THE DEVELOPMENT OF AN AUTOMATIC FREEWAY MERGING CONTROL SYSTEM

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INTRODUCTION

The problem of adapting existing facilities to ever increasing traffic demands has plagued cities through the ages. Traffic conditions were so bad in Julius Caesar's Rome that he prohibited parking in certain downtown areas, devised a one-way street system, and even banned wheeled vehicles from the center of Rome during the day.

Even in more recent times in modern cities, the surface street system composed of locals, collectors, and major arterials proved inadequate in handling expanding traffic volumes. Operational problems on the streets included congestion at intersections, vehicle-pedestrian conflicts and conflicts between vehicles moving and parking. This led to the provision of additional capacity in the street system through programs of street widening along established rights-of-way. Congestion was not relieved, however, and in many cases the problems were compounded. This indicated the need for controlling intersections to assign rights-of-way to the many conflicting movements.

The most vigorous attempt to eliminate traffic congestion was the development of the freeway. The freeway provided a new approach; it released the roadway from old alignments, from abutting property, from intersections at grades, from outmoded design standards, and from old right-of-way limitations. The consturction of freeways, however, did not eliminate the problem of congestion and in many cases concentrated it on the freeway while freeing the movement on the street system.

Fundamentally, the capacity of any subsystem can be increased by physical expansion on the one hand or by better control of the existing plant on the other. Historically, both methods have been applied to the surface street traffic problem and the first method has been applied to freeway facilities. Whereas early freeways were four-lane facilities, many new freeways are ten lanes wide. The second method -- the control of existing freeways -- is gaining increasing conceptual acceptance throughout the country as a means of achieving a more nearly optimal operation of the street-freeway system achieved by allocation of traffic demands to available system capacity.

This paper presents the operational aspects of the merging control equipment in use at the Telephone Road interchange on the inbound Gulf Freeway. The equipment is being used to evaluate several control theories but has not been installed for a period of time sufficient to allow a report on the comparison of theories at this time. This comparison of theories will be reported later. This paper presents only a discussion of the equipment operation and some general observations regarding the traffic operation under the different Modes.

Freeway Surveillance and Control

It is generally agreed that one key to significant progress in operation of urban freeways lies in improved surveillance techniques. The term "surveillance" has developed in the highway terminology primarily in the last decade and denotes the observation of conditions in time and space. Initially, urban freeway surveillance was limited to moving police patrols. Recently, helicopters have been used for freeway surveillance in many metropolitan areas. Efficient operation of high density freeways is, however, more than knowing the location of stranded vehicles or the qualitative description of the degree of congestion by high flying disk jockeys.

Television surveillance became an operational reality in the late 1950's both in the U. S. and Europe. The Port of New York Authority utilized closed circuit television for monitoring traffic in the Hudson River Tunnels and in Germany a well publicized TV system was developed to monitor traffic at a major, complex urban intersection.

Experimentation with closed circuit television as a freeway surveillance tool was initiated on the John C. Lodge Freeway in Detroit. This afforded the opportunity of viewing a long area of highway in a short, almost instantaneous period of time made possible by spacing cameras along the freeway so that a complete picture could be obtained of the entire section of roadway. The system was put into use in the summer of 1961.[1]

During the period in which the television system was being made operational, the staff of the Detroit Project considered the requirements and specifications of an automatic detection system. To improve surveillance, classification and speed sensors with the necessary relay racks, analog computers and display panels were added. In the summer of 1962, the John C. Lodge Freeway became a Control Project as well as a Surveillance Project when use of lane signals, on-ramp signals and variable speed signs was initiated. Six months later, on-ramp closure signals became operational. Thus, in four short years an entirely new concept in freeway traffic control was developed based on a closed circuit television surveillance system and traffic detection and measuring system, with capabilities of transmitting control messages to matrix variable speed signs, lane controls and ramp controls.

In the case of television surveillance alone, evaluation of freeway operation depends mostly on the visual interpretation of the observers. Many traffic people believe that this is not enough. The Chicago Surveillance Project maintains that even trained observers offer no uniform objectivity. In other words, the quality of operating conditions can be detected by observing operating characteristics. When the characteristics are in certain predetermined levels of operation, certain previously designated courses of action may be taken.

The Chicago Area Expressway Surveillance Project was established in 1961 under the research program of the Illinois Division of Highways financed by federal, state, county and city funds.[2] Its objective was to develop, operate, and evaluate a pilot network surveillance and control system to reduce travel time to increase traffic flow over the Congress (now the Eisenhower) Expressway. Thus, unlike many projects which end their responsibility for traffic at the edge of the road, this project was equally concerned with the arterial subsystems that feed the Expressway or receive vehicles from it.

As indicated before, some of the most significant advances in freeway surveillance and control have been obtained on research facilities other than freeways. Most notably is the work of The Port of New York Authority in the Holland Tunnel. In November, 1963, a new tunnel traffic control system was authorized for the south tube of the Lincoln Tunnel. Anticipated benefits are more effective use of tunnel capacity and more efficient patrolling with fewer police officers. Features include a traffic surveillance system of vehicle detectors which includes traffic condition display and control devices; a special computer which receives traffic information and activated controls to prevent congestion from occurring inside the tunnel; closed-circuit television; two-way radio communication between control centers and police in the tunnel; and a monorail for speedily moving tunnel police to any point in the tunnel.[3]

The Gulf Freeway Project

In most cases, the primary use of television has been for operational rather than research purposes. The National Proving Ground for Freeway Surveillance, Control, and Electronic Traffic Aids on the John C. Lodge Freeway - now jointly sponsored by twelve states - served as the first major installation which was planned for and now continues a program of research per se. It has provided technical knowledge and experience to several new television surveillance projects at the Baytown Tunnel in Texas; the Gulf Freeway in Houston, Texas; and at the Interstate Freeway in Seattle, Washington. The Baytown Tunnel and Seattle Projects are primarily operational; The Gulf Freeway Surveillance and Control Project is a combined research and operational project.

In September, 1963, the Texas Transportation Institute was authorized to initiate studies in the area of freeway surveillance and control in order to increase the efficiency of existing urban freeways and to determine how to improve the level of service of future facilities. A research project sponsored by the Texas Highway Department and the U. S. Bureau of Public Roads was formulated with the basic objective of developing criteria for the design and operation of automatic surveillance and control systems which would permit the attainment of acceptable levels of service on heavily traveled urban freeways during peak periods of demand.

This research project was conceived as centering around a study of the Gulf Freeway in Houston, Texas. It was reasoned that the development of a system of automatic surveillance and control for this facility would furnish an excellent pilot study from which technology could be developed that would be applicable to freeway systems in other parts of the nation. The research work was interpreted as consisting of three steps:

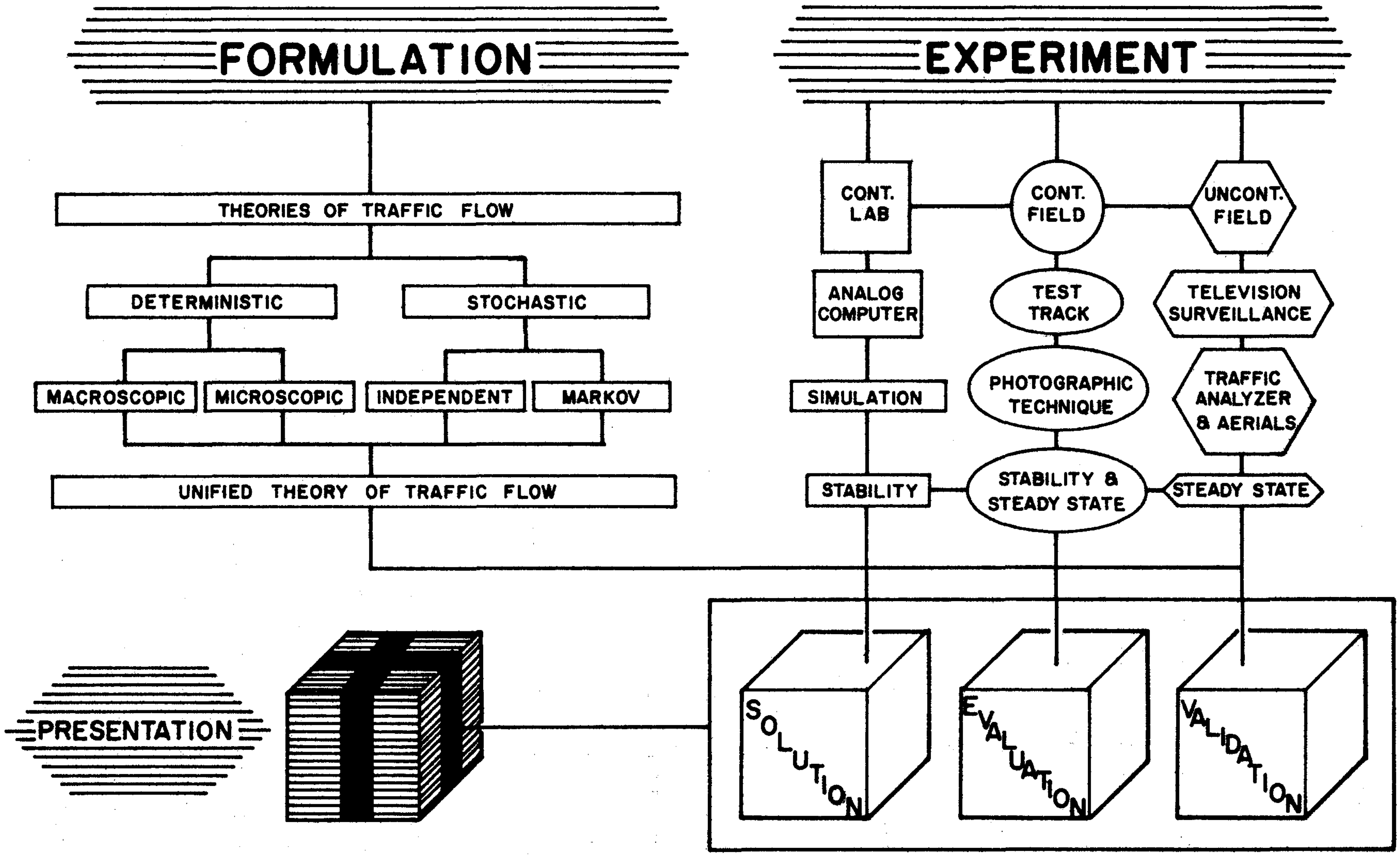
(1) To develop basic research on the characteristics of operation on both the freeway and connecting at-grade arterial system in order to determine the requirements of the proposed surveillance and control system.

(2) To experiment with detection and sensing equipment and to develop prototypes of eventual automatic controllers that could anticipate the build up of congestion and react to prevent it.

(3) To install and evaluate the final automatic surveillance and control system.

