change was an increase of 330 vehicles. Similarly, the volume change immediately downstream of the Des Plaines ramp was estimated to be a decrease of 392 vehicles, while the measured change was a decrease of 320 vehicles. The estimated increase in volume of traffic moving toward the expressway on First Avenue compared closely with the measured change (160 compared with 149 vehicles and 177 compared with 149 vehicles). Similar close agreements in traffic volume changes occurred on Harlem and Roosevelt. The greatest difference between the estimated change in volume and the measured change occurred on the expressway downstream of First Avenue. A decrease of 72 vehicles had been estimated while the measured change was a decrease of 330 to 360 vehicles. This greater than expected decrease in expressway volume is compensated for by the increase in the frontage road volume. Apparently 300 to 350

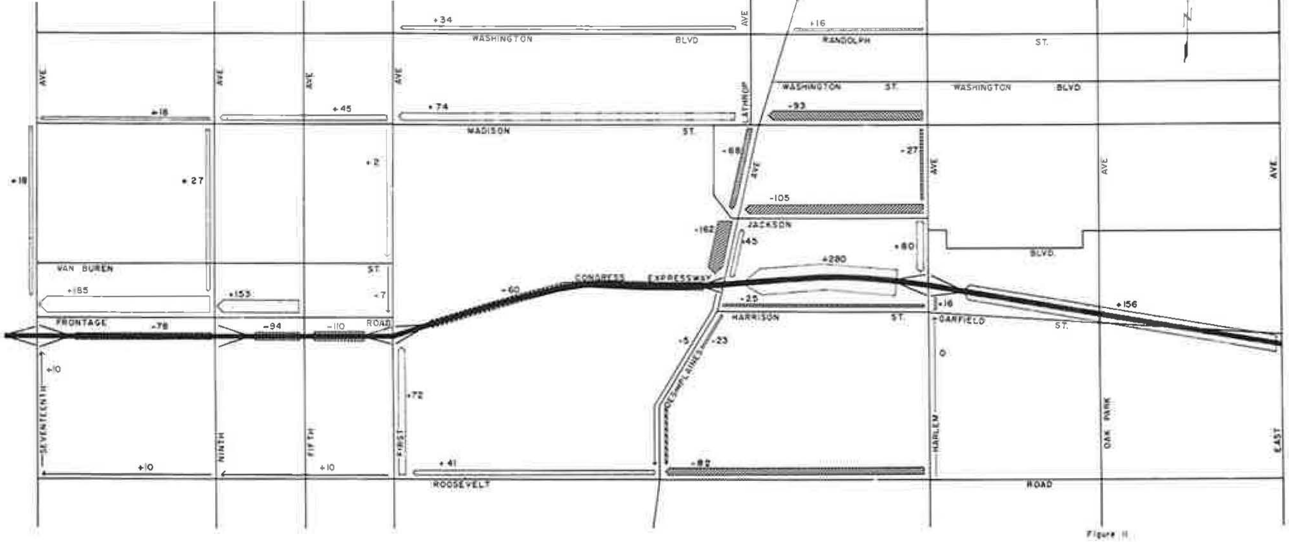

Figure 10. Change in network volume (4 to 5 PM) due to ramp control.

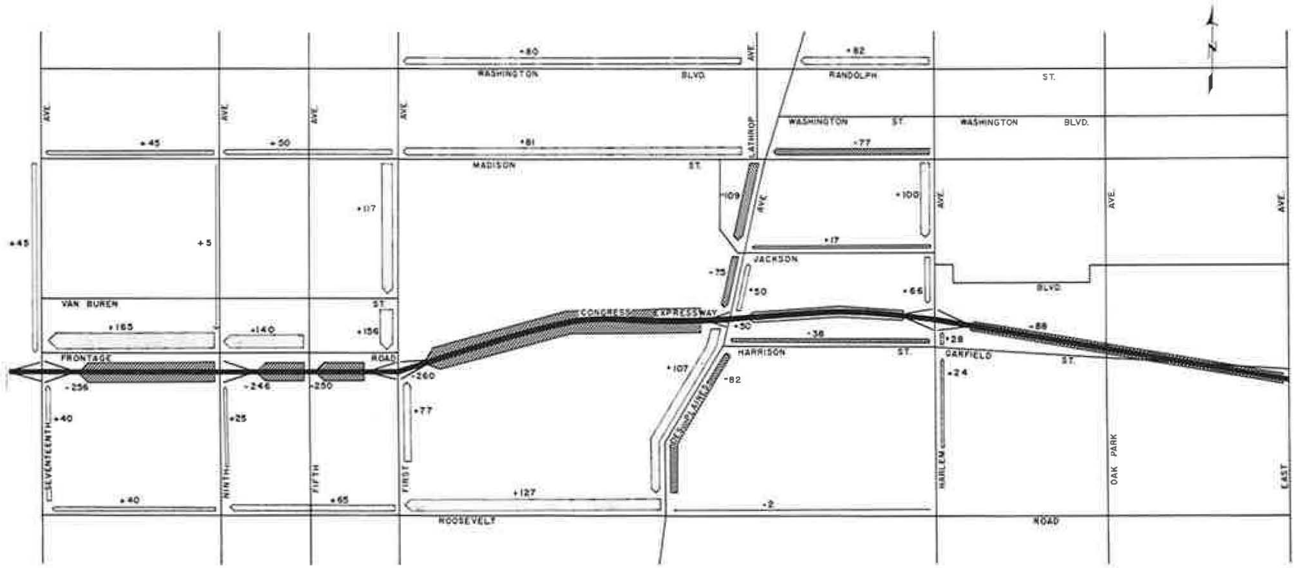

Figure 11. Change in network volume (5 to 6 PM) due to ramp control.

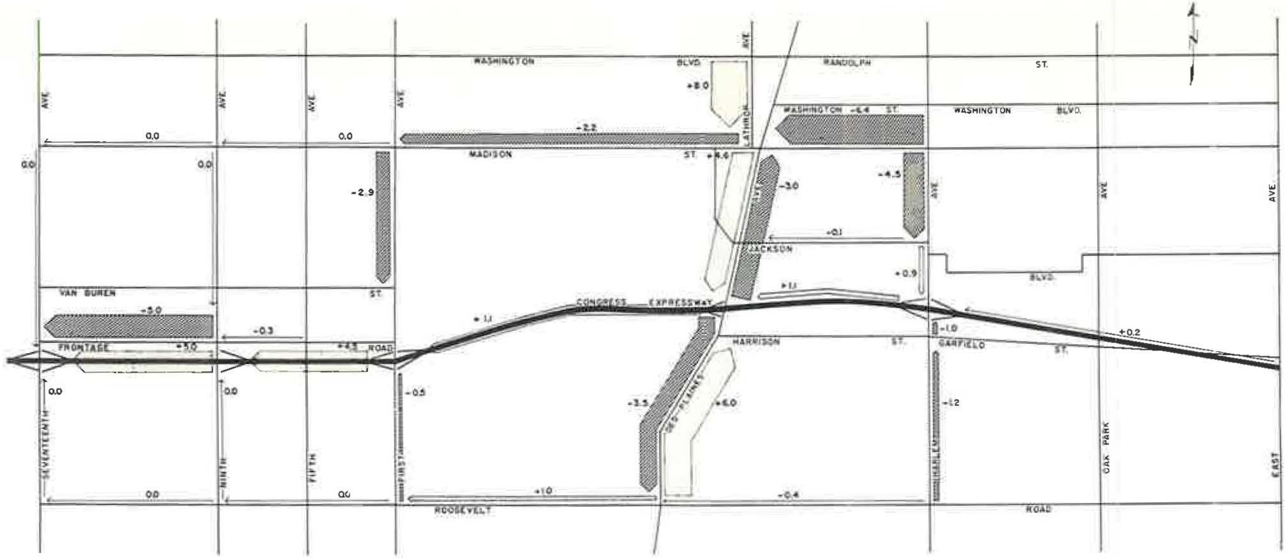

Figure 12. Change in network volume (4 to 6 PM) due to ramp control.

