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16. Abstract

The digital computer control of a small network of traffic signals near the Gulf Freeway is described. The design and development of the traffic control system theory, software, and hardware are presented. Three types of traffic control strategies were implemented and evaluated. These were existing pretimed, progressive pretimed, and progressive traffic responsive control. Progressive traffic responsive control produced the most effective results.

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COMPUTER CONTROL OF THE WAYSIDE-TELEPHONE ARTERIAL STREET NETWORK

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Research Report 165-3

Development of Urban Traffic Management and Control Systems

Research Study Number 2-18-72-165

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ABSTRACT

The digital computer control of a small network of traffic signals near the Gulf Freeway is described. The design and development of the traffic control system theory, software, and hardware are presented. Three types of traffic control strategies were implemented and evaluated. These were existing pretimed, progressive pretimed, and progressive traffic responsive control. Progressive traffic responsive control produced the most effective results.

KEY WORDS: Traffic control, computer control, intersection control, diamond interchange control, traffic operations, frontage roads.

DISCLAIMER

The contents of this report reflect the views of the authors who are responsible for the facts and accuracy of the data presented herein. The contents do not necessarily reflect the official views or policies of the Federal Highway Administration. This report does not constitute a standard, specification or regulation.

SUMMARY

This report describes an initial research study of a digital computer traffic control system located in the Gulf Freeway corridor in Houston. Four intersections were controlled by an IBM 1800 digital computer. Two of the intersections were conventional intersections and two were diamond interchanges located at the freeway. The design and development of the traffic control system theory, computer software and system hardware are presented and control results evaluated.

The primary objectives of this study were to implement computer control and to compare the performances of progressive pretimed and progressive traffic responsive control with the present isolated pretimed control. Additional study requirements were that the control system have real-time control capabilities and be able to implement special traffic control strategies for favoring freeway traffic diverted along the frontage roads.

The efficient control of traffic in this small, four intersection network, located along Wayside Drive, Telephone Road, and the Gulf Freeway is very important to the overall movement of traffic in the Gulf Freeway corridor. Traffic volumes are heavy during the morning and evening rush hours with a large amount of truck traffic. The computer control of the two diamond interchanges in the network provided an additional challenge.

Existing pretimed control was duplicated and implemented by the computer control system from February until May of 1972. Progressive pretimed signal control based on new manually collected data was

implemented from June until September. With the completed installation of the network's 33 traffic detectors to measure traffic volumes, progressive traffic responsive control began in September and was run on a nearly continuous basis until February of 1973.

As a result of this research, the real-time control of a small network of traffic signals has been successfully accomplished with the cooperation and support of the Texas Highway Department and the City of Houston. The technology for the coordinated computer control of complex diamond interchanges has been developed and implemented. More specific findings are:

1) The average overall travel time was reduced 28 percent by using the progressive traffic responsive computer control system as compared to the existing pretimed control system.

2) The progressive traffic responsive computer control system showed an 11 percent reduction in overall travel time when compared with progressive pretimed control using recent traffic data. A favorable benefit-cost ratio of 2.03 would result.

3) Real-time traffic responsive computer control under heavy volume conditions requires an accurate measure of the true demand existing on each intersection approach if excessive delays are to be avoided.

4) Diamond interchanges can be interconnected and controlled to favor and progress frontage road traffic.

Implementation

This report describes the traffic control software and hardware systems used to control diamond interchanges and normal traffic signals using an IBM 1800 digital computer. The system was implemented on the Wayside-Telephone network adjacent to the Gulf Freeway from February, 1972, until February, 1973. Computer control is presently continuing.

Based on the successful operational results of this Wayside-Telephone network computer control system and recognizing the need for highly efficient traffic control at other diamond interchanges along the Gulf Freeway, it is recommended that other diamond interchanges along the Gulf Freeway be brought under centralized traffic responsive computer control. It is further recommended that serious consideration be given to providing frontage road progression capabilities for all diamond interchanges having continuous one-way frontage roads in urban areas. More specific to the study area, the implementation of a digital minicomputer traffic control system is recommended at the Scott, Cullen, Griggs, and Woodridge diamond interchanges located along the Gulf Freeway.

Recommendations for Further Research

1) The effectiveness of lane occupancy for measuring demand under all loading conditions should be investigated.
2) Studies should be conducted to determine how rapidly existing traffic flow conditions should be updated in real time.