Surveillance Projects as Research Facilities

Inherent in the research process are theory formulation, experimentation, and evaluation. Theory formulation includes the establishment of the criteria for system optimization and the formulation of a mathematical model. Experiment can be of



TRAFFIC RESEARCH PROCEDURE

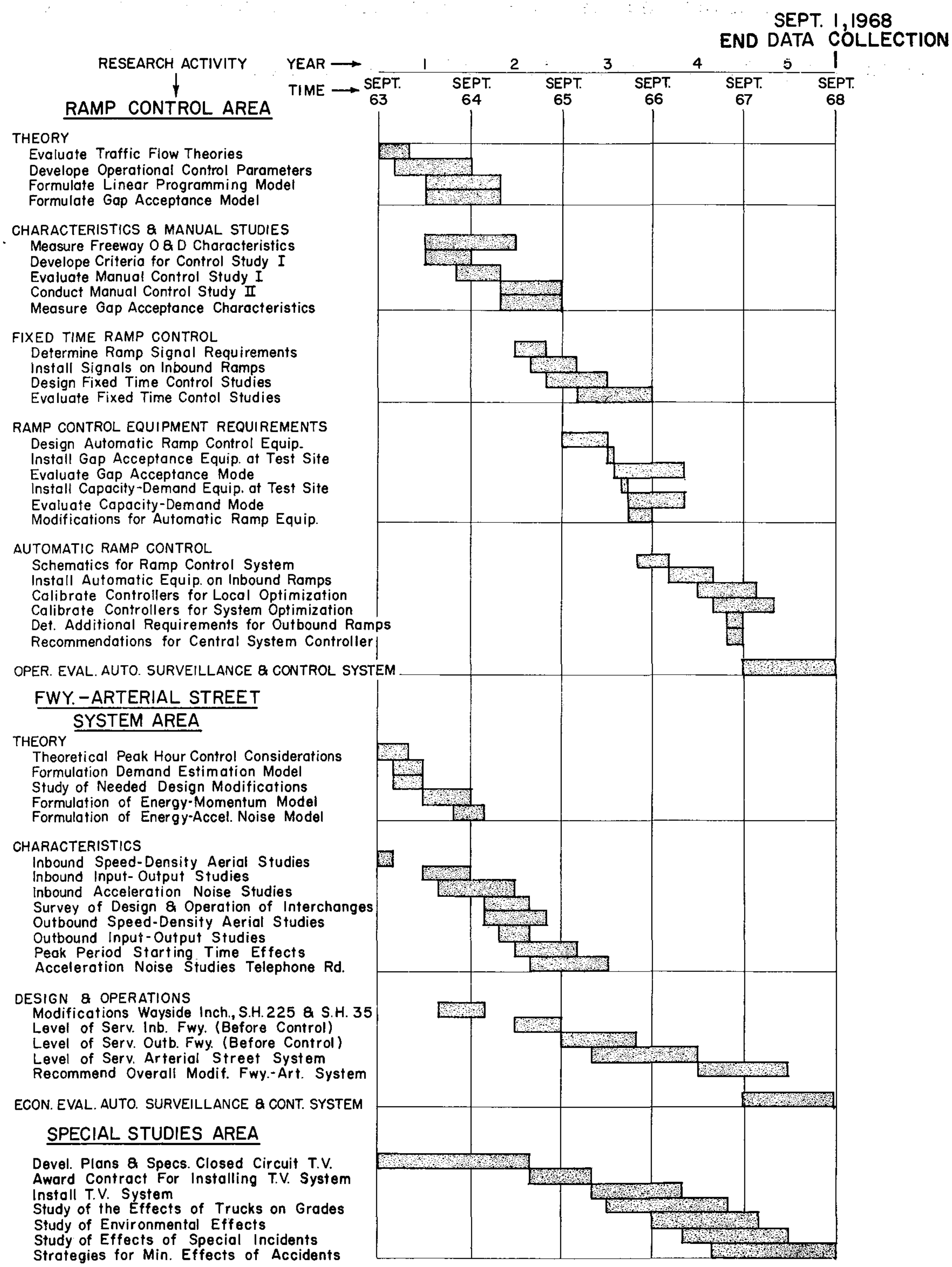
FIGURE 1

either a controlled or uncontrolled nature. Controlled experiments, in traffic research, may be either in the laboratory or in the field. Examples of the former are simulation, both analog and digital; examples of the latter are test tracks such as the one operated by General Motors and to some extent the tunnel and freeway surveillance and control projects identified in the previous section.

The steps in the traffic research process are diagrammed in Figure 1. The implication is that controlled lab experiments are an attempt at solution where other models fail. The controlled field experiments of the test track are useful in evaluating theories but actual validation must be based on real world traffic. The last step and probably the most important is presentation.

The procedure described in Figure 1 has served as a guide in the conduct of research on the Gulf Freeway Surveillance and Control Project. In order to reach the three broad objectives discussed previously, it has been necessary to proceed through numerous studies involving different aspects of the total research problem. The three principal research areas - Ramp Control, the Freeway-Arterial Street System, and Special Studies - are shown in Figure 2 which is the project work plan. The various activities listed in the figure indicated broad research steps that have been taken and will be taken in these three areas.

The organization of the activities of Figure 2 under Theory, Characteristics, etc., clearly indicate deference to the first two axioms -- "Formulation" and "Experiment" -- of the research philosophy depicted in Figure 1. The importance placed on the third axiom, "Presentation," is evidenced by fourteen formal Project Research Reports [4-17] in the three-year duration of the project. In this way, the research effort and results are being fed back to the planners and designers of the next generation of freeway facilities.



WORK PLAN FOR GULF FREEWAY SURVEILLANCE AND CONTROL PROJECT

FIGURE 2

THE EVOLUTION OF RAMP CONTROL CRITERIA

When demand exceeds the capacity of part of a system, there is a self-aggravating deterioration of operation and build-up of congestion. Classical control systems are employed either to make the facility flexible enough to accommodate fluctuations in demand or to reduce the magnitude of the demand fluctuations. Freeway surveillance and control projects are necessarily limited to the latter. One approach, pioneered by the Detroit Project, is to inform the motorist of traffic conditions on the freeway ahead by utilizing land controls and variable speed messages. A second and more positive approach is exercised at the point (the entrance in the case of tunnel control) or points (on-ramps in the case of freeway control) of ingress.

The metering of traffic, the process of controlling the amount of entering traffic to prevent congestion, was developed by the Port of New York Authority. The first step was the identification of the bottleneck at the foot of the tunnel upgrade. Secondly, a mathematical model[18] was formulated to describe the behavior of vehicular traffic in the tunnel. One significant feature of the model was its prediction of shock waves upstream from the bottleneck. The remedy consisted of metering traffic at the entrance of the tunnel (1) to prevent the development of instability by keeping traffic density below some critical value and (2) to keep the traffic demand below the bottleneck capacity.

Based on the success of metering in the tunnel, a similar control plan was formulated for the Eisenhower Expressway by the staff of the Chicago Project. Two bottlenecks on the outbound facility were identified within the study area.[19] The one farthest upstream is caused by a reduction in the number of lanes from four to three without a corresponding reduction in traffic demand. The second bottleneck, further downstream and the last bottleneck on the out-bound expressway, is caused by a combination of fairly high volumes on an entrance ramp which is located at the top of a three percent upgrade of approximately 1,000 feet and the geometric features including the upgrade, a reverse curve and a tunnel effect caused by several closely spaced railroad overpasses.

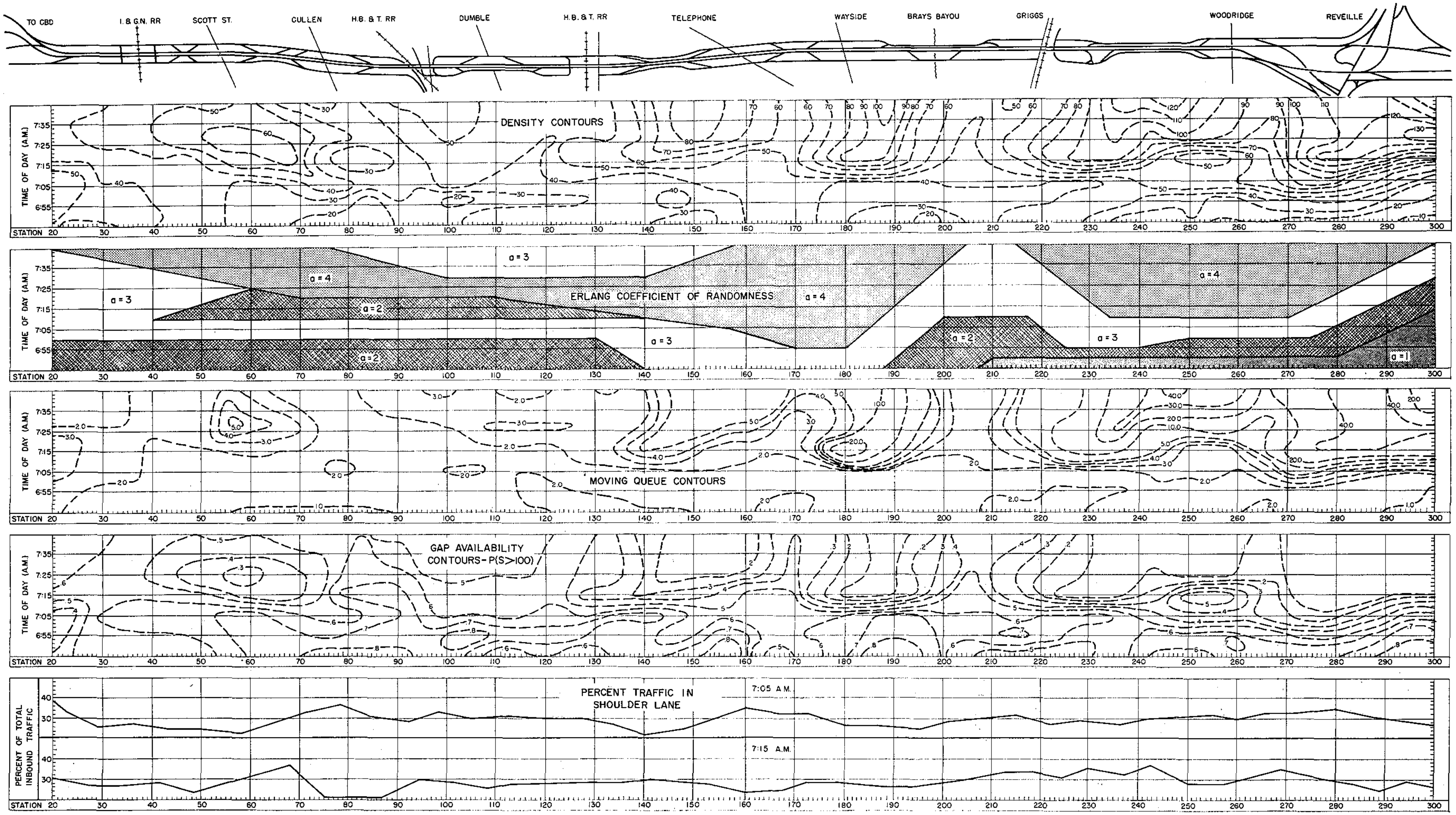
Two metering techniques were developed. One technique utilized a point density or occupancy measurement on the freeway about a quarter mile upstream of the entrance ramp to the metered and the other utilized a volume measurement on the freeway about one-half mile in advance of the entrance ramp. For operational use, the technique based on occupancy was selected in which a value of fifteen percent occupancy in the center lane was used as a control parameter for initiating metering. From a relationship established between the center lane occupancy and the maximum allowable ramp volume, a metering rate was established for various levels of occupancy.