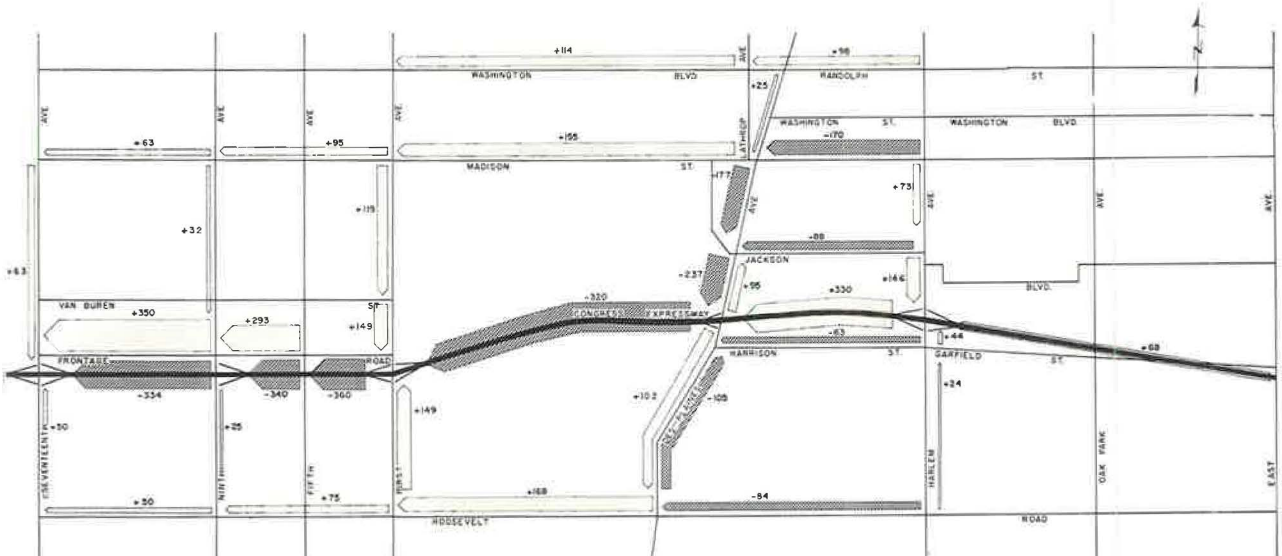

Figure 13. Change in network speed (4 to 5 PM) due to ramp control.

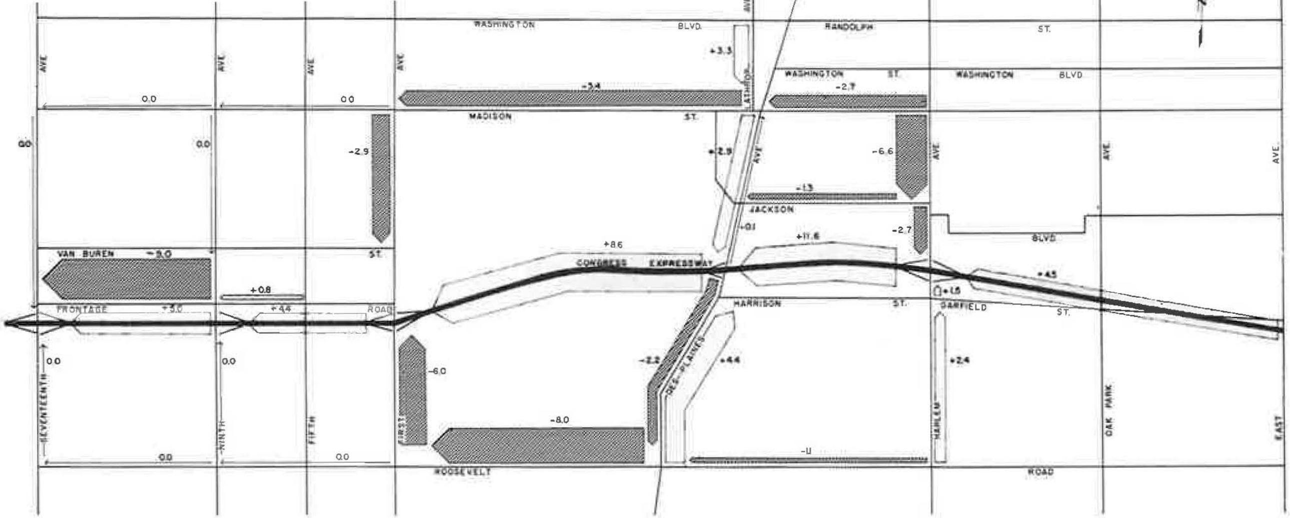

Figure 14. Change in network speed (5 to 6 PM) due to ramp control.

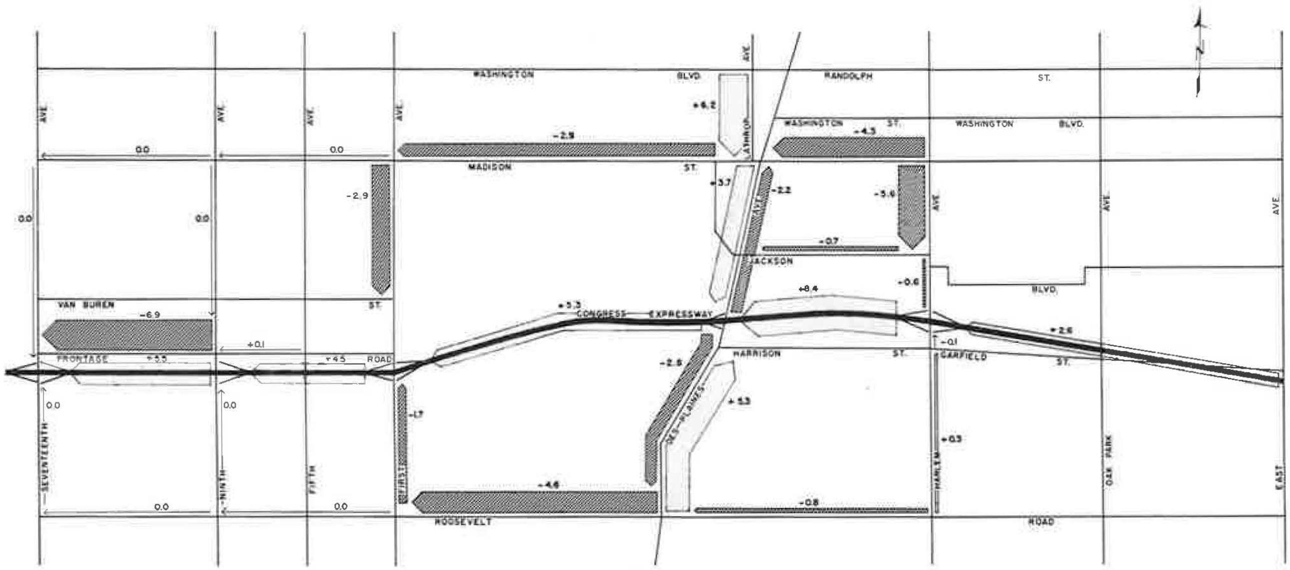

Figure 15. Change in network speed (4 to 6 PM) due to ramp control.

vehicles either proceeded west on the surface streets beyond First Avenue and then traveled to the Seventeenth Avenue ramp via the frontage road or, on approaching the metered First Avenue ramp, the traffic selected the frontage road and entered the expressway by the Seventeenth Avenue on-ramp.