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THE CONTROL SYSTEM STUDY

Scope of Study

This report describes an initial research study of a digital computer traffic control system located in Houston. The study design, control strategies used, system design, and control results are presented and evaluated. This study was conducted by the Texas Transportation Institute, Urban Transportation Systems Program, and the Texas Highway Department in cooperation with the Federal Highway Administration and the city of Houston.

Study Objectives

The primary objectives of this study were to implement computer control and to compare the performances of two types of computer control a) progressive pretimed control and b) progressive traffic responsive control with the present isolated pretimed signal control. An IBM 1800 computer was used as the control computer. The study was conducted from September, 1971, until February, 1973. Additional study requirements placed on the computer control system were that it have real-time control capabilities and be able to implement special traffic control strategies for favoring freeway traffic diverted along the frontage roads.

Considerable effort and consideration were given to the design of this computer traffic control system study. However, it was an initial effort and was implemented with a minimal budget and with existing field traffic control equipment. Besides the basic positive results obtained in the study, much knowledge and understanding were gained by the study staff, Texas Highway Department, and city of Houston personnel on the design and operation of computer traffic control systems.

Study Area

Four intersections were selected for this initial computer control effort in view of their importance to the effective movement of traffic within the Gulf Freeway corridor. As shown in Figure 1, two of the intersections are conventional intersections and two are diamond interchanges located along the Gulf Freeway. Thirty-two traffic, detectors, thirty loop and two radar detectors, were installed by the city of Houston throughout the network during the study. When all the detectors were installed about midway through the study, an estimate of existing traffic volume counts on a minute by minute basis could be made for each approach to each intersection. Figure 1 also shows the locations of the detectors. Approaches having no detectors required volume estimations from other upstream detectorized approaches.

In general, traffic volumes in the network could be classified as heavy during the morning and evening rush hours. A considerable amount of truck traffic travels this area going to and from the Port of Houston. Additionally, this area could be described as being the mobile home sales center of Houston. Traffic flow is frequently impeded by the delivery of large mobile homes.