Some researchers who followed the Chicago experiments were more impressed by the use of a freeway capacity-demand ralationship as a control parameter for ramp metering. One of the co-authors (Wattleworth[11, 17, 20]) has long favored this "capacity-demand" criteria in which an individual ramp would be metered according to the difference between the upstream freeway demand and downstream freeway bottleneck capacity. He has also developed a linear programming model in which several entrance ramps in a freeway system could be metered so as to maximize the output of the system subject to constraints assuring that the demand will not exceed the total directional capacity at each freeway bottleneck.[19,20]

In a paper presented in 1963, another co-author (Drew[4, 8, 21]) describes a "moving queues" model based on coordinating ramp metering with the detection of acceptable gaps in the outside freeway lane. An acceptable gap is defined as one equal to or larger than the critical gap (that gap for which an equal percentage of ramp traffic will accept a smaller gap as will reject a larger one) for a merging ramp vehicle. Moving queues or platoons occur when the time headway or gap between successive vehicles is less than an arbitrary "queueing headway." Since the arbitrary queueing headway is taken as the critical gap, the number of ramp vehicles to be metered in some time-constant equals the number of moving queues detected. The average number of vehicles per moving queue, as the reciprocal of the probability of a gap larger than the critical gap, provides a rational index of freeway operation.

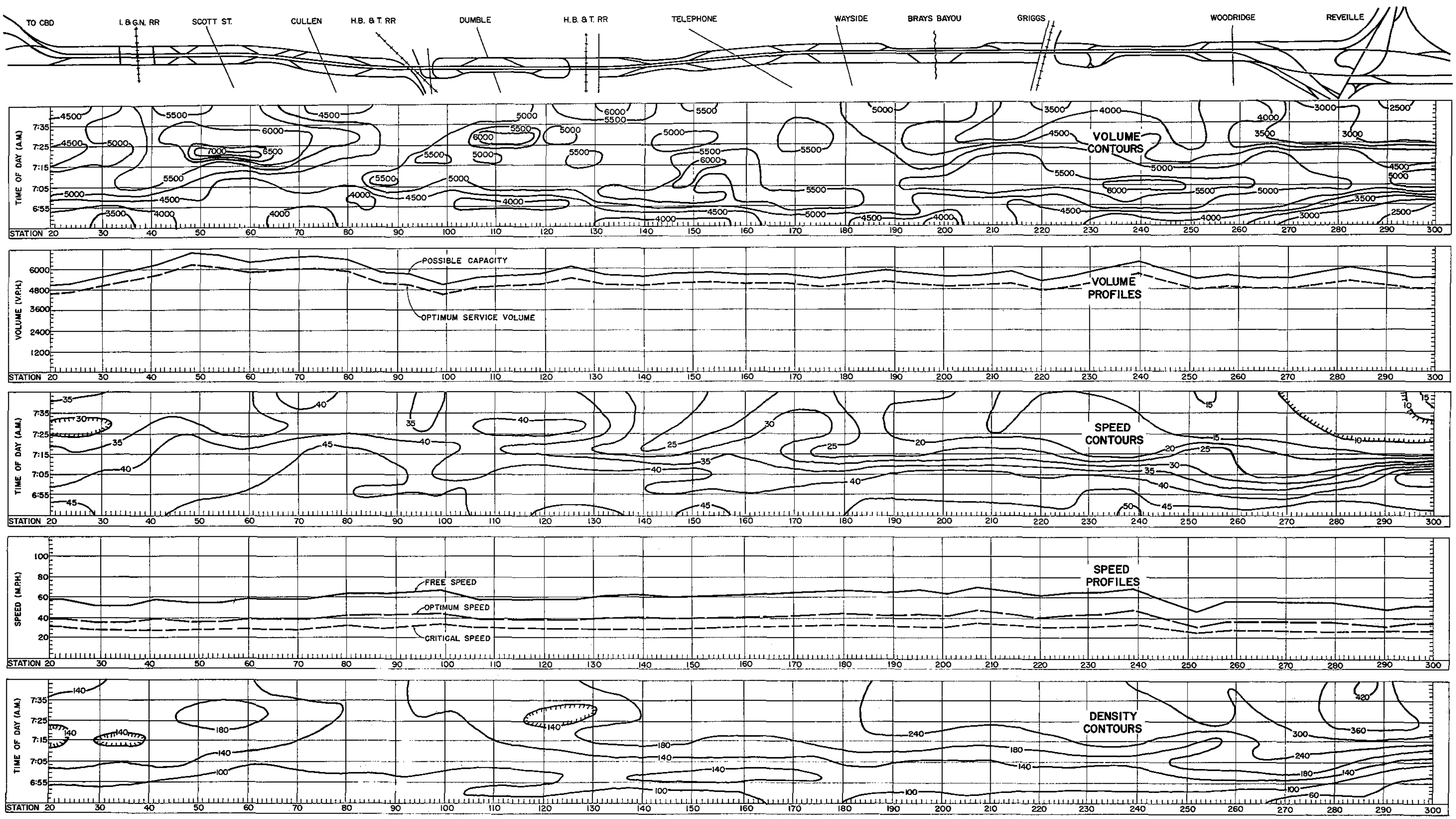
Interesting aspects of the model are the flexibility of metering a single ramp vehicle per available acceptable gap on the freeway (hereafter referred to as the "gap acceptance mode"), or metering ramp vehicles in bunches. The latter -- the "bulk service" technique -- is described in a previous Project Report.[16]

Figures 3, 4, and 5 present summaries of the freeway characterisitics utilized in three promising ramp metering philosophies. The figures apply to the gap acceptance mode, capacity-demand mode for the total freeway, and the capacity-demand mode for the outside lane. The data were obtained from time-lapse aerial photos of the inbound Gulf Freeway during the morning peak period. The various



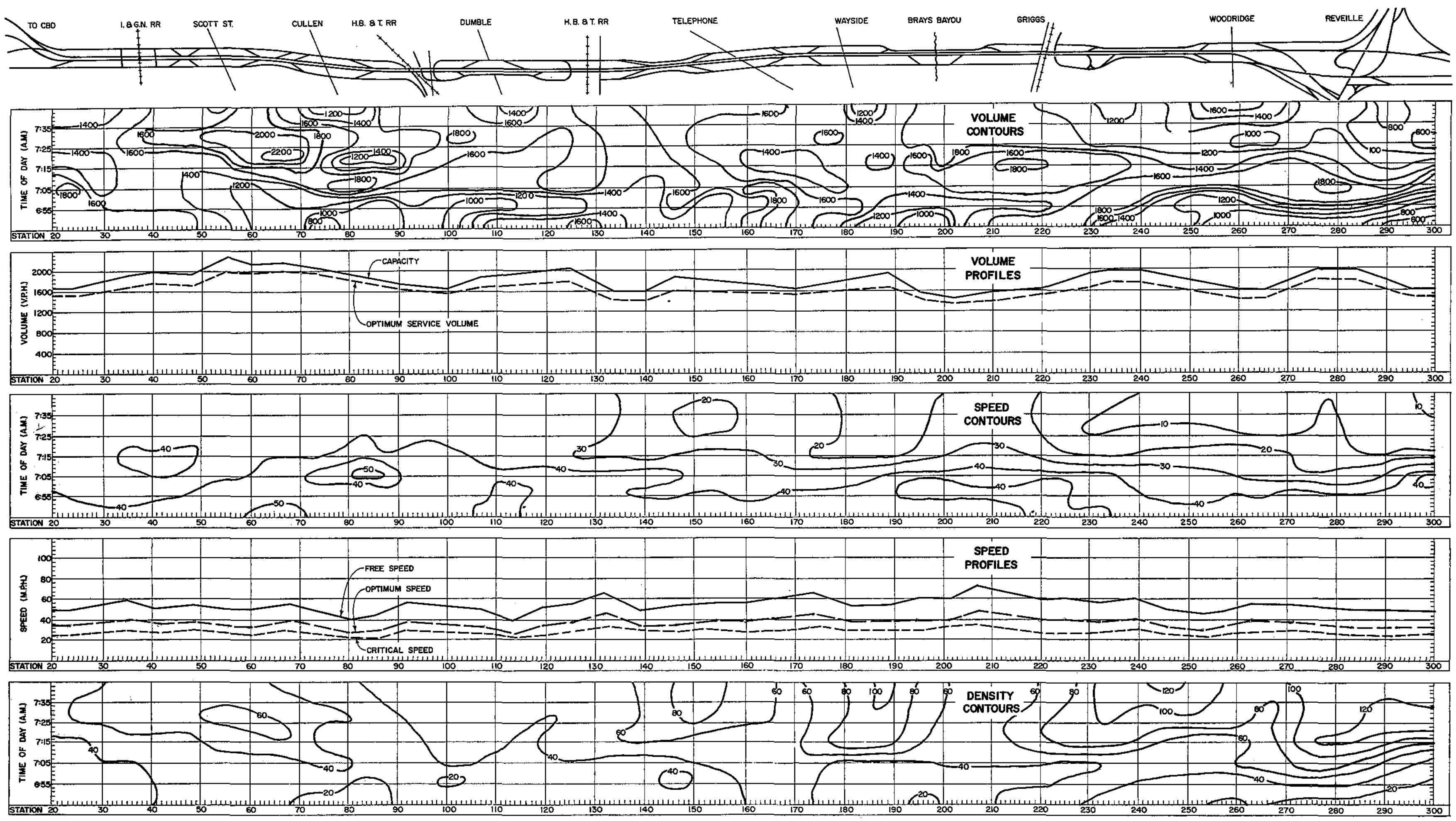
INBOUND DISTRIBUTIONAL CHARACTERISTICS ON SHOULDER LANE

FIGURE 3



CHARACTERISTICS AND CONTROL PARAMETERS FOR TOTAL INBOUND TRAFFIC

FIGURE 4



CHARACTERISTICS AND CONTROL PARAMETERS FOR OUTSIDE LANE

FIGURE 5

"critical" and "optimum" control parameters plotted on the profiles are applications of the "energy-momentum" description of level of service.[14] The operating characteristics summarized in the figures will prove valuable in the calibration of the models and the selection of controller settings for the new experimental ramp control installation which will be described in the following section.

Comparison of Ramp Metering Theories

The concept of metering freeway entrance ramps during the peak periods to improve freeway operations is receiving increasing acceptance among traffic engineers. The real objective (and one which is frequently overlooked) is to operate the ramp controls in a manner which produces the greatest net improvement in operation to the overall system of freeways and arterial streets in the area of influence of the freeway. The net improvement is usually measured in terms of decreased travel time or delay time in the system.