Effect on Average Speeds.—Changes in average speeds on the various links of the study area were obtained for 4 to 5 PM, 5 to 6 PM, and for the total 2-hr period, and are graphically presented in Figures 13, 14 and 15, respectively.

Between 4 and 5 PM average speeds on the expressway were only slightly increased (0.2 to 5.0 mph). Average speeds on the surface streets varied from an increase of 8.0 mph to a decrease of 6.4 mph. Generally speaking, surface streets with increased traffic volumes had slightly reduced average speeds, while surface streets with decreased traffic volumes had slightly increased average speeds.

Greater changes in average speeds occurred between 5 and 6 PM. On the expressway, speeds increased by 4 to 12 mph. Average speeds on the surface streets varied from an increase of 4.4 mph to a decrease of 9.0 mph.

The measured changes in average speeds for the total 2-hr period (Fig. 15) indicate that speeds on the expressway and on Des Plaines Avenue toward the expressway increased, while speeds on the remainder of the surface streets decreased. The largest increase in average speeds occurred on the expressway between Harlem and Des Plaines (8.4 mph), while the largest decrease in average speeds occurred on the frontage road

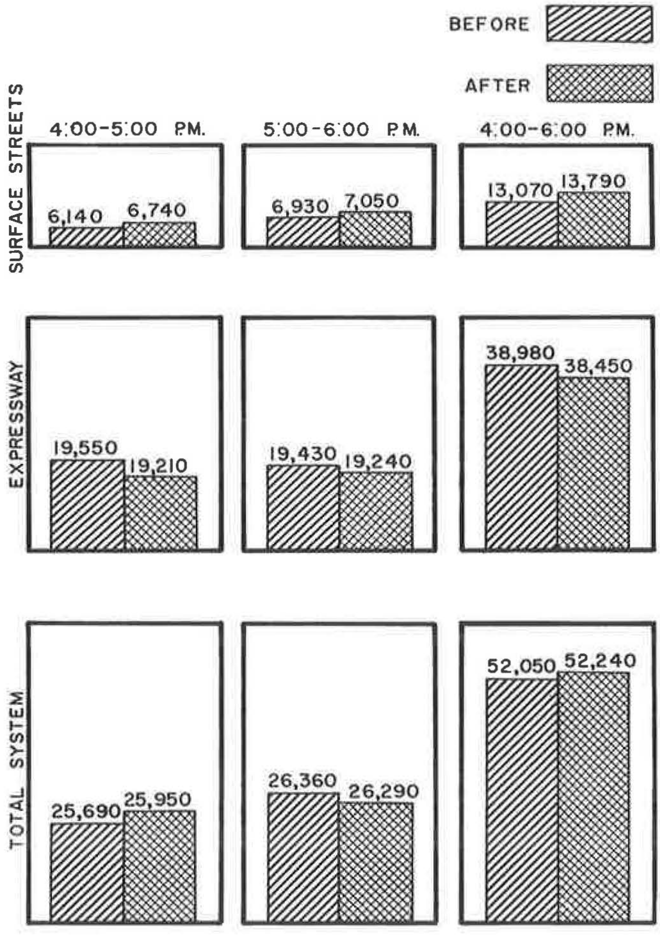

Figure 16. System travel—vehicle-miles.

between Ninth and Seventeenth Avenue (6.9 mph). In addition to the fact that more vehicles were affected by the speed changes on the expressway, the magnitude of the increase speeds on the expressway was slightly larger than the decrease speeds on the surface streets.

Evaluation Summary. —The volume measurements obtained for each link of the study area during the before and after studies permitted the calculation of vehicle-miles of travel for each link, route, network sub-system, and for the total network. A summary of the effect of control on vehicle-miles of travel is shown in Figure 16.

There was an increase of 600 (9.8 %), 120 (1.7 %), and 720 (5.5 %) veh-mi of travel on the surface streets for the period of 4 to 5, 5 to 6, and 4 to 6 PM, respectively. On the expressway the travel for the period 4 to 5, 5 to 6, and 4 to 6 PM decreased 340 (1.7 %), 190 (1.0 %), and 530 (1.4 %) veh-mi, respectively. For the total system of surface streets and expressway the travel for the period 4 to 5, 5 to 6, and 4 to 6 PM changed by 260 (+1.0 %), -70 (-0.3 %), and 190 (+0.4 %), respectively. The results indicated that between 4 and 5 PM more traffic was diverted to the surface streets than required, and for each of the 1-hr periods there was only a slight change in travel on the total system.

The average speeds combined with the volume measurements obtained for each link of the study area during the before and after studies permitted the calculations of vehicle-minutes of travel for each link, route, network sub-system, and for the total network. A summary of the effect of control on vehicle-minutes of travel is shown in Figure 17.

There was an increase of 4,400 (22.6 %), 3,700 (18.0 %), and 8,100 (20.2 %) veh-min of travel on the surface streets for the period of 4 to 5, 5 to 6, and 4 to 6 PM, respectively. On the expressway the travel for the period 4 to 5, 5 to 6, and 4 to 6 PM decreased 1,400 (5.1 %), 9,200 (23.8 %) and 10,600 (16.0 %) veh-min, respectively. For the total system of surface streets and expressway the travel for the period 4 to 5, 5 to 6, and 4 to 6 PM changed by +3,000 (+6.4 %), -5,300 (-8.9 %), and -2,500 (-2.4 %), respectively.

In comparing the estimated change in vehicle-minutes with the measured change, it is apparent that the diversion of ramp traffic increased the travel time on the surface streets more than anticipated, and did not decrease the travel time on the expressway as much as anticipated. It was estimated that, with control, the vehicle-minutes of travel on the surface streets would be 43,100 veh-min, while actual measurements indicated 48,100 veh-min, or a further increase of 5,000 veh-min. A review of the increases on the various links indicated that on First Avenue between Madison Avenue and the expressway the estimated increase was 600 veh-min, while the measured increase was 3,700 veh-min, or a further increase of 3,100 veh-min. The error in the estimate for this one link accounted for more than one-half of the difference between the estimated and measured vehicle-minutes of travel on the total surface streets. In reference to the expressway, it was estimated that with control the vehicle-minutes of travel would be 51,800, while actual measurements indicated 55,100 veh-min, or a difference of 3,700 veh-min. This smaller than expected reduction in vehicle-minutes of travel on the expressway was apparently due to greater volumes than expected on the expressway section upstream of the Des Plaines on-ramp and an overestimation of the capacity of the section upstream of the Des Plaines on-ramp where there is a reverse curve and a 1,000-ft three percent up-grade.

In addition to the vehicle-miles and vehicle-minutes of travel on the expressway for the selected six days (three days of the before study and three days of the after study), similar calculations were made for the remaining days of the study. Vehicle-miles, vehicle-minutes, and average speeds for 4 to 5, 5 to 6, and 4 to 6 PM for each study day are given in Table 2.