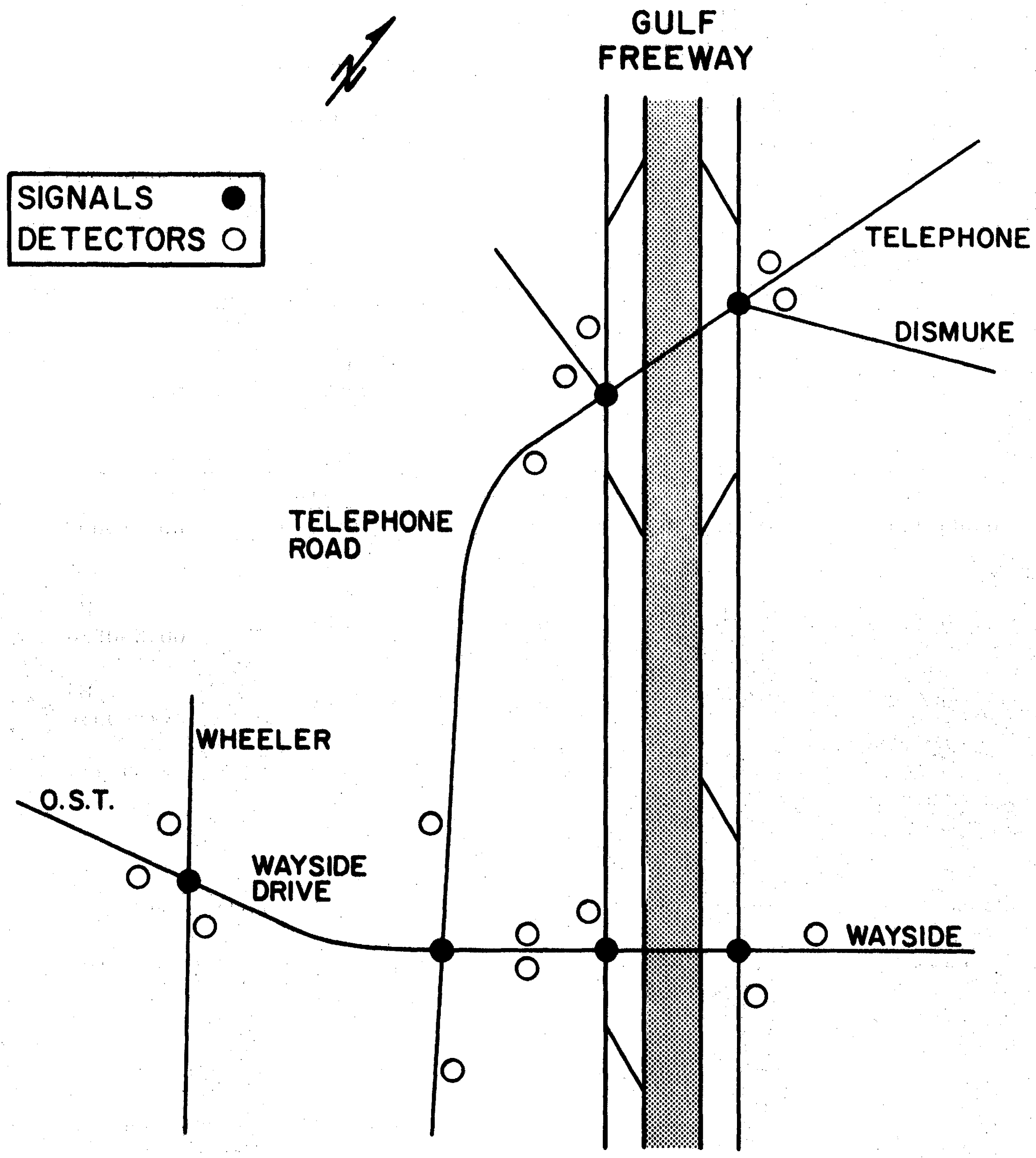

FIG. 1 – LOCATION OF SIGNALS AND DETECTORS IN THE WAYSIDE – TELEPHONE STREET NETWORK

TRAFFIC RESPONSIVE CONTROL STRATEGY

Overview

The traffic responsive control strategy used in this study will be presented as implemented on the IBM 1800 computer. Since existing traffic control hardware at the intersections was used, basic remote control of the traffic signals was effected by advancing the cam of each pretimed controller. Thus, the signal phase sequence at each intersection was fixed and was not changed from that normally existing.

A computer program was written to determine the desired cycle length, phase splits, interval lengths, and offsets of the progressive intervals for the intersections. A new set of splits, phase lengths, and offsets was computed every six minutes or 1/10-th of an hour during traffic responsive control.

Cycle Length

Several factors were considered during the development of a method for computing the system cycle length. The Gulf Freeway-Wayside diamond interchange can operate with a 70 second cycle length during the peak periods whereas the Gulf Freeway-Telephone diamond cannot because of the additional phase on one side due to a diagonally intersecting street. Table 1 shows the existing pretimed cycle lengths of the four basic intersections as established by the city of Houston.

As can be seen in Table 1, the cycle length normally varies from 70-80 seconds during the peak hours and ranges from 60-70 seconds during the off-peak hours. An analysis of the Gulf Freeway-Telephone diamond interchange indicated that it could not satisfactorily operate at a cycle length less than 65 seconds due to the four phases existing on one side. Since most of the intersections operate at 75 seconds during the peak periods, this cycle length was selected as the design cycle length during rush hour traffic conditions.

Table 1

Cycle Lengths in Seconds for AM, PM and Off-Peak Traffic Flow as Used by the City of Houston

Condition	Gulf-Wayside	Wayside-Telephone	O.S.T.-Wheeler	Gulf-Telephone
AM 6:30-8:00	70	70	75	80
PM 4:00-6:45	75	75	75	80
Off-Peak	60	60	60	70

The method selected for computing the cycle length is based on the volumes that exist at a particular point in time. When the volumes reach the peak hour levels, a cycle length of about 75 seconds will result. During very low traffic flow, a cycle length of about 65 seconds will result. The range of allowable cycle lengths is from 65-80 seconds. A maximum change in cycle length of five seconds is permitted from one six-minute update to the next.