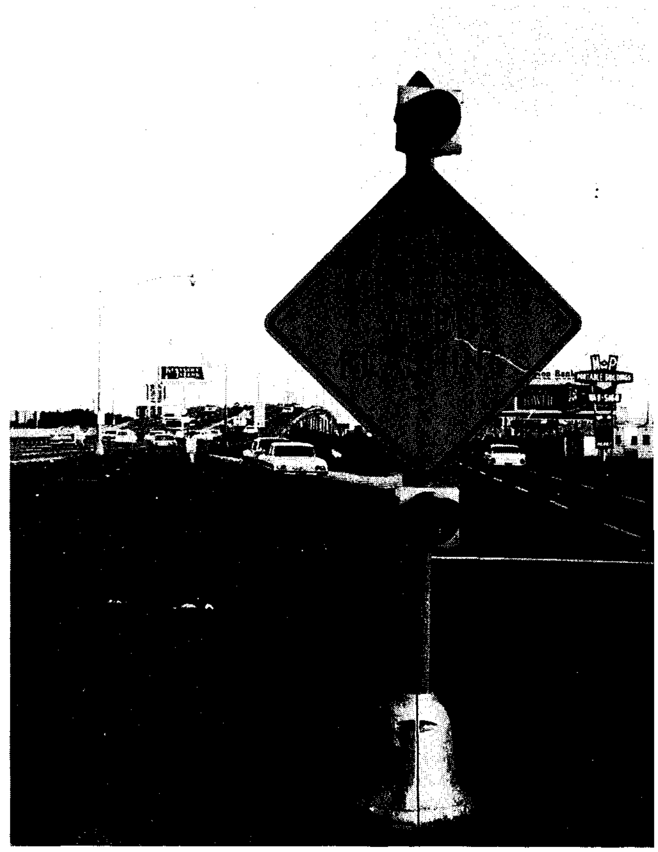
In view of the latter objective of obtaining the best possible operation out of an existing street-freeway system, and the fact that the concept of ramp control has received acceptance, surprisingly little work has been done to determine the control objectives. Some work was done at the Chicago Area Expressway Surveillance Project but this was quite limited in nature.[22] Several early control experiments demonstrated the importance of considering the arterial streets as well as the freeway in evaluating the effects of ramp controls. In each of these control studies, the decrease in travel time on the freeway during the control period was offset or more than offset by a corresponding increase in travel time on the arterial streets.[19, 23, 24] The adverse effect on the arterial streets was attributed in each case to the diversion of large volumes of traffic from the freeway to streets which were already operating near capacity. The benefits caused by the controls are critically dependent on the type of control operation. For this reason it is felt that study of the various control theories has not received its due consideration since the proper control theory is the very essence of ramp control.

Manual Operation of Ramp Signals on Gulf Freeway

Following the two studies of ramp control on the Gulf Freeway using ramp closures and ramp metering by City of Houston policemen, work was begun on the design, installation and evaluation of automatic ramp metering equipment.[13, 16] The first phase of this research was to install at eight ramps traffic signals, and associated advisory signs and signals to which various control equipment could be connected. These installations, shown in Figure 6, were completed on September, 1965.

The signals have been operated daily from 7:00 to 8:00 a.m. on weekdays by the surveillance project staff. Each signal operator is located adjacent to the signal controller and operates the signal with the manual push button as shown in Figure 7. The operator records the ramp volume, queue lengths and signal violations at one minute intervals (see Figure 8). In addition to the eight ramps which are metered two entrance ramps near the downtown end of the freeway are closed during part of the control period and most of the normal entrance ramp traffic uses the frontage road instead of the freeway.

Manual operation of the ramps has provided data on driver acceptance of this type of control, on the effect of ramp metering on freeway traffic flow, and on



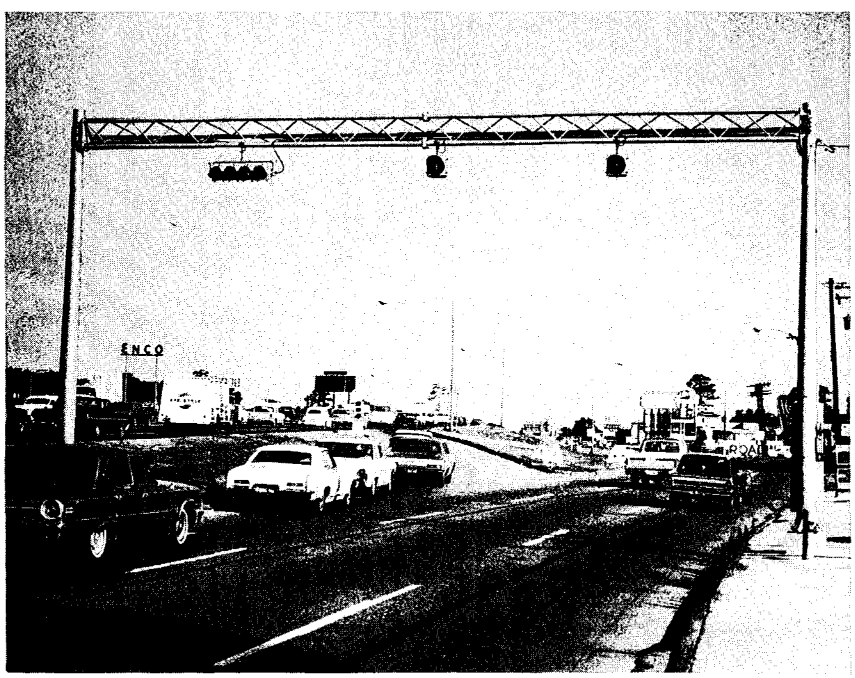


Figure 6. Ramp control sign and signal installations.

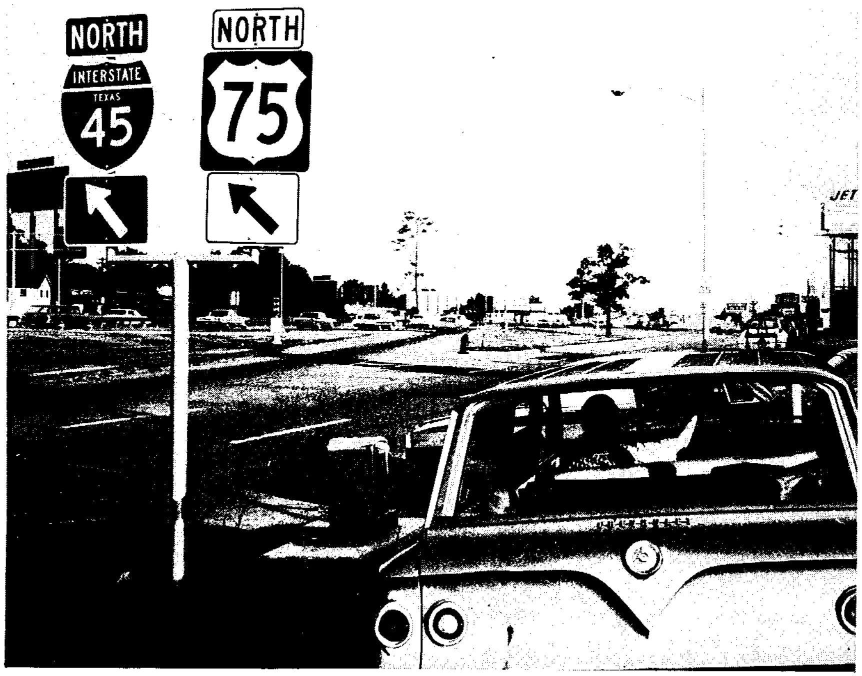


Figure 7. Location of signal controller and operator.

Figure 8. Operation of signals and collection of data.

various characteristics used in the development of the automatic equipment, such as detector locations, ramp traffic travel times, and gap acceptance. Even after the development and installation of an automatic ramp controller on the Telephone Road entrance ramp, it has been necessary to operate the other seven signals manually to maintain control of flow conditions into and out of the Telephone Road study area.

Control Procedure

The initial control plan issued to the operators of the eight inbound ramps was the same as that in Control Study II,[16] which used policemen instead of traffic signals for ramp metering. Fixed time metering rates were scheduled for specific time periods for each ramp. These schedules were developed from capacity-demand relationships obtained on traffic studies conducted during recent months. After the drivers became accustomed to the signals, improvements over Control Study II were noted. These improvements are attributed to two factors: 1) the removal of the policemen who were visible from the freeway lessened the tendency of freeway traffic to slow down in the vicinity of the merging area and 2) better adherence to the control plan was achieved with project personnel. In Control Study II some of the policemen deviated from the prescribed control plan by metering the ramps according to their subjective evaluation of the freeway and ramp traffic conditions.

In addition to the schedule of metering rates, each signal operator was given instructions 1) to reduce the rate if the merging area of the ramp became congested and 2) to increase the rate if the queue formed behind the signal interferes with crossing traffic at adjacent intersections.

As data were collected at the controlled ramps and freeway count stations, the control plan was adjusted to take advantage of changing traffic patterns.

Further improvements have been made at several entrance ramps by making the metering rates dependent on traffic volume counts taken just upstream of the ramp merge area. A capacity-demand procedure, similar to Mode II operation was outlined for four ramps. Freeway counts, made at one minute intervals, are relayed to the signal operators at the downstream ramps by walkie-talkie radios. The operators subtract these demand counts from a nominal capacity assigned to the merge area to determine the allowable ramp volume for the following minute. Maximum and minimum rates are assigned to the ramps to lessen congestion in the ramp merging area and to reduce violations of the ramp signal. The addition of traffic responsive control has improved operating conditions by reducing ramp traffic delays, and improving flow rates over downstream bottlenecks.

PROTOTYPE RAMP CONTROL INSTALLATION

The prototype ramp control installation at Telephone Road was developed and designed by the Automatic Signal Division of the Laboratory for Electronics Corporation according to the operational and performance specifications of the staff of the Gulf Freeway Surveillance and Control Project. This is believed to be one of the first attempts to have equipment developed to perform the required functions rather than to see what functions can be performed with "off-the-shelf" equipment. Although lip service has often been paid to the determination of which ramp metering theory is superior for use in an operational control system, practical considerations have often dictated that "the selection of parameters to be measured (be) tempered by limitations of the manufactured detection equipment available".[2]

The Gulf Freeway Surveillance and Control Project had some advantages in this regard over some earlier freeway surveillance and control projects. The decision was made early in the project's history to separate the surveillance and control functions of the electronic equipment to be installed on the freeway. The surveillance was (and is) accomplished by manual methods, aerial photography and the recently installed closed circuit television system. These means were and are being used for research purposes leading to the development of the final ramp control system design. The Project Work Plan shown in Figure 2 shows that it took more than two years of background work including theory formulation, characteristics measurements, manual studies, and fixed-time ramp control -- before performance specifications for and equipment system for a single automatically controlled traffic-responsive freeway entrance ramp could be written. It would have been much longer except for the technical knowledge and experience provided by the older Surveillance Projects. For example, the metering installation -- the arrangement of the signal and loop detectors -- is similar to the design used in the ramp signals of the Chicago Project. Thus, one detector is used to indicate demand on the ramp and a second will be used to indicate that a vehicle has passed the signal. The experience gained through the use of this equipment at the Telephone Road entrance ramp should permit a rapid development of a control system for the entire inbound Gulf Freeway.

The location of the test installation is the inbound entrance ramp of the Telephone Road interchange on the Gulf Freeway. The equipment assembly produces the following modes of control: Mode I - Gap Acceptance, Mode II - Demand-Capacity, Mode III - Reduced Capacity - Demand and Mode IV - Single Lane Demand - Capacity. The idea of using essentially two controllers (one for Mode I and one for Modes II, III, and IV) will eventually permit comparative analysis and is in keeping with the research orientation of the Project. Each of the modes of operation will be briefly discussed.

Detection Configuration and Override Operation

At the Telephone Road location on the inbound Gulf Freeway, twelve detectors were installed to operate the metering controls on the Telephone Road entrance ramp. The overall configuration of detectors, control signal, ramp, television camera and trailer is shown in Figure 9. A block diagram illustrating operations is shown in Figure 10.