Conclusions. —The following are the conclusions drawn from the initial experimentation with manual control:

1. Origin-and-destination studies of ramp traffic proved extremely valuable in estimating the redistribution of traffic on the network.

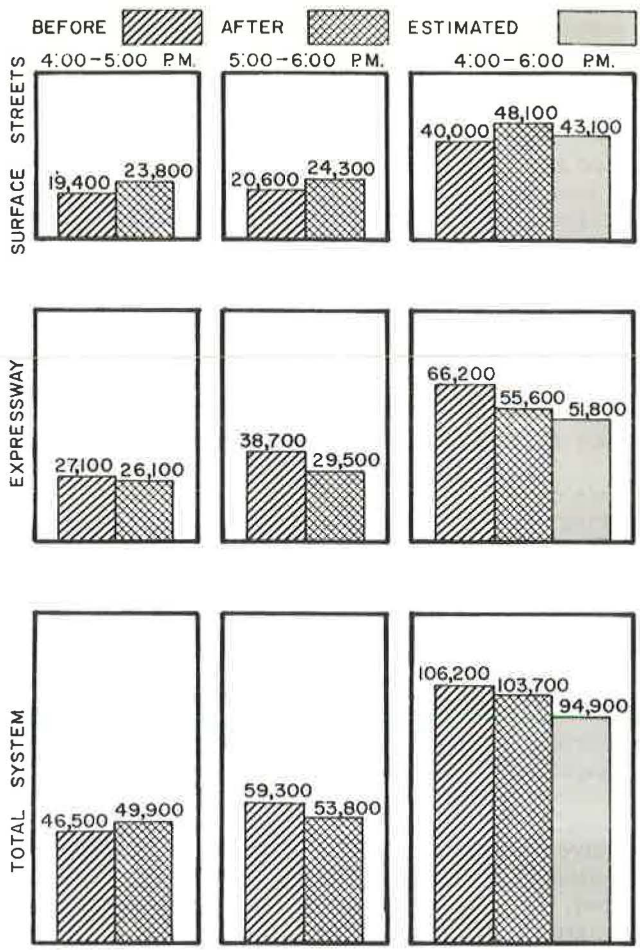

Figure 17. System travel—vehicle minutes.

2. Considerable difficulty was encountered in accurately estimating the changes in travel time, particularly on those links operating at or near capacity.

3. The selection of the period of time and the degree of control is extremely critical in optimizing network operations and, in the case of the Des Plaines ramp, control on most days was exerted too soon and was too restrictive.

4. An informed public will cooperate when reasonable controls are exerted and are generally quick to adjust to a revised control of network operations.

5. The high frequency of unpredictable events, which may have serious consequences on expressway traffic, focuses attention on the need for rapid detection of such events and requires that any control system must have flexibility for handling traffic when such events are detected.

6. Ramp metering as a technique for controlling expressway operations proved satisfactory in maintaining free-flow conditions, permitting maximum entry to the expressway, and providing smooth merging operations. However, metering on a uniform time spacing basis was not practical due to the presence of certain longer vehicles which required greater time for clearance.

7. In this particular control experimentation the vehicle-miles of travel on the surface streets slightly increased, while the vehicle-miles of travel on the expressway slightly decreased. The vehicle-miles of travel on the total network remained essentially unchanged.

TABLE 2

CONGRESS EXPRESSWAY

Week	Day	Veh-Mi 4-5	Veh-Mi 5-6	Veh-Mi 4-6	Veh-Min 4-5	Veh-Min 5-6	Veh-Min 4-6	Avg. Speeds 4-5	Avg. Speeds 5-6	Avg. Speeds 4-6
(a) Before Study										
	May 6	16,880	19,960	36,840	27,300	42,200	69,500	37.1	28.4	31.8
	7	19,250	20,060	39,310	25,900	40,000	65,900	44.5	30.2	35.8
	8	19,800	20,110	39,910	27,200	33,200	60,400	43.6	36.3	39.7
One	9	19,600	18,120	37,720	29,500	43,000	72,500	39.9	25.3	31.2
	10[1]									
	13	19,440	19,520	38,960	29,500	34,300	63,800	39.4	34.1	36.6
	14	16,090	18,700	34,790	24,700	34,400	59,100	39.1	32.6	35.3
	15	19,400	20,200	39,600	23,800	28,900	52,700	48.9	42.0	45.1
Two	16	17,730	18,110	35,840	21,700	27,400	49,100	48.9	39.6	43.7
	17	19,010	19,150	38,160	25,000	32,800	57,800	45.5	34.9	39.5
Averages		18,580	19,330	37,910	26,100	35,100	61,200	42.7	33.0	37.1
(b) After Study										
	June 3	18,710	17,590	36,300	-[1]	-[1]	-[1]	-[1]	-[1]	-[1]
	4	19,350	18,730	38,080	24,900	29,000	53,900	46.4	38.6	42.4
	5	19,090	19,450	38,540	26,400	29,000	55,400	43.4	40.1	41.7
Five	6	19,180	19,540	38,720	27,000	30,500	57,500	42.6	38.5	40.4
	7	18,810	19,250	38,060	27,200	33,200	60,400	41.5	34.7	37.8
	10	16,790	18,080	34,870	29,400	33,100	62,500	34.3	32.8	33.4
	11	18,420	18,760	37,170	27,300	39,000	66,300	40.5	28.9	33.6
	12	18,290	18,450	36,740	27,100	39,800	66,900	40.5	27.8	32.9
Six	13	19,260	19,730	38,990	25,900	34,500	60,400	44.7	34.3	38.8
	14	19,280	18,890	38,170	26,400	39,700	66,100	43.7	28.5	34.6
Averages		18,720	18,850	37,570	26,800	34,200	61,000	41.9	33.1	36.9

[1] Data not complete.

8. The vehicle-hours of travel expended on the surface streets between 4 and 6 PM increased by 135 veh-hr, while the expressway travel decreased by 177 veh-hr. The vehicle-hours of travel on the total network remained essentially unchanged.

INITIAL EXPERIMENTATION WITH AUTOMATIC CONTROL

The knowledge gained from the initial experimentation with manual control and the results of a theoretical study of peak period control of an expressway system (2) clearly indicated the distinct advantage of ramp control utilizing traffic-adjusted metering as compared with time-clock complete ramp closure. Therefore, the next phase of ramp control was the development and evaluation of an automatic ramp metering device.

General Description

It is envisioned that the ramp metering scheme will require a metering device on the ramp and also changeable message displays at the entrance to the ramp and at locations some distance in advance of the ramp, so that intended ramp traffic could select parallel routes with little or no adverse distance. These changeable displays would indicate whether the ramp in question was open, metered, or closed (metering rate of zero). To confine this first step toward automatic control to the ramp metering device, a single on-ramp was selected on a portion of the study area where a frontage road existed (First Avenue on-ramp, see Fig. 8). By selecting this location, if the ramp is metered or closed, the intended ramp traffic could choose the frontage road as a parallel route, encounter no adverse distance, and postpone its entrance to the expressway to the Seventeenth Avenue on-ramp. The only advance display required would be at the entrance to the ramp, and it was decided that in this initial experimentation this display would be manually controlled.