Phase Splits

The percentage of time allocated to each phase is in direct proportion to the percentage of the total intersection critical lane volumes that exist on each phase. That is,

$$G_p = \frac{V_p}{\sum_{p=1}^{n} V_p} \times C \qquad (1)$$

G_p = green time for phase p in seconds

V_p = critical lane volume for phase p during last six minutes

C = cycle length in seconds

n = number of phases at the intersection

Regardless of the traffic volume existing on a phase, each phase must be at least a minimum length of time. The minimum lengths presently selected, the sum of green, amber, and all-red (if present) are given in Table 2. The minimum lengths vary depending on the importance of the phase, pedestrian crossing times, and other considerations.

Table 2

Minimum Phase Lengths in Seconds

Movement*		Gulf-Wayside	Wayside-Telephone	O.S.T.-Wheeler	Gulf-Telephone
	1	15	10	30	18
East	2	13	15	12	11
Side	3		15	12	13
	4	20			22
	1	15			14
West	2	13			
Side	3				13
	4	20			22

*See Figure 2

Diamond Interchange Control

The control philosophy used at the two diamond interchanges is the standard four-phase with overlaps (1, 2). Figure 2 illustrates the movements involved in four-phase operation. The distribution of green times depends basically on the distribution of demands as given by Equation 1. The mathematical description of the four-phase operation is straight-forward. For each side of the diamond interchange in Figure 2, the following equations must hold:

For side W

$$G_{W1} + G_{W2} + G_{W3} = C \qquad (2)$$

and for side E

$$G_{E1} + G_{E2} + G_{E3} = C \qquad (3)$$

where G_{W1} is the green plus amber for the inbound arterial phase W1, etc., and where C is the cycle length. The phase overlap is accounted for using

$$G_{W3} + G_{E3} = C - 0 \qquad (4)$$

where 0 is the sum of the offset or overlap times from G_{W1} to G_{E3} and G_{E1} to G_{W3}. Equation 4 is evaluated first, followed by Equations 2 and 3.

The left turns at the W and E sides of the diamond interchange, G_{W3} and G_{E3}, are computed from

$$G_{E3} = \frac{V_{W1} + V_{W2}}{V_{W1} + V_{W2} + V_{E3} + V_{E4}} [C - 0] \qquad (5)$$

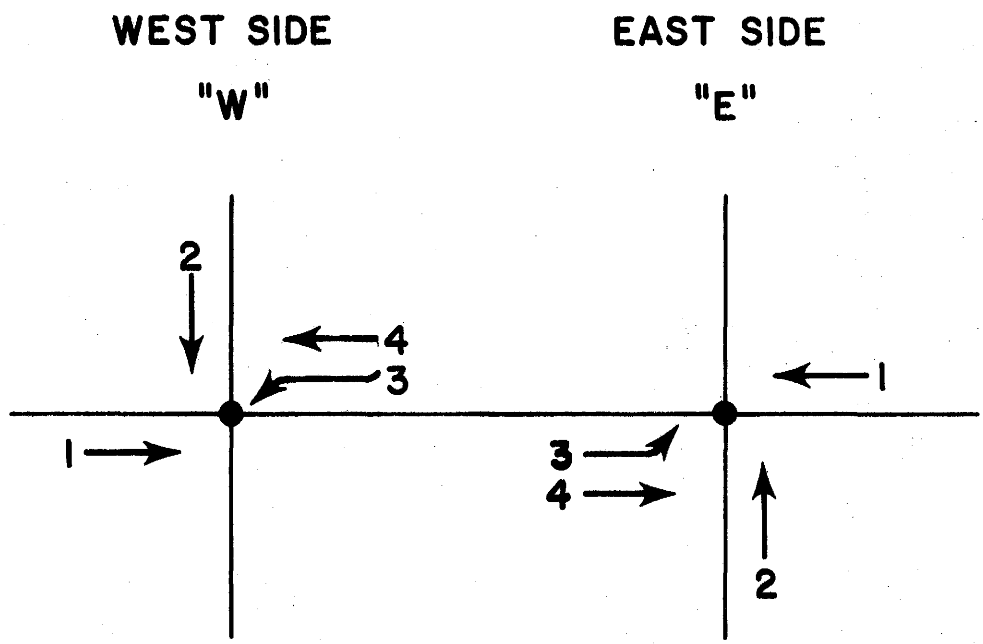

FIG. 2 — TRAFFIC MOVEMENTS AT A CONVENTIONAL DIAMOND INTERCHANGE

subject to

$$M_{W1} + M_{W2} - 0 \leq G_{E3} \leq C - M_{E1} - M_{E2} \quad (6)$$

and

$$M_{E3} \leq G_{E3} \leq C - 0 - M_{W3} \quad (7)$$

leaving

$$G_{W3} = C - 0 - G_{E3} \quad (8)$$

where M_{W1} equals the minimum green for phase 1 of the W side of the interchange (as given in Table 2), etc.