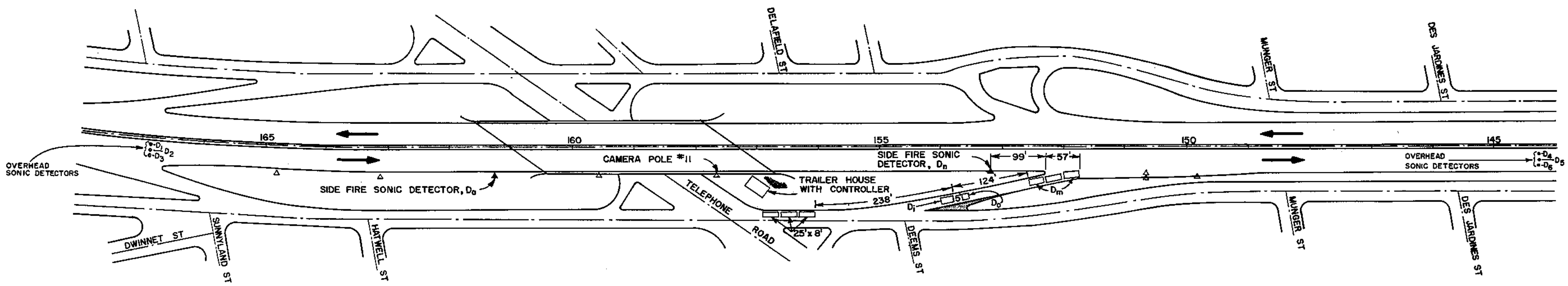
The three overhead sonic detectors, D_1, D_2, and D_3, located about 1,500 feet upstream of the entrance ramp nose are used to determine the freeway demand.

The speeds at the location of these detectors are also monitored.

Two side-fire sonic detectors are located to detect vehicles in the right lane of the freeway upstream of the entrance ramp nose. Detector D_a is located on a luminaire standard 950 feet upstream of the ramp nose and is used to detect gaps in the right lane of the freeway. Detector D_n is also mounted on a luminaire standard and is about 100 feet upstream of the nose. Its primary function is to yield the speed near the merging area and the speeds from this detector are extensively used in the control systems being tested.

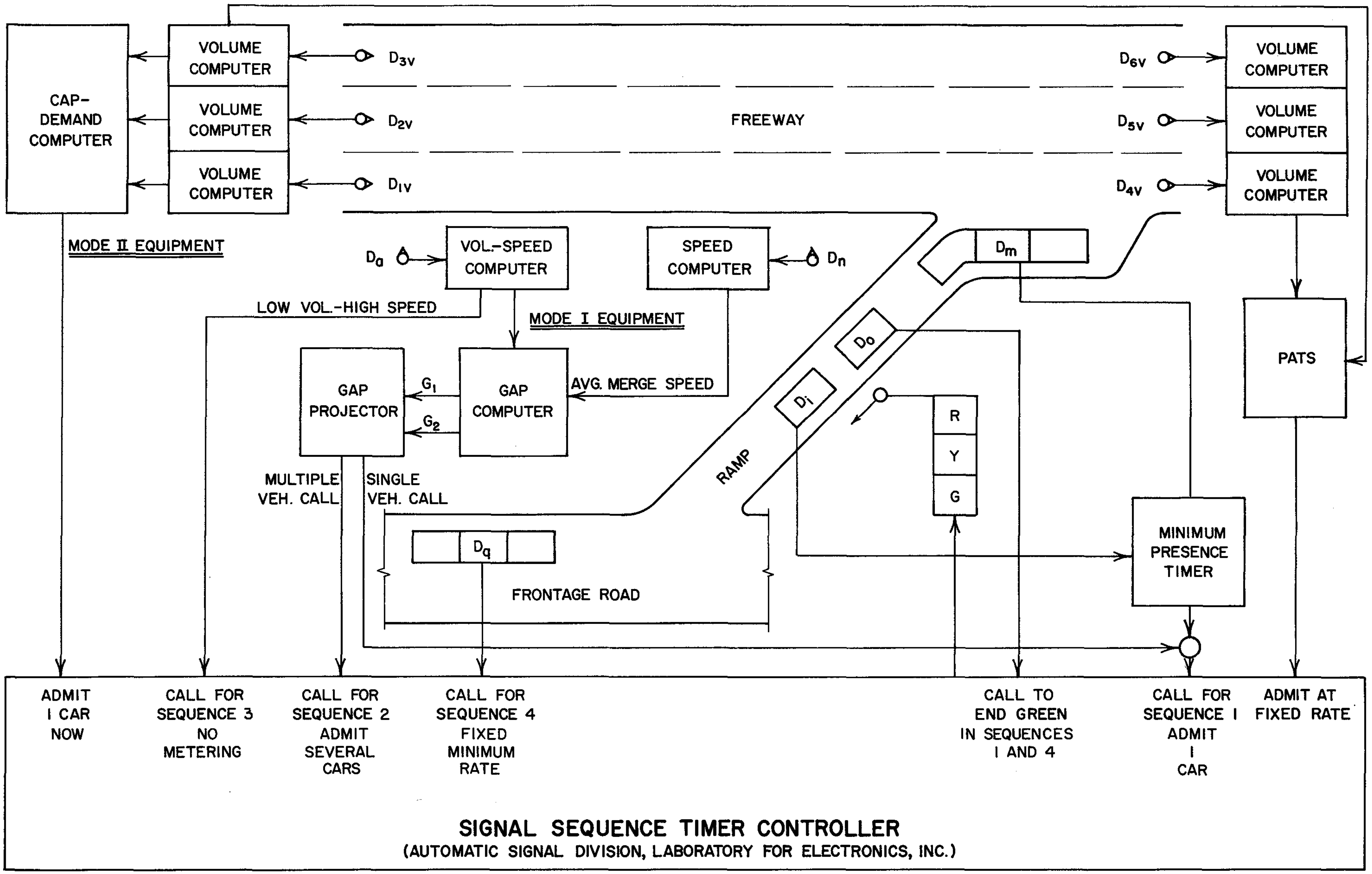
Three overhead sonic detectors, D_4, D_5, and D_6, are located about 850 feet downstream of the ramp nose and are used primarily to detect reduced-capacity operation. Low speeds in this area indicate congestion from a downstream bottleneck. Volume counts at this location can be used to estimate the capacity of the critical bottleneck.

Several detectors are located on the ramp and frontage road to aid the metering operation and this operation is quite similar to that developed on the Chicago Area Expressway Surveillance Project.[19] Two loop detectors are used at the signal location. The upstream detector, D_i, is used to indicate the presence of a vehicle waiting for a green indication at the signal. A green indication of the signal cannot occur without a call being received from detector, D_i. The second detector, D_o, can be used to record signal violations. If a call is received on D_o while the signal indication is red, a violation is counted. Two other detectors provide override operation which preempts the metering rates that would otherwise be called for under Mode I, Mode II or Mode III. A detector (D_m in Figures 9 and 10)



PLAN VIEW OF TELEPHONE ROAD STUDY AREA

FIGURE 9



GULF FREEWAY RAMP CONTROL BLOCK DIAGRAM

FIGURE 10

is located so as to detect vehicles which stop on the acceleration lane. When a call from this detector is held for 5 seconds, indicating that a vehicle is stopped there, the ramp signal is held in red until the vehicle is able to clear the acceleration lane. This feature prevents the development of frequent queues of ramp vehicles in the merging area which lead to poor merging operation and many "false start" type of rear-end accidents.

On some occasions the queue formed at the ramp signal reaches about 14 or 15 vehicles and threatens to back into the Telephone Road intersection with the frontage road. In order to minimize this possibility, a detector (D_q in Figures 9 and 10) is located in the left lane of the frontage road about 350 feet from the ramp signal to indicate when the queue is near the intersection. When detector D_q is occupied by one vehicle for more than 5 seconds a fixed, relatively high (5-600 vehicles/hour) metering rate is employed to reduce the length of the ramp queue. This high metering rate is called for only when there are no vehicles stopped on the acceleration lane and when the speeds on the freeway are above the critical level. In other words, no attempt is made to clear the ramp queue if doing so will cause deterioration of the merging operation.

In addition to the detectors which are used for the operation of the ramp signal, several other detectors are located in the merge area to aid in the research associated with the metering. These are side-fire sonic detectors mounted on poles near the freeway. These detectors are not discussed in detail since they pertain to the research and not ramp signal operation.

When the studies at the Telephone Road entrance ramp have been completed, it is planned to move the equipment to another ramp to avoid any conclusion that may be a result of the particular situation at Telephone Road. A ramp with a higher volume will be selected to determine the ability of each Mode to handle the larger ramp demand.

Trailer Configuration

A trailer located in the outer separation near Telephone Road (see Figure 9) houses the computers associated with the three modes of control, the ramp controller, a closed-circuit television monitor and a 30-channel event recorder. Figure 11 shows a schematic of the computer racks in the trailer. The rack on the left contains the computer equipment for the gap acceptance mode and the signal controller. The rack on the right contains the computer equipment used with the demand-capacity mode and the reduced capacity-demand mode.

A closed circuit television monitor is located in the trailer near the computer racks. Normally the merging operation is monitored to provide a quick, subjective evaluation of the ramp controls and to aid in the calibration of the computers. The pan feature of the camera allows a 350° rotation so the upstream traffic conditions can be checked if it appears that some disturbance has taken place.

The 30-channel event recorder is used to monitor all detector actuations and also records the range of operating speeds at several freeway locations. In addition, it records which of the overrides is in effect and indicates the signal indication. In this way it is possible to tell not only when a vehicle is released at the signal but whether the normal mode of operation or an override caused the release of the vehicle.

When the closed-circuit television system is installed, the ramp control equipment will be moved to the monitor room of the control center to centralize the operations and to better evaluate the freeway operations through use of the T. V. system.