Therefore, the primary purpose of this initial experimentation was to develop, test and finalize a ramp metering device. It was not intended at this stage to provide major expressway operational improvements except those which would result from improved merging operations at the First Avenue ramp entrance to the expressway. However, from previous studies it is clear that s successfully developed ramp metering device operating at the First Avenue ramp in conjunction with the next ramp upstream (Des Plaines Avenue ramp), would result in substantially improved expressway operations. Consequently, while this initial work is limited to developing the ramp metering device, the next logical steps would include developing advance displays and installing ramp metering devices at ramps further upstream, and then operational improvements on a continuous basis could be obtained. This series of developments is a necessary step toward the immediate objective of the Expressway Surveillance Project, which is the operation of an automatic pilot network information-control system.

Development of Automatic Ramp Metering Device

Three forms of metering devices were initially considered. The essential element of each was either movable gates, changeable message signs, or modified traffic signals. The movable gate had the distinct advantage of a physical barrier which is a desirable feature for ramp control. However, considerable sophisticated control appeared to be required during operation to insure against damaging vehicles or the gate itself. The use of a changeable message sign received attention, but disregard by some motorists for such control information in previous similar situations (3, 4) made this method less attractive. A modified traffic signal appeared most promising because of its simplicity and its previously proven effectiveness in controlling traffic. Therefore, the standard traffic signal should be modified for this application to convey to the motorist its unique application, and by so doing, enhance driver observance.

Before experience with the manual ramp metering, only a single detector located in advance of the ramp signal seemed to be required, and the delay until the next green signal indication could be controlled by a simple timer. In this way if the desirable ramp volume was 600 veh/hr, the timer would be set for 6 sec (3,600 sec/600 veh). However, experience with metering large trucks and concern about limiting the flow to one vehicle per green indication gave rise to the consideration of using two detectors. The detector in advance of the signal would indicate a ramp vehicle demand, and the second detector beyond the signal would indicate that a vehicle was in the process of passing or had passed. Another benefit of the two-detector system was that a light and bell alarm could be actuated if the vehicle violated the ramp signal indication (the situation when the ramp signal is red although a vehicle is detected entering the second detector zone).

Having decided to use the two-detector system in this initial installation, the exact locations for the detectors had to be selected. The first detector had to be close enough to the ramp signal so that a waiting vehicle would not be stopped between the detector and the ramp signal, and yet far enough away from the ramp signal so that the next ramp vehicle would not stop in advance of the detector. The second detector had to be close enough to the ramp signal so that a reasonably high metering rate could be maintained, while far enough away from the ramp signal so that a vehicle waiting for the green indication would not actuate the second detector. The locations for the two detectors in relationship to the ramp signal and stop line were established and are shown in Figure 18. The distance from the ramp signal to the ramp nose is 282 ft and the distance back to the frontage road is 158 ft.

The actual installation is shown in Figure 19. In the top photograph are the three advance signs. The first sign can be manually changed to read "Ramp Open Ahead," "Ramp Metered Ahead," or "Ramp Closed Ahead." The legend of the second sign on the left reads "Ramp Signal Ahead," while the third sign (located on right) indicates "Form Single Lane." The 3-lane one-way frontage road is shown in the top photograph. The lower photograph, a close-up showing the pavement markings, ramp signals, and controller, was taken during the first week of operation with a police officer present.

The basic steps in controlling the ramp metering device are shown in Figure 20. (The ramp metering device was designed by William L. Parker of the Expressway Surveillance Project and the hardware development was a joint venture with O. T. Gustus of Bell and Gustus.) In reference to Figure 21, measurement is obtained on the expressway and transmitted to the computer center for computation. The levels of the

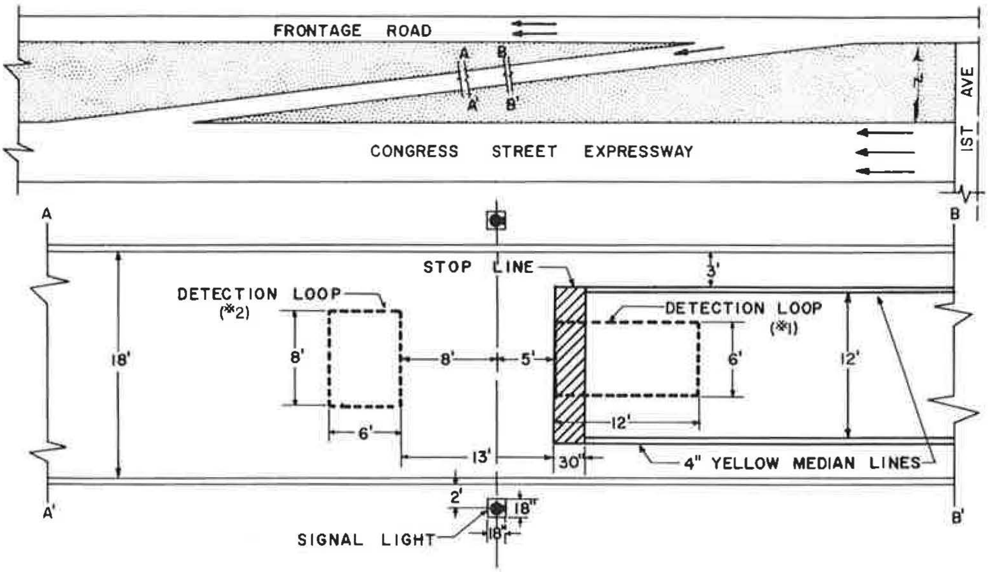

Figure 18. Ramp metering equipment.

measurement signifying free-flow conditions, impending congestion, or the presence of congestion are indicated by the level monitor. A control panel was constructed and connected for the transmission of control action on an automatic basis, but with a manual override. In the event that no control is required (free-flow conditions), the ramp signal rests in green. In the event of impending congestion, one of five metering rates is selected. The five metering rates are obtained by disengaging the timer and operating in a vehicle-actuated mode (basic metering), or by connecting the timer and pre-selecting four time delays (reduced metering). In the event of expressway congestion, the ramp is manually closed and when the vehicles already on the ramp are cleared, the ramp signal is locked in red.

Conduct of Control Experimentation

In late July 1963, the Project Advisory Committee approved the recommendation of the staff for automatic ramp metering control at First Avenue. The activities connected with the development and evaluation of the ramp metering device are shown in Figure 21. The design and construction of the ramp metering device were completed in August, and it was installed and tested during early September. The planning for the conduct of the evaluation was undertaken in August and early September. Publicity and handout of traffic bulletins at the on-ramp were accomplished during the second week of September. Operations with the ramp metering device began on Monday, September 16. To handle any difficulties that might arise and to encourage initial compliance, arrangements were made for a State Police officer to be present at the ramp during the initial week of operations. Starting on Monday, September 23, a police officer was not present except for normal routine police activities, and a preliminary evaluation of the performance of the metering device and associated equipment, and its effect on driver behavior and compliance began. In addition to this evaluation, schemes for metering based on mainline volume and occupancy combined, and mainline occupancy were tested and refined. The initial procedure used for metering operations was based on mainline occupancy, and the rules for control are, as follows:

1. Metering commences as soon as the mainline lane two occupancy equals or exceeds 15 percent provided it is after 3:30 PM and will begin regardless of percent occupancy at 3:50 PM.