Signal Progression

In general, good progression can be provided in both directions along O.S.T.-Wayside and along Telephone Road, with slightly better progression at the lower cycle lengths of 65-70 seconds. This is simply due to the existing geometry of the network. Travel time studies were conducted to determine the desired offsets between intersections as operating conditions changed. It should be noted that two-way progression is normally provided through each diamond interchange and between the Gulf Freeway-Telephone interchange and the Wayside-Telephone intersection.

Incident Conditions on Freeway

The two diamond interchanges at the Gulf Freeway were selected with an objective of having the capability of providing a high level of service to frontage road traffic when freeway-to-frontage road diversion occurs during incident conditions on the freeway (3, 4). This high level of service is not possible with present control.

The control program is capable of providing a large amount of green time to either the inbound or outbound Gulf Freeway frontage roads. In addition, progressive movements can be provided along either the inbound or outbound frontage road when desired. For this network, however, a considerable offset shift of approximately one-half cycle is required to install frontage road progression patterns relative to normal operations.

HARDWARE SYSTEM DESIGN

The hardware system design is presented before the computer programming software in an effort to clarify the software design. The hardware system includes the transmission system, detection system, and the method of computer-to-field controller communications. Also included are error detection devices, control center displays, and computer hardware used for data acquisition and control.

Transmission System

The transmission system connects the IBM 1800 computer to the field controllers and vehicle detection equipment. The transmission system consisted in part of buried multiconductor cable, owned by the Texas Highway Department, which extends along the freeway. The city of Houston installed overhead cable to the two intersections that do not touch the freeway. Leased time division multiplexing equipment was used on the cable to provide additional transmission channels.

Detection System

The detection system, consisting of 32 volume (pulse) and/or occupancy (presence) detectors, includes both radar and loop detectors. Each loop detector is composed of an inductive loop and amplifier unit. The loop is 6' by 6' and consists of three coils of No. 14 gauge insulated wire placed in the pavement. An amplifier unit in a nearby cabinet is connected to the leads of the loops. An oscillatory circuit is calibrated according to environmental and electrical conditions.

As the vehicle enters the electromagnetic field of the loop, or as a vehicle passes through the field of the radar detector at a speed greater than 3 MPH, a shift in the phase of the circuit causes contact closure in a relay. This relay closure is sent by the transmission system to the computer which records the closure and translates it into a vehicle passage.

Computer to Controller Communication

The signal control program uses two hardware control lines to drive each controller in the field. One end of each line is connected to an electronic-contact-operate device, or ECO, at the computer. An ECO consists of 16 solid state switches controlled by computer instruction. Each switch activates or deactivates a bit, which is a binary digit having a value of 0 or 1. The computer determines the appropriate bit pattern, consisting of 0's or 1's, to operate the controllers. The bit pattern is used by the ECO to close a selected relay contact for a 1 bit and open the contact for a 0 bit. When the contact is closed, a circuit is formed transmitting +24 volts to the controller. When the 0 bit is present at the ECO, no voltage is sent to the controller. Figure 3 illustrates a sample ECO bit pattern. This status bit pattern remains the same until a new pattern is needed to effect a change in phase at one of the intersection controllers.

0 0 0 0 1 0 1 1 0 0 1 0 0 0 0 0

4 Contacts Closed, 12 Open

Figure 3 - ECO BIT PATTERN

The other ends of the control lines are connected to relays in the field controllers. The first control line carries +24 volts to close a relay in the controller. This action disconnects field control and allows the digital computer to drive the drum portion of the controller. The drum is a bank of cams that opens and closes contacts in the signal lamp circuits as it rotates. Each time the computer applies voltage on the second control line, or advance line, for 400 milliseconds, then releases it, there is a drum advance with a resulting change to the next signal phase.