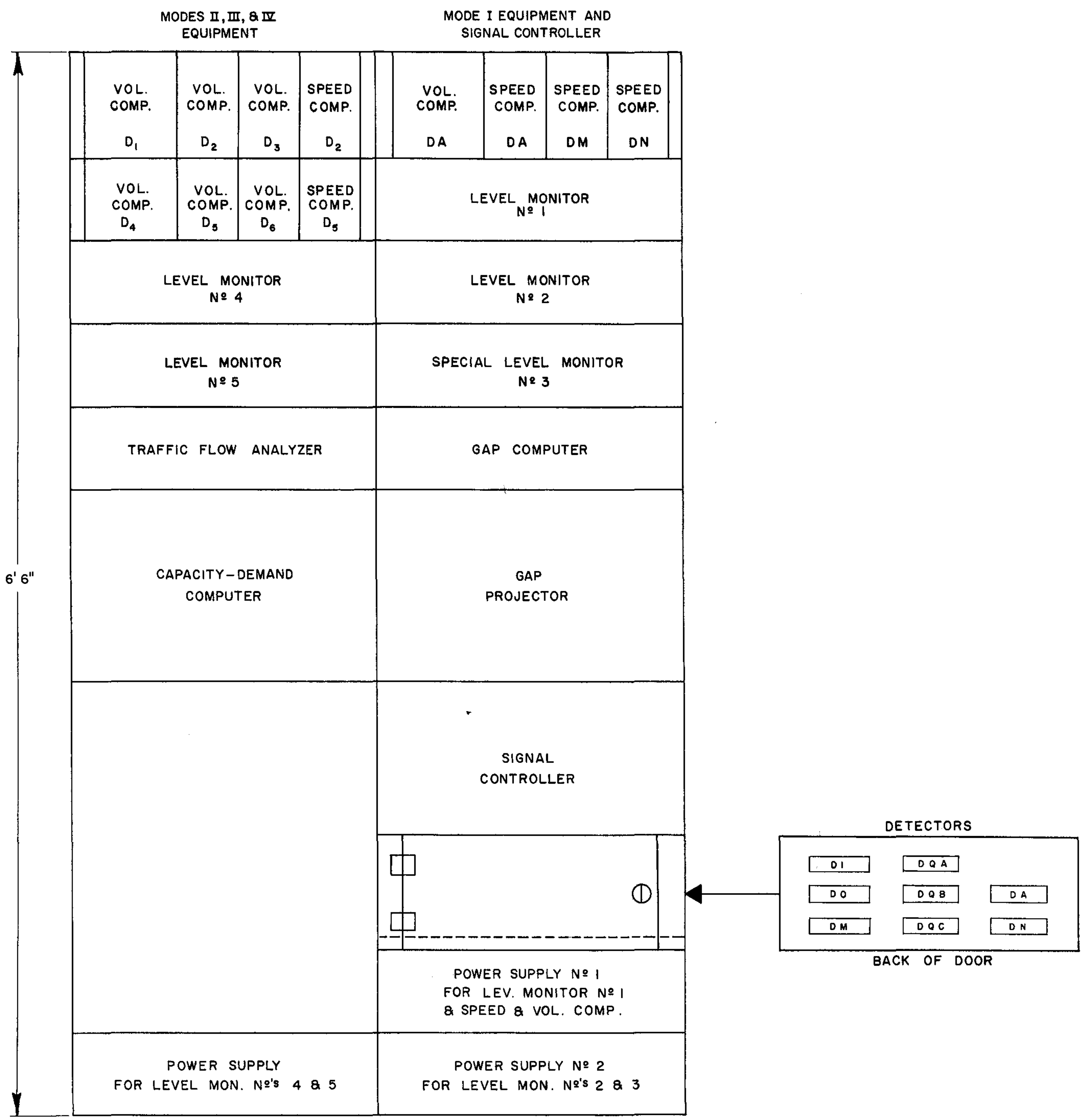
OPERATION OF THE GAP ACCEPTANCE MODE

The Gap Acceptance Merging Control Model, designated Mode I, was installed in March at the Telephone Road inbound entrance ramp. The control of the signal is completely automatic. Loop detectors on both sides of the signal provide the calls for the green and red signals. Control is designed for either single vehicle or multi-vehicle entry.

The control of the ramp signal is accomplished basically by the detection and projection of acceptable gaps. However, the overrides previously discussed provide the basis for control from time to time. The time-space diagram in Figure 12 has been prepared to illustrate the operation of the gap acceptance control mode.

Gap Projection

A sonic detector is mounted in a side fire position on a luminaire standard about 950 feet upstream of the ramp nose (see Note 1 in Figure 12). The detector measures all gaps in the outside lane and calculates the speed of traffic flow (see Note 2 in Figure 12). When a gap is detected that is equal to or greater than the designated acceptable gap size, it is projected in the controller at a rate defined by the vehicle speed in the outside lane. If a ramp vehicle is waiting at the ramp signal, a call for the green signal is made when the projected gap reaches the position in time, designated the decision point, at which the travel time of the gap to the merge area is the same as the travel time of the ramp vehicle from the signal to the merge area (see Note 3 in Figure 12). However, the green signal will not be called if there is a ramp vehicle over the merge detector (see Note 6 in Figure 12).



COMPUTER AND CONTROLLER CONFIGURATION

FIGURE 11

If the gap is equal to or greater than the designated acceptable gap size for more than one vehicle, the controller holds the green signal until the gap passes the decision point (see Note 7 in Figure 12).

Speed of Outside Lane Traffic

A sonic detector is mounted in a side fire position on a luminaire standard at the nose of the entrance ramp. The detector measures the speed of traffic flow, which is used to select the size of the acceptable gap.

Other Aspects of Operation

A background cycle rate, set on the fixed rate control, is put into effect as a supplement to the normal metering controls. The signal continues to release vehicles when acceptable gaps are available, but it also releases vehicles after a specified maximum waiting time. The difference between this rate and that called by the queueing detector is that the background cycle rate is a minimum setting, in the range of 150 to 200 vehicles per hour. The queueing override takes precedent over the background cycle rate.

Many aspects of merging operation pertinent to the gap acceptance mode are illustrated in Figure 12. For example, notes 8, 9 and 10 describe lane changes. Whereas a lane change from the outside lane upstream (Note 8) usually means that an available acceptable gap will not be filled by a metered ramp vehicle, a lane change to the outside lane upstream (Note 10) usually results in a ramp vehicle being metered into less than an acceptable gap. Observance of operation at the Telephone test facility over the past 4 months indicates that these lane changes in the area between the gap detector and the nose are not frequent enough to be of any consequence.

The "occupancy of the merge area" override feature, explained in a previous section, is depicted in the time-space diagram (Figure 12, Note 6) in conjunction with a violation by a ramp vehicle (Note 5). Such violations are rare; approximately 95% of the ramp drivers comply.

General Comments on the Gap Acceptance Merging Control Model

The significance of the Gap Acceptance Merging Control Model lies primarily in its conceptual appeal. Note the use of the term "merging control" rather than "ramp control" in describing the model. The Gap Acceptance Mode is the only metering system that microscopically aids the ramp driver in the merging maneuver. This is important and shall be explained in more detail.

When the volume of traffic on a freeway begins to approach capacity, the merging driver is sometimes placed in an extremely difficult position. The number of acceptable gaps in the freeway stream decreases sharply as the freeway volume increases. At these higher volumes and especially on entrance ramps with poor geometric designs, the merging driver cannot always defer his decision to merge until he is on the acceleration lane. Rather he must detect the location of gaps in the oncoming stream before he reaches the acceleration lane. Operating this way, he must then project the location of a gap onto the acceleration lane in order to decide whether or not it will be available to him. This in turn requires he estimate his own speed and acceleration as well as the speed of the gap in order to decide whether there will be sufficient space for the merging maneuver to be completed successfully with the limit of the acceleration lane.

Michaels and Weingarten[26] do not think it is possible for the driver under these circumstances to reliably solve the appropriate equations of motion. They state:

> "It is obvious that as the main stream volume approaches capacity, the merging driver's task becomes for all practical purposes impossible. Thus, effective ramp metering will require the equations of motion to be solved automatically whenever a vehicle enters a ramp. Mathematically, the problem is quite simple requiring a knowledge of the location of gaps and their speed. Knowing something about the accelerating capability of the ramp vehicle and the length of the ramp and acceleration lane, a perfectly determinate solution is possible. Instrumentation to carry out these operations is well within the state of the art of existing electronic technology."

The gap oriented system installed at the Telephone Road interchange does locate freeway gaps and their speeds; it compares these gaps to a "critical gap" which is the size gap required by the ramp drivers for merging; it does take into account the acceleration capability of the ramp vehicle and the length of the ramp and acceleration lane; and it does solve the equations of motions automatically before the metering signal is actuated to allow a vehicle, or vehicles, to make a smooth merge. In addition of increased efficiency, other factors are improved -

safety and higher ramp capacity for a comparatively low cost on installation.

Considering safety, any speed differential at a point in the traffic stream in either a longitudinal or transverse direction is dangerous. A vehicle that stops in a travel lane is in particular danger; it is a safety hazard to the remaining traffic, to its driver, and to its occupants. This is indicated by the high percentage of accidents that are of the rear-end type occurring at induced stop and yield locations such as in the freeway merging area. The Gap Acceptance Mode virtually eliminates ramp vehicles stopped in the merging area, thereby contributing greatly to safe operation.

The Mode I metering system affords the opportunity for increased ramp capacity over some other metering models. In systems which meter ramp vehicles one at a time, the ramp capacity is obviously a function of the ramp cycle length. Since it takes about four seconds to go through the ramp signal cycle - the maximum metering rate is at a rate of one vehicle ever four seconds or 900 vph. The Mode I system can meter at a faster rate because it has the flexibility to meter more than one ramp vehicle whenever large freeway gaps are detected.

The proposed gap oriented merging control system is relatively inexpensive because only the outside lane of the freeway is sensed for characteristics rather than all the freeway lanes. Moreover, since time is one of the simplist variables to measure, the detection of acceptable gaps can be obtained with a comparatively simple analog device.

In conclusion, the Gap Acceptance Mode Provides the merging driver with the necessary information to know that a sufficient gap is available. Second, because of its nature, it is automatically a metering system. Such a dynamic merge aiding and metering technique appears to be a very attractive and inexpensive way of maintaining high efficiency of flow on a freeway and at the same time of obtaining high ramp capacity and merging safety.

OPERATION OF THE DEMAND-CAPACITY MODE

The second mode of automatic ramp metering which is being evaluated at the Telephone Road entrance ramp is the demand-capacity mode. Many facets of its operations are similar to those of Mode I. The same basic signal operation is used; two loop detectors on the ramp indicate 1) the presence of a vehicle waiting at the signal and 2) the passage of a vehicle past the signal. The controller preempts also operate in the same manner in Mode II as in Mode I; namely, 1) when a ramp vehicle stops in the merging area, the ramp signal remains red until the vehicle merges, 2) a background cycle which defines the maximum waiting time at the signal is also used and 3) when the queue of vehicles at the ramp signal has a length of 14 or 15 vehicles, a preset high metering rate is used.

Under Mode II control, the metering rate on the ramp is adjusted according to the freeway demand rate so as to keep the total merging rate less than capacity (or service volume) (see Figure 13). In this way, freeway congestion can (theoretically) be prevented since demand is kept less than capacity.

Estimation of Capacity

In Mode II the limiting capacity is the total (3-lane) directional capacity. For an entrance ramp of substandard design, the capacity may be the capacity of the actual merging section. For a well designed entrance ramp, the merging capacity may be greater than that of a downstream bottleneck or of the downstream freeway.

Detailed freeway operational studies can be used to locate the actual bottleneck. Counts at the bottleneck are used to estimate the capacity. In spite of that fact that the demand rate is computed over a very short time period (approximately 15 seconds) the capacity is based on 15-minute counts and this provides some factor of safety. The capacity settings can also be altered through experience gained operating the signal.

Estimation of Demand

The freeway demand or flow rate on the freeway approaching the merging area is obtained from three overhead, sonic detectors located 1,500 feet upstream of the entrance ramp nose. In this way the total approach flow in the three lanes is determined. Also, the length of contact closure when a vehicle is detected is used to estimate the vehicle's speed and from this the speed of the traffic stream is estimated.

The contact closures from the demand detectors cause signals to enter an analog computer (Figure 11) which computes the running average demand rate. The averaging time must be based on other critical times in the system and in this case is quite short (about 15 seconds).

This demand rate is the rate at which demand is approaching the merge area on the freeway. If the merge capacity or other limiting capacity is known, the difference between the capacity and demand is the rate at which "available capacity" is approaching the merge area (see Figure 13). This "available capacity" can be used by vehicles from the entrance ramp. The time headway between the release of successive vehicles from the ramp signal is obtained by integration of the demand-minus-capacity function. When this integral equals one an available capacity of one vehicle is approaching the merge area and a vehicle is released (see Figure 13) unless one of the override functions is in effect.

One feature of the demand-capacity mode, then, is that it assures that over long periods of time the merging demand will not exceed the limiting capacity.