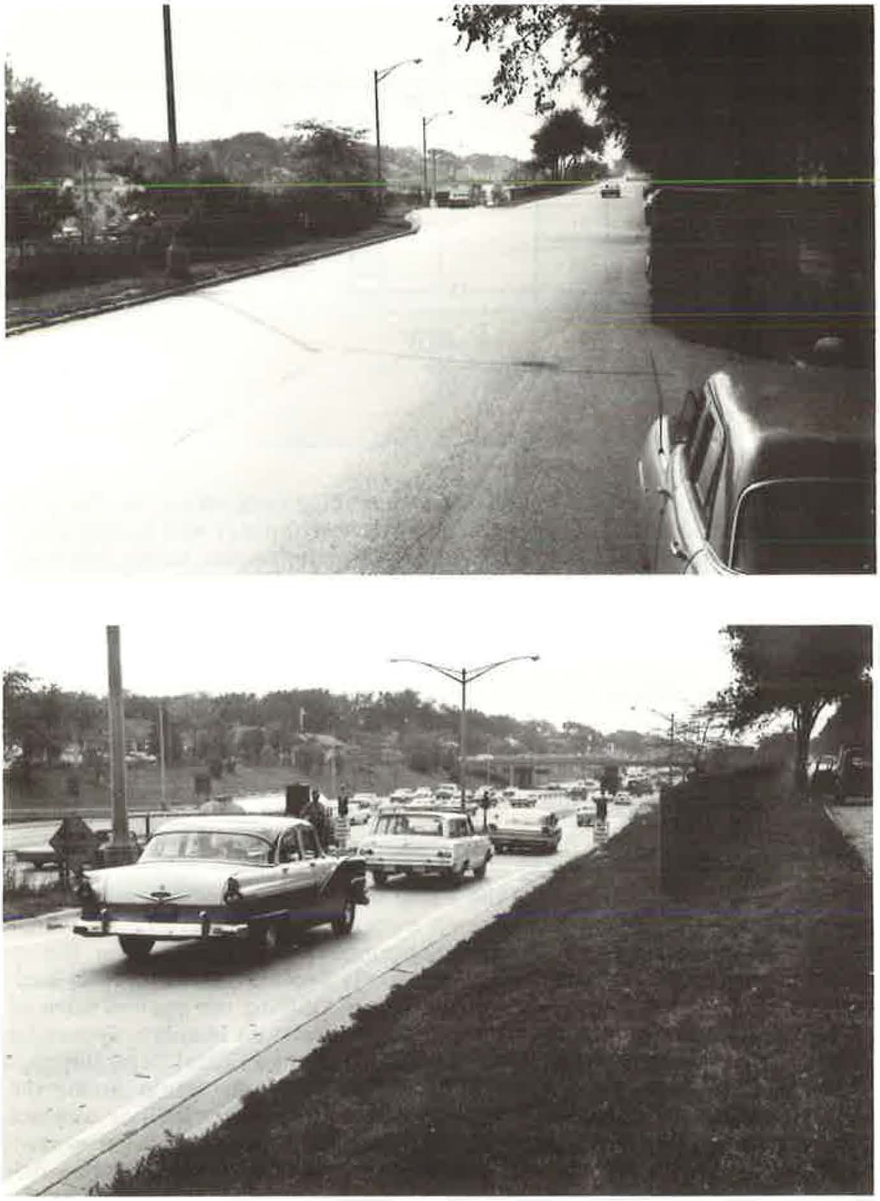

Figure 19. Ramp metering equipment.

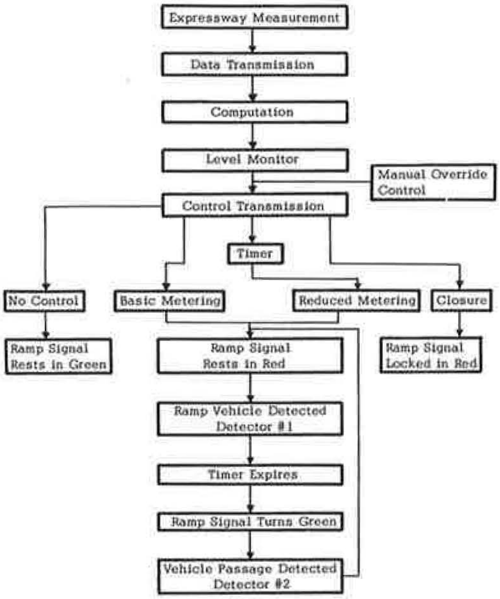

Figure 20. Ramp metering operation.

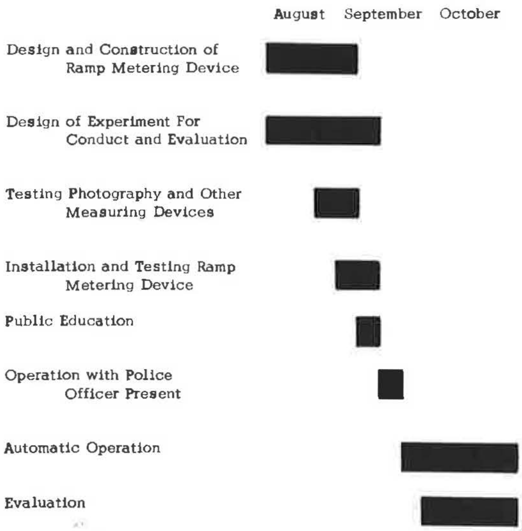

Figure 21. Study calendar.

TABLE 3

Percent Occupancy	Metering Rate Number	Clearance Delay[1] (sec)	Timer Setting (sec)	Total Clearance Time (sec)	Metering Rate (veh/min)
15	1	5	0	5	12
16	1	5	0	5	12
17	1	5	0	5	12
18	2	5	2	7	8.5
19	2	5	2	7	8.5
20	2	5	2	7	8.5
21	3	5	3	8	7.5
22	4	5	4	9	6.5
23	5	5	7	12	5.0
24	5	5	7	12	5.0

[1] Time required for driver of a ramp vehicle to see that signal has changed to green, accelerate, and clear second detector. Estimated clearance time of 5 sec is based on a starting delay of 2 sec; a detector configuration as shown in Figure 19; 85 percent of ramp vehicles being passenger vehicles, having an average length of 20 ft, an average acceleration rate of 10 ft/sec; and 15 percent of ramp vehicles being trucks, having an average length of 40 ft, an average acceleration rate of 6 ft/sec.

2. The metering rate will be automatically set based on percent occupancy obtained from an occupancy computer and level monitor. The permitted metering rate for various levels of occupancy is given in Table 3.

3. The ramp entrance to be closed as soon as the mainline lane two occupancy equals or exceeds 25 percent and provided it is after 3:30 PM. The queue already on the ramp to be discharged at metering rate number 5.

4. Metering operation will be terminated as soon as the mainline lane two occupancy is less than 15 percent and provided it is after 6:00 PM.