There are two hardwire confirm lines from a controller to the digital computer. Each time the drum advances, the voltage of the first return line changes. This voltage alternates between +0 volts (ground) and +24 volts. The voltage is +0 volts when the first main street green interval is on and, each time the drum advances thereafter, it changes to the alternate voltage. The second return line sends +24 volts to the computer when the main street green phase is on and transmits +0 volts the rest of the time. In this way, interval lengths, cycle lengths, and offsets may be measured by the computer.

During control, the signal control program, INTER, senses whether an output voltage from the ECO device actually changes the status of the controller by monitoring these confirming return voltages. In the case of no confirm received, a 400 millisecond pulse on the advance line is sent by the computer for a second time before control is dropped back to the field controller.

Error Detection Device

There are also other situations which require control to be returned to the field controller. These situations are detected by an error detection device external to the computer. A contact on the ECO, described earlier, emits a 5-cycle per second signal of +24 volts. The signal control program, INTER, controls this signal pulse. If the field controllers are under digital control and there is a power failure, hardware failure, or program failure, the controllers would remain in their present status indefinitely. For this reason, a failure is detected external to the computer by the device monitoring the 5 cycle per second signal. When the signal pulse is lost, the external device relinquishes control to the field controllers by opening the circuits from the ECO to the controllers.

Control Center Display

The control center display consists of miniature lights representing the signal lights and the vehicle detectors. The display is shown in Figure 4. The lights are operated on 5 volts using a steering diode matrix to light only the desired lamps. The diodes are fed by six stepping relays which are wired for the sequence of each intersection. The advance lines to the field are connected in parallel to the stepping relays. Activity in the field is simulated when not under computer control by using the monitor portion of the signal control program. During control, the display is kept in step with the field controllers. Another display shows the present interval number in the field for the intersection when requested.

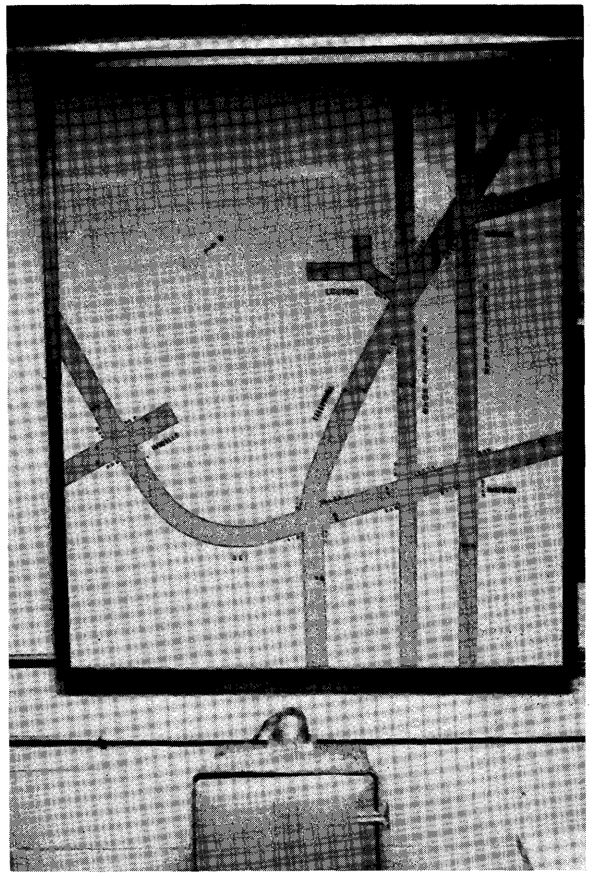

Figure 4 - Wayside-Telephone Network Display

Data Acquisition Computer Hardware

Each volume detector in the field is allocated to a certain input terminal connected to the digital computer. An actuation of the detector causes +24 volts to be transmitted to the input terminal. This causes other computer programs to be interrupted while volume program RANDM updates the volume count for that detector. This is the event recording method rather than the periodic scan method for obtaining volume data.

Technical Problems

During the research study, there were a number of technical problems which required solutions. The problems and their solutions are noted for future system designers.

The foremost problem was the difficulty in maintaining digital control over the rather old pretimed three dial intersection traffic controllers. Each controller required testing to determine the correct length of time for the cam advance pulse. It was also necessary to determine the elapsed time between the issuance of each advance pulse and the reception of a corresponding confirm signal from the controller.