General Comments on the Demand-Capacity Metering Control Model

Like the gap acceptance model, the demand-capacity merging model has a great deal of conceptual appeal. Since congestion develops at a bottleneck when the demand exceeds the capacity there, it seems quite natural and logical to control freeway entrance ramps so the demand at each point in the system does not exceed its capacity.

At an entrance ramp which has a poor geometric design the merging capacity may be lower than the capacity of adjacent freeway sections. In these cases a control scheme concerned only with the merging operation might be successful (except in reduced-capacity situations). However, at an entrance ramp with good geometrics the merging capacity seldom is the governing capacity since a ramp of this kind can merge vehicles at a higher rate than that which can be maintained under stable flow downstream.[27,28] Also at many locations curves, grades, lane reductions or other geometric features can create bottlenecks between ramps. For these circumstances the actual (downstream) capacity would be used in the Mode II operation rather than the capacity of the merging area itself.

Total directional volume (or flow) is the only traffic measurement which satisfies the continuity equations[11,20] (input equals output plus storage) and is, therefore, the only measurement useful in systems considerations.[17,20] If the freeway controls are to be operated to optimize (or at least to try to optimize) the operation of a system it will be necessary to use total flow measurements related to demands and capacities in all parts of the system for control purposes. The use of control parameters other than total directional flow can necessarily be directed to operation in a relatively small area and are not well suited for systems purposes.

At the present time the Mode II operation at Telephone Road is exclusively of the single vehicle entry type. Under normal conditions the metering rate is high enough to avoid the formation of lengthy queues. However, for application to entrance ramps with higher demand volumes any one of several systems for metering several vehicles at a time could be used. For example when the freeway volume decreased below a predetermined level it would be possible to integrate the capacity minus demand function until a two vehicle available capacity were obtained and the green time on the ramp signal would automatically be altered to allow two vehicles to pass the metering signal.

An average of two additional detectors per entrance ramp would be required to operate Mode II (and Mode III) compared to Mode I operation. This additional cost (which is a fairly minor part of the overall detection and control equipment cost) permits system control analysis.

Similarity of Modes I and II

There is a great deal of conceptual similarity between Mode I or gap acceptance operation and Mode II or demand-capacity operation. Both use a single control parameter and use various overrides to the metering to respond to temporary problems associated with the metering operation. The control parameter associated with Mode I is the acceptable gap and the operation in the merging area and on the freeway is a function of the value of the critical or acceptable gap used for control purposes. If an extremely small value of critical gap is used, vehicles will either accept some extremely small gaps thereby generating frequent shock waves in the merging area or many vehicles will reject their gaps and will be forced to stop to wait for a large gap. If a large value of critical gap is used, the merging operation will probably be very good since few vehicles from the ramp will be released to the freeway. The delay to vehicles on the ramp, however, would naturally be higher for higher values of critical gap.

Similarly for Mode II the control parameter is the three-lane capacity. For higher capacity settings more vehicles would be released from the ramp to the freeway causing some smaller gaps to be accepted and more gaps to be rejected and generally leading to a lower level of service in the merging area. A higher level of service in the merging area can be obtained by using a lower capacity setting thereby allowing fewer vehicles from the ramp to enter the freeway. Under either mode of operation a high merging level of service can be achieved at the cost of higher delay to vehicles on the ramp or a low ramp delay can be achieved at the cost of reduced merging level of service.

The basic conceptual difference between the two modes is that Mode I is more microscopic than Mode II. Under Mode I operation a gap on the right freeway lane is selected for each ramp vehicle and the signal is operated so as to try to match the ramp vehicle to its gap. The success of this matching depends upon the stability of traffic flow between the detection point and the merge point and upon the stability of ramp travel times between the ramp signal and the merging area. Mode

II is a more macroscopic approach. A vehicle is released from the ramp signal when a unit of capacity is detected on the freeway. No attempt is made to match the vehicle to a particular gap. In fact, the unit of capacity may be in the left lane and the merging takes place in the right lane. It is assumed for Mode II operation that lane changing will be accomplished to reach the lane distribution on which the capacity value was based.

OPERATION OF THE DEMAND-ADJUSTED CAPACITY MODE

In Mode II normal operating conditions on the freeway are presupposed and only the metering override features can be used to adjust the metered flow rate to reduced-capacity operation such as that found during periods of inclement weather, accidents or stalled vehicles. Such occurrences are quite frequent, however, and a metering system must make provision for them if the freeway system is to be operated in an optimal manner under prevailing conditions.

Mode III utilizes the demand-capacity operation similar to the operation under Mode II with the exception that the assumed merging capacity can automatically be reduced in the event of special occurrences which reduce the downstream freeway capacity. This is done essentially by lowering the horizontal capacity line in Figure 13. The amount this capacity is lowered is a function of the magnitude of the capacity reduction on the freeway.

Reduction of Speed at Downstream Detection Station

A downstream capacity reduction can be detected by a decrease in speed downstream. When the speeds in the center lane at the downstream detection station (detector D_5) fall below 30 mph for more than 5 seconds a capacity reduction is applied to the nominal capacity setting (usually 5900 vph). The capacity reduction is an on-off function and can be set at any value up to 3000 vph.

Reduction of Speed at Ramp Nose and at Upstream Detection Station

A capacity reduction in or near the merging area can be detected by speed reductions at both the ramp nose (D_n) and at the upstream detection station (D_2).

The capacity used for the ramp control is reduced by a fixed, preset amount when the speeds at both of these locations fall below a predetermined level (usually set at 30 mph) for a critical time period (usually 5 seconds). A range of speed settings as well as the critical time setting is available and the capacity reduction can be set on any amount up to 3000 vph.

Reduction of Speed in Ramp Merge Area

The speed of vehicles from the ramp which are merging (detector D_m) can be placed in 9 ranges and there can be a different capacity reduction (up to 1000 vph) associated with each speed range. Thus when a freeway incident makes the merging maneuver more difficult for the ramp vehicles, the reduced merging speeds lead to a reduction of the capacity value used for the controls.

Density Increase

The detectors located on the ramp and freeway define a closed system.[20] The input rate to the system can be obtained from the upstream detection station (D_4, D_5 and D_6). When the capacity downstream of the entrance ramp is reduced, the output rate decreases before the input rate decreases while the density in the system increases. Thus, the storage rate (input rate minus output rate) can provide an indication of a reduced-capacity situation. In addition the output rate can be used to estimate the reduced capacity.

The Mode III equipment monitors the freeway input rate (D_1, D_2 and D_3) and the freeway output (D_4, D_5 and D_6) when the input rate exceeds the output rate by more than the critical amount for a critical length of time (perhaps 30 seconds) a reduction is applied to the controlling capacity. The reduction can be up to 3000 vph.

Projection of Discontinuities in Traffic Flow[29]

Barker[29] has shown that under stable flow, discontinuities are projected downstream at a rate dependent on the speed of traffic. A high volume (or low volume) wave can be seen to pass two detection stations and the times between passage of the waves at the two points are equal to the travel time between the points. When the capacity is reduced at a point near the downstream location, this wave propagation pattern is changed due to storage of vehicles between the in and out sections.

The Traffic Flow Analyzer* detects discontinuities of flow in the center lane (this could be changed to include all lanes) of the freeway. It operates in much the same manner as the Density Increase (input minus output) correction factor. At present the Traffic Flow Analyzer examines the flow in only one lane whereas, the Density Increase correction factor is based on the flow in three lanes. Also the Traffic Flow Analyzer offsets in time the input flow pattern by an amount equal to the travel time between the input and output detectors. Thus, the output flow is compared to the flow that is projected to that station from the input station. When the input falls below the output by a certain critical amount for a critical period of time (both adjustable) a reduction is placed on the capacity used for control purposes.

Possible Future Modifications of Mode III Equipment

Under present Mode III operation most of the reductions applied to the control capacity are on-off functions. When certain conditions are met a certain correction

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*This equipment was conceived of and developed at its initiative by the Automatic Signal Division of the Laboratory for Electronics, Inc.

is applied. It appears to be desirable to have the amount of the capacity reduction be a function of the severity of the problem causing it to be called. For example if a 100 vph input minus output rate for a minute period is deemed critical and the conditions are met, the correction factor would be called. However, if the input minus output were 500 vph for a minute a larger correction factor would seem appropriate.

When the downstream capacity is reduced the counts at the downstream detection station (D_4, D_5 and D_6) can be used to estimate the new capacity.[17] At the present time the equipment cannot automatically adjust the downstream capacity according to the downstream counts under reduced capacity operation. This can be done manually by adjusting the nominal Mode II capacity but automatic operation is more desirable.

OPERATION OF SINGLE-LANE DEMAND-CAPACITY MODE

In Mode IV the capacity of the merging (right) lane is the control parameter and the difference between this capacity and right-lane demand upstream of the ramp is integrated to obtain the release time of vehicles on the ramp. The operation of Mode IV is identical to that of Mode II except that single-lane demand and capacity are used instead of the lane demand and capacity.

GENERAL DESCRIPTION OF CONTROL EQUIPMENT OPERATION

Comparison of Various Modes of Operation

Gap acceptance equipment for Mode I operation was installed at Telephone entrance ramp in March, 1966, and Demand-Capacity equipment for Mode II and Mode III operation was installed in June, 1966.

The controls on the equipment provide a wide range of readings in order that these same controllers can be used at other ramps with different geometric designs and traffic conditions. For each of the two controllers, a basic set of dial settings were established from data taken at the ramp prior to the signal installation. After several days of operation, the initial settings were refined based on subjective evaluation to provide more efficient traffic flow.

Thereafter, data for both Modes I and II were collected on alternate days. It should be stressed at this point that comparisons made at this time are based on the control settings outlined below. The characteristics of the two modes of operation can and will be changed by changing these controls in subsequent studies.

Mode I Operation

The minimum cycle length for Mode I is approximately 4 seconds. In most cases, the minimum recycle time is usually determined by the D_o detector at the signals which must be cleared before a green signal can be given.

The minimum acceptable gap settings which have been used to date are as follows:

D_n Speed MPH	Acceptable Gap Sec.
+55	2.7
50-55	2.5

(cont'd)

D_n Speed MPH	Acceptable Gap Sec.
45-50	2.3
40-45	2.1
35-40	2.2
30-35	2.4
25-30	2.6
20-25	2.8
15-20	3.0

D_n speed is an average of 10 vehicles and the speed of an individual vehicle is based on the length of time the sonic detector is activated.

The fixed rate setting which acts as a background cycle has a rate time out of 25 seconds. This time is reset when the green signal is actuated. The guaranteed rate setting which is called by the queue detector being occupied has a cycle time of 6 seconds.

Travel time from the signal to the merge area is assumed to be 10 seconds.

Mode II Operation

The minimum cycle length for Mode II is approximately 6 seconds. A fixed capacity setting of 5,900 vehicles per hour has been used to date. The volume computers are set on a twenty-second average. The same guaranteed rate and fixed rate settings used for Mode I apply for Modes II and III.

Mode III Operation

On occasions it was necessary to reduce the capacity settings of Mode II. To accomplish this, the correction factors dependent on D_5 speed, D_n speed and input minus output volumes were used. These preliminary settings were:

D_5 speed less than 40 MPH reduces capacity 120 VPH

D_n speed less than 40 MPH reduces capacity 120 VPH

Input minus output volume greater than

300 VPH reduces capacity 120 VPH

Ohter reduction factors such as D_m speed, D_n speed change and PATS have not been tested.