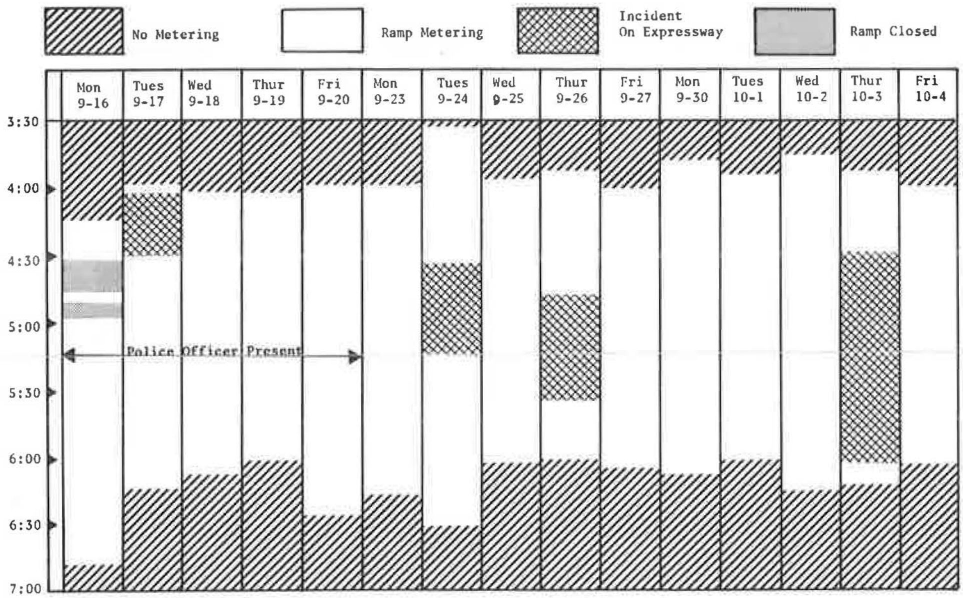

Figure 22. Degree of control and incidents during first three weeks of metering operations.

The period of time that the First Avenue on-ramp was controlled and a record of incidents on the expressway during the first three weeks of operations are shown in Figure 22. Metering normally began between 3:30 and 3:50 PM and ended between 6:00 and 6:20 PM. The weather was excellent during the 3-wk period and there was no precipitation during metering operation. Considerable congestion was encountered on the first day of operations and resulted in temporary ramp closures, and extended the period of metering. Apparently the public was interested in observing the ramp metering after being informed of the initial operations by radio and newspaper. A "gaper's block" occurred in both directions and was further affected by low-flying helicopters operated by local radio stations. Other incidents occurring on the expressway which affected the ramp control are also shown in Figure 22.

Measurements were taken on the expressway and at selected ramps using the pilot detection system. In addition, field observations were made at the ramp to record violations, hazardous maneuvers, queue lengths at the foot of the ramp and behind the ramp signal, and any malfunctions or difficulties with the metering device. These measurements permitted the preliminary evaluation of the initial automatic ramp metering operations at the First Avenue on-ramp.

Evaluation of Control Experimentation

Effect of Metering on Ramp Volume.—The average 4 to 6 PM accumulative ramp volume for a three-day period (Tuesday, Wednesday, and Thursday) before metering is compared with a similar three-day period during the first two weeks of metering in Figure 23. Before metering, the 2-hr volume was 810 vehicles, whereas with metering, the 2-hr volume was reduced to an average of 770 the first week and 780 the second week, or a reduction of 30 to 40 vehicles. Apparently during metering operations a small percent (4 to 5%) of the vehicles approaching the ramp and seeing a queue of vehicles, select the option of continuing west on the frontage road. The diversion is greatest between 4:30 and 4:45 PM when the queues on the ramp are generally the longest. The percent of traffic diverted was surprisingly low, particularly considering the attractive alternate route, and would indicate the acceptance of the metering device by a large proportion of the ramp traffic.

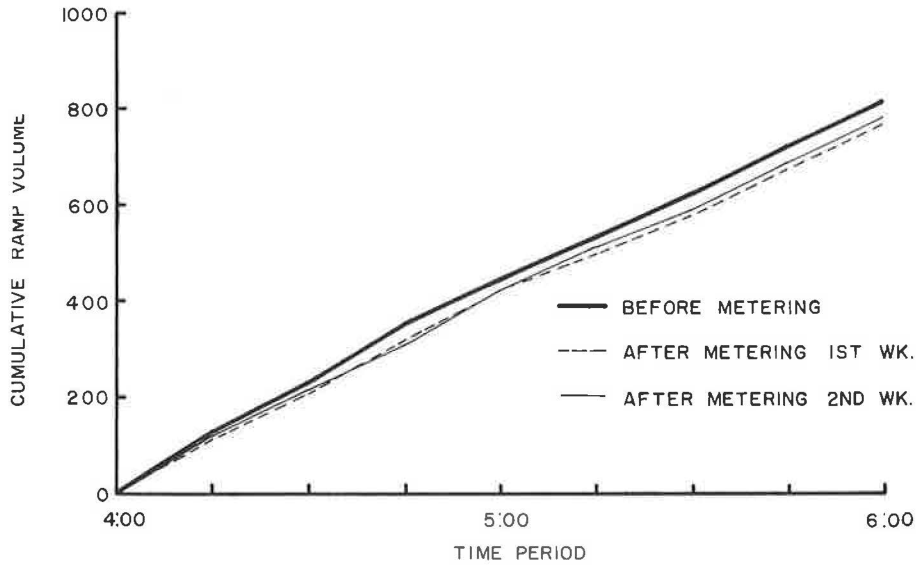

Figure 23. Cumulative ramp volume before and after metering.

Effect of Metering on Expressway and Merging Operations.—One measure of the effect of ramp metering on expressway operations is the percent occupancy level on the expressway just upstream of the metered ramp. Earlier studies had indicated that free-flow conditions existed when the percent occupancy was less than approximately 15 percent, and congested flow occurred when the percent occupancy was greater than 25 percent. Therefore the average minute percent occupancy in lane two at the First Avenue mainline station was recorded for the period of 4 to 6 PM for three weekdays (Tuesday, Wednesday, and Thrusday) before metering operations, and for the same time of day and for the same days of the week during metering operations. The cumulative frequencies of the average minute occupancies between 4 and 5 PM and between 5 and 6 PM are given in Table 4. The cumulative frequency data indicate that ramp metering had little effect either on the level or the distribution of average minute percent occupancies. As mentioned earlier and as confirmed by the tabulated values, expressway congestion did not occur at this location either before or during metering operations.

A measure of satisfactory merging is the absence of stopped ramp vehicles at the foot of the on-ramp. This is particularly critical at this on-ramp because of the short acceleration lane and the proximity of an off-ramp a short distance downstream. The number of stopped vehicles per 15-min period between 4 and 6 PM for two days before and after metering operations were recorded and are shown in Figure 24. During the 2-hr period the average number of vehicles stopped before metering and with metering was 110 and 92 vehicles, respectively. This was a reduction of 18 stopped vehicles or 16 percent. It appears possible that with further refinements in the metering technique the number of stopped vehicles can be reduced further. In addition, observation of the merging operations, a review of time lapse movies, and comments from a number of ramp users substantiated that merging operations had been improved by uniformly spacing vehicles and adjusting the space based on expressway conditions.

Effect of Ramp Metering Device on Ramp Traffic Behavior.—In addition to studying the merging operations and ramp volumes, measurements were taken of the length of queue behind the ramp metering device and of undesirable ramp maneuvers. The length of queue resulting from the ramp metering for each minute between 4 and 6 PM for three days is shown in Figure 25. The maximum queue length was 20 vehicles with the longest queues being observed from 4:00 to 4:10 PM and from 4:30 to 4:40 PM. Approximately 10 to 12 vehicles could be stored on the ramp and about the same number on the frontage road back to First Avenue.