Although there are now few detector failures, outages were extensive at the beginning of the study. Many supposed detector failures were due to 1) incorrect wiring, 2) improperly tuned or inoperative detectors, and 3) faulty time division multiplexing reception. Wiring was visually checked by observing vehicle passage via television surveillance and the electronic signal received at the computer input modules. A detector checking program has been implemented which samples each detector station and requires at least one but no more than N_i actuations during a six-minute period. N_i is the maximum vehicles expected at location i during that time. If a detector is malfunctioning, a fallback value is chosen for that approach volume based on time of day.

Even though all 32 detectors now function, there are other problems concerning volumes from the two radar detectors which send a pulse output. Two or more vehicles may appear to be only one actuation, especially during high-density traffic flow. For this reason, radar vehicle indications are adjusted with respect to volumes of nearby stations and time of day. Long queues may build up when green times do not reflect the true volume. Such frequently was the case for many detector outages until proper corrective action was taken at the OST-Wheeler intersection.

The main street green and cam advance confirms, like detector actuations, are transmitted to the control center by means of a time division multiplexer device. Multiplexer fibrillation, a transmission noise caused by loss of sync or AC-induced voltage spikes on the input lines, occurs frequently on the confirm inputs. A program was written to overlook fibrillation by ignoring improperly timed confirms and those confirms not occurring immediately after the advance pulse. Fibrillation may appear to be a confirm when the time interval is the right length. In this case, the computer might assume that the controller is not in the proper state and drop control. Control of the Wayside and Telephone intersection was frequently dropped due to this type of fibrillation. A capacitor was placed on this confirm line, and no control drops have taken place since then due to fibrillation.

Other inaccuracies in measurement of demand occurred during initial efforts of progressive traffic responsive control on Wayside between Telephone and the outbound frontage road. Queueing occurred on the northbound Wayside approach to the freeway when there was a heavy right turning movement at the Telephone northbound approach to Wayside. The sensed demand volume decreased as vehicles stopped over the loop sensors. This caused shorter green times for the queue approach, which, in turn, caused more stoppage, and the system progressively worsened. One solution would be to sense the time the detectors were occupied (or loop occupancy) to measure existing demand. Another solution is the use of an additional set of loops to aid in measuring true demand.

Initiating control is sometimes as much of a problem as dropping control, especially at the Telephone diamond interchange. This diamond is not in progression with the Wayside and Telephone interchange during normal fixed-time control. When the computer initiates control, these interchanges are placed in two-way progression, while progression is maintained along Wayside. Care must be exercised when doing this because the Telephone diamond may be considerably out of step. An attempt to install progression may cause very large adjustments to be made to the green splits and, consequently, some red phases may last two minutes at the Telephone diamond until progression is accomplished. The logical method is to wait until the interchanges are close to being in step with progression before initiating computer control. On the other hand, progression can be implemented slowly, but this may require thirty minutes for implementation. Work continues in this area for better implementation procedures. Other problems were encountered, but the problems and solutions discussed here are, hopefully, informative to one interested in the technical aspects of this study.

COMPUTER SOFTWARE SYSTEM

The computer software system is composed of seven programs. Figure 5 shows these programs as boxes 1-7 in a flow diagram of the computer's software system. The following is a list and brief description of each of these programs:

1. MPX - The multiprogramming operating system schedules execution of all programs on a priority basis.
2. START - Initializes control variables at start or restart of the operational system.
3. RANDM - Updates volumes by vehicle actuation of subprogram execution.
4. DSCAN - Monitors confirms from the field controllers each 0.1 seconds.
5. INTER - Measures cycle and interval lengths and offsets, drives field controllers and control center displays.
6. SUPER - Monitors control variables, stores data on disk, checks for bad detectors.
7. TRAFF - Analyzes present volumes, occupancies, and time; sends new cycle and interval lengths, offsets, and adjusted progressive interval lengths if necessary.

The Multiprogramming Executive System (MPX) is an operating system program supplied by IBM and adapted for use by staff programmers. All other computer programs were written by personnel of the Texas Transportation Institute. INTER, DSCAN, and RANDM are written in assembler language and require 2000 words together with required COMMON variables. On the

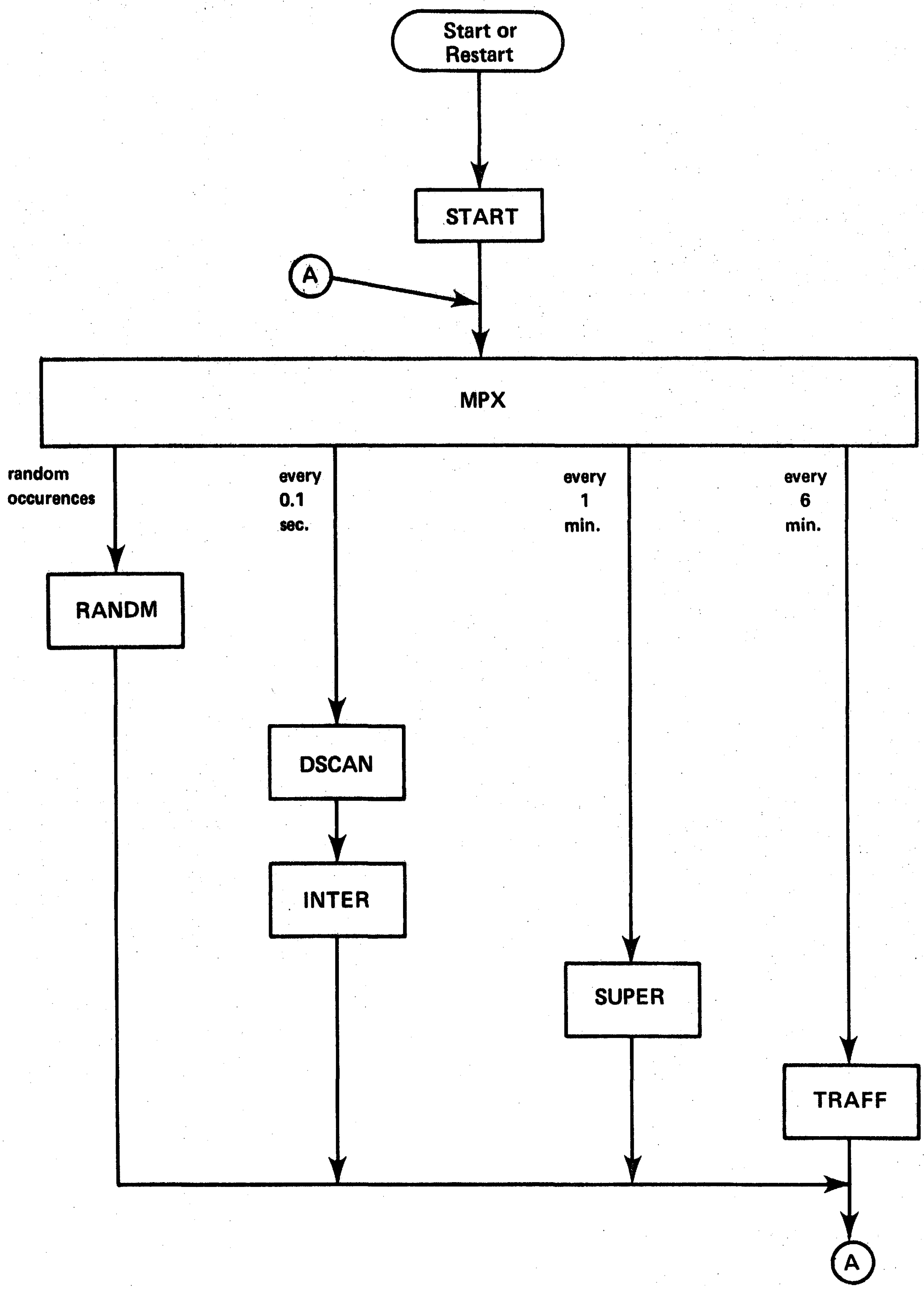

FIG. 5 – WAYSIDE-TELEPHONE COMPUTER SOFTWARE SYSTEM

other hand, TRAFF requires over 6000 words, since it is written in FORTRAN language. The entire system, somewhat modified and stripped down, could probably fit into an 8000 word minicomputer.

Multiprogramming Executive System (MPX)

MPX supervises the concurrent execution of up to 24 programs, on a priority basis. MPX allows 24 priority levels, one for each allowable operating program. It is thus possible to execute program INTER every 0.1 seconds and program SUPER every 60 seconds without missing any execution of program INTER