Mode IV Operation

To date the ramp controls have not been operated on Mode IV.

General Comparison of Operation

Four weeks of operation, alternating daily between Mode I and II, was completed with settings on the controller as outlined. Basic differences in operation were noted based on these initial controller settings:

1) Ramp Volume - The peak hour volumes were higher during Mode II operation. This indicated some traffic diversion during the Mode I operation due to generally lower metering rates.

2) Signal Violations - Mode I operation resulted in a higher percent of signal violations. This is probably due to the irregular pattern of operation and the longer delay in the ramp queue.

3) Merge Detector - The merge detector was occupied a greater number of times for a longer length of time under Mode II operation due primarily to the higher meteringrates at some times when the outside lane has a high rate of flow.

4) Queue Detector - Mode I had a greater number of queue detector calls as a result of lower metering rates.

5) Mode II operation has a more uniform distribution of time headways of vehicles leaving from the signal because the continuous changing of demand on the freeway is not so abrupt as to result in a highly irregular vehicle departure pattern on the ramp. Mode I is dependent on the distribution of gaps which result in metering rates that range from 1 each 4 seconds to 1 each 25 seconds, that can occur at any time.

6) When slowdowns are projected through the study section, Mode II metering rate is increased due to the decrease in detected upstream demand, causing more vehicles to call in the merge detector.

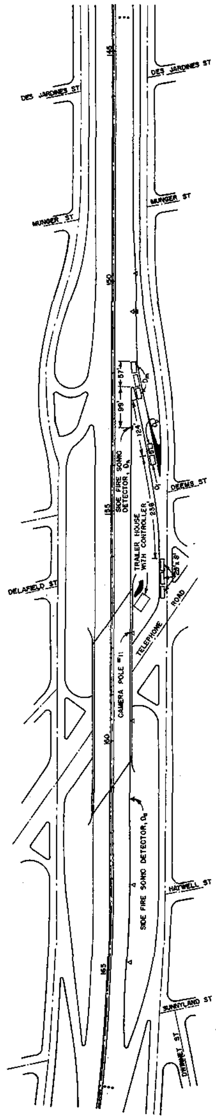
7) When shock waves are projected through the study section, the gaps projected from the D_a detector in the Mode I controller do not move on the roadway in the same relative position as will during free flow. The result is that when the shock wave is between the merge area and the D_a detector the ramp vehicles are not able to match their projected gap.

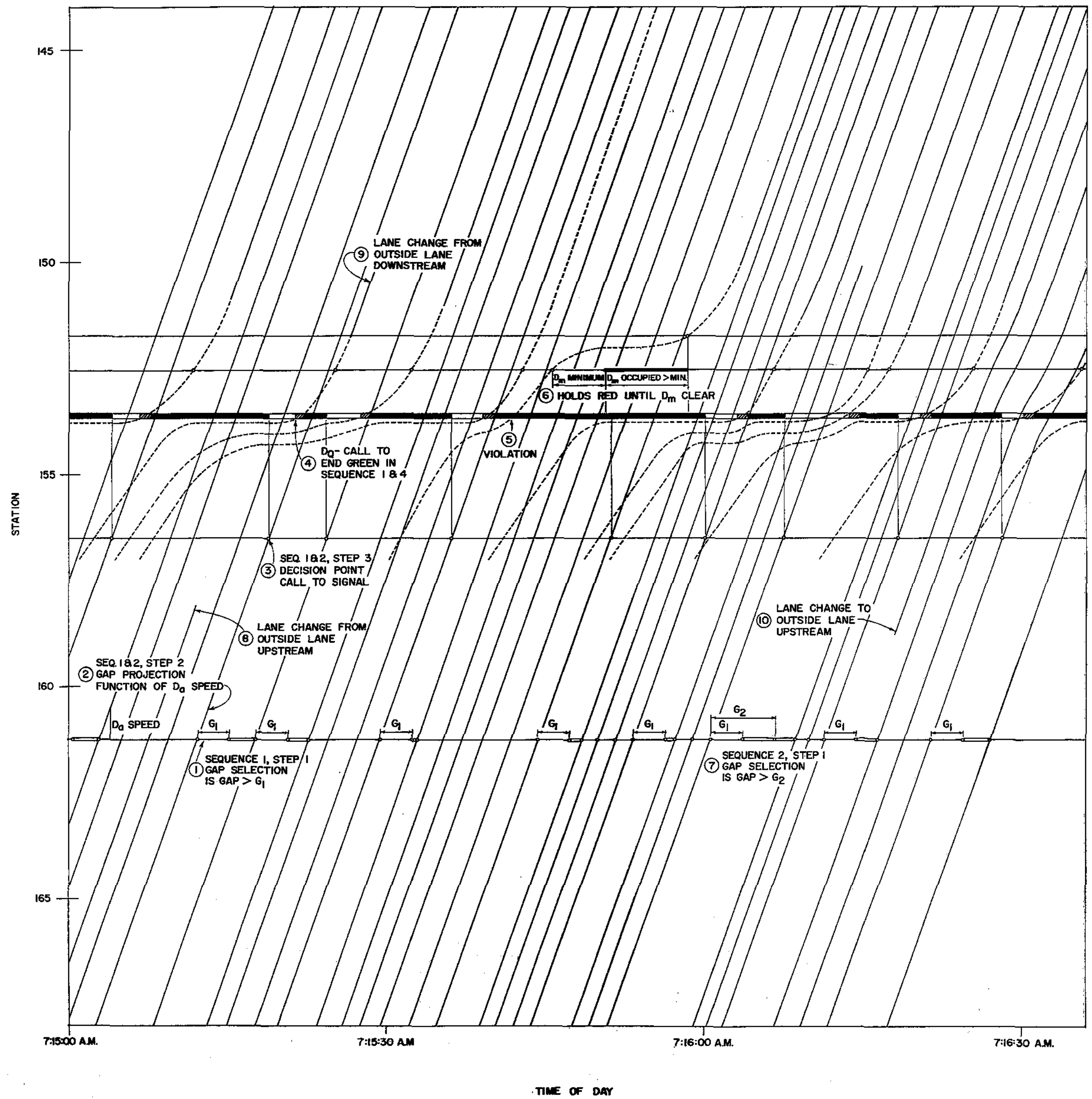
8) Travel times from the ramp signal to the merge area are lower for Mode I than for Mode II, indicating an easier merging maneuver for Mode I.

DIRECTION OF FUTURE RESEARCH

The report has described the equipment installation by which a ramp can be metered on the basis of any one of four ramp metering theories. During the next year one major phase of the work on the Gulf Freeway Surveillance and Control Project is the evaluation of the conditions under which each metering theory is best. In order to fully evaluate all theories it is anticipated that the operation of the signal at Telephone Road will be evaluated when the metering rate there will be based on the percent occupancy in the center lane which is the technique being used in Chicago.[19, 22, 30] Plans are being made to obtain equipment so that this mode of operation can be fully evaluated on the Gulf Freeway.

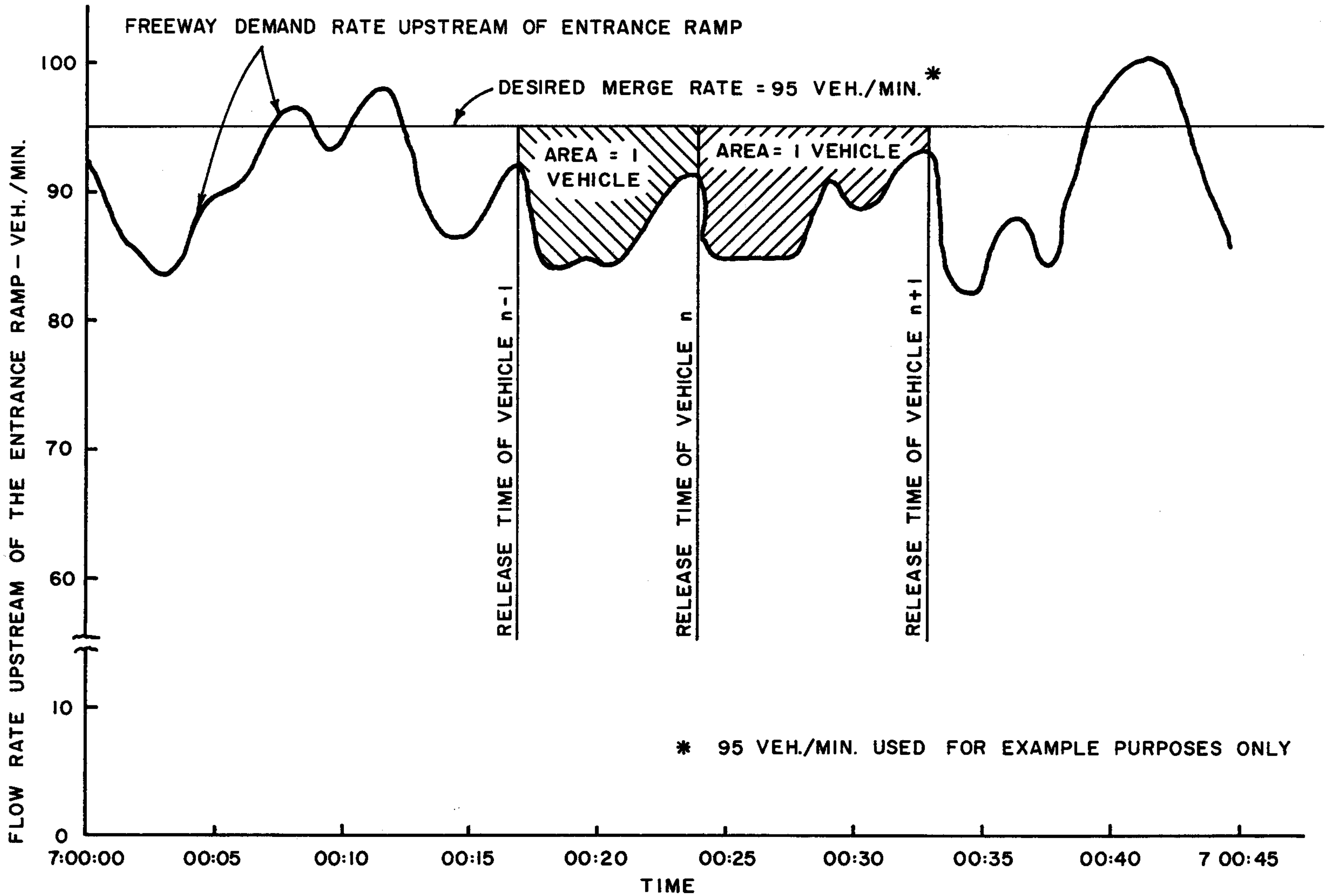
During the year the ramp metering signal system for all entrance ramps on the entire inbound Gulf Freeway will be designed and hopefully installed. The system design must naturally depend on the outcome of the earlier research on the different modes of control. By the latter part of 1967 it is anticipated that the entire system of signals for the inbound Gulf Freeway will have been installed and will be operating.





TIME-SPACE DIAGRAM ILLUSTRATING OPERATION OF GAP ACCEPTANCE RAMP METERING MODE

FIGURE 12



RELATIONSHIPS AMONG FREEWAY DEMAND RATE, DESIRED MERGE RATE AND RELEASE TIMES OF VEHICLES FROM THE RAMP SIGNAL

FIGURE 13

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