After the first week of operations when the police officer was present, a record of

TABLE 4

CUMULATIVE FREQUENCY OF AVERAGE MINUTE OCCUPANCIES, FIRST AVENUE MAINLINE, LANE TWO

Percent Occupancy	Cumulative Frequency					
	4-5 PM			5-6 PM		
	Without Metering	With Metering	Difference	Without Metering	With Metering	Difference
7	0	0	-	0	0	-
8	1	0	+1	0	0	-
9	1	1	-	1	0	+1
10	2	1	+1	1	1	-
11	4	3	+1	1	1	-
12	12	7	+5	6	4	+2
13	21	16	+5	8	10	-2
14	35	30	+5	24	21	+3
15	51	46	+5	42	38	+4
16	67	65	+2	60	58	+2
17	79	80	-1	74	76	-2
18	87	91	-4	88	89	-1
19	95	96	-1	97	96	+1
20	97	99	-2	98	98	-
21	99	99	-	100	99	+1
22	99	99	-	100	100	-
23	99	99	-	100	100	-
24	100	99	+1	100	100	-
25	100	99	+1	100	100	-
26	100	99	+1	100	100	-
27	100	100	-	100	100	-

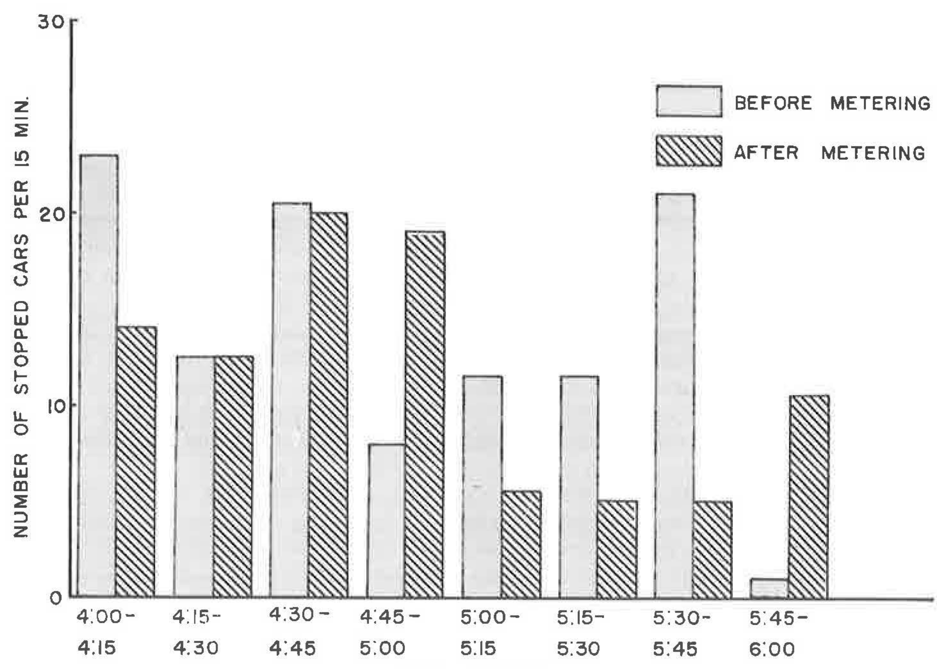

Figure 24. Frequency of stopped vehicles in the merging area.

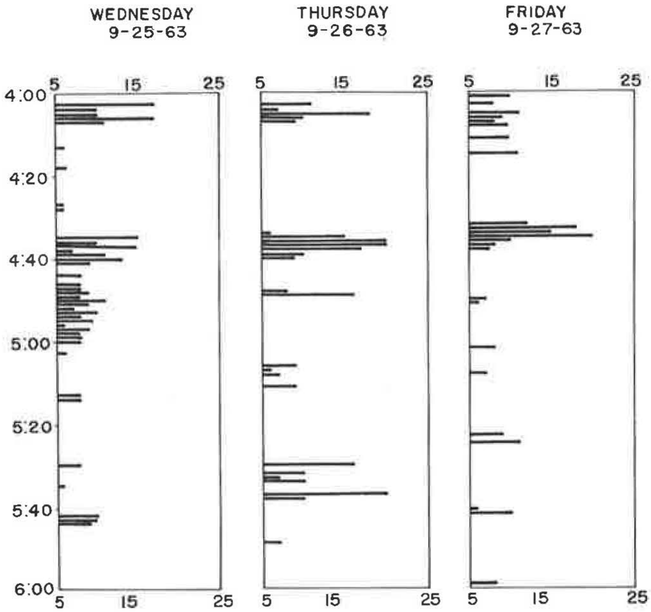

Figure 25. Length of queue due to ramp metering.

the number of vehicles proceeding through the red indication was kept for each afternoon period for three weeks. The number of violations varied from 14 to 32 vehicles per afternoon, with an average of 20 vehicles. The average percent of violations was 2.6 percent. Most of the violations occurred when a queue of vehicles was not present, and more than 90 percent were passenger vehicles. Apparently about one-third of these vehicles violated the ramp metering device unintentionally because when the alarm light and bell were actuated these vehicles either stopped or, in some cases, stopped and attempted to back up.

The most noticeable defect in the automatic ramp metering device has been the occasional situation when a ramp vehicle stops in advance of the first detector loop and is not detected by the system. When this happens the signal indication remains red and can only be changed to green by the stopped vehicle advancing to the first detector loop. It has been observed that either the driver of the vehicle releases his brake and finally advances far enough to be detected on his own, or the driver receives encouragement from the drivers of vehicles stopped behind him. Although this situation is not too common (an average of six such occurrences per afternoon), it does cause an unnecessary increase in the queue length and total delays.

Two minor modifications have been made in an attempt to eliminate this difficulty. First, the informational message on the two signal pedestals has been changed from "Wait for Green Light" to "Wait for Green at Line." Second, the stop line has been moved 5 ft downstream to the location of the ramp signals. Studies are now under way to evaluate the effectiveness of these measures.

Conclusions.—The following are the conclusions drawn from the initial experimentation with automatic ramp control:

1. The utilization of a modified traffic signal appears to be satisfactory for metering ramp traffic. A large proportion of the ramp traffic (over 95%) operates in a satisfactory manner and complies with the regulations pertaining to the ramp metering operations.

2. The most noticeable defect of the ramp metering operation has been vehicles stopping in advance of the first detector and consequently not receiving a green indication. Minor modifications have been made to handle this situation.

3. The percent of traffic selecting the frontage road in preference to the metered

TABLE 5

Mainline Occupancy %	Metering Rate (veh/min)	
	Initial	Revised
15	12	9.5
16	12	9.5
17	12	9.5
18	8.5	9.5
19	8.5	7.2
20	8.5	7.2
21	7.5	7.2
22	6.5	5.3
23	5.0	5.3
24	5.0	3.9

TABLE 6

Upstream Expressway Vol. (veh/min)	Metering Rate (veh/min)[1]
86	14
86-91	9.5
91-93	7.2
93-95	5.3
95	3.9

[1]When lane 2 occupancy exceeds 22%, a metering rate of 3.9 veh/min is used.

ramp was surprisingly low, and would indicate the acceptance of the metering device by a large proportion of the ramp traffic.

4. The traffic operations in the freeway-ramp merging area were improved by ramp metering as indicated by a reduction in the number of stopped ramp vehicles in the merging area.

5. The queue of vehicles formed by the ramp signal were normally less than ten vehicles in length except for the two brief periods immediately after 4:00 and 4:30 PM when queue lengths varied between 10 and 20 vehicles.

6. The number of vehicles which violated the ramp signal varied from 14 to 32 vehicles per afternoon, with an average of 20 vehicles (2.6% of ramp traffic).

7. The relationship between mainline occupancy and the permitted metering rate was modified to reduce the number of stopped vehicles in the merging area. The initial and revised metering schemes are given in Table 5.

8. Metering schemes using mainline occupancy and volume combined have been tested and a revised metering scheme is given in Table 6.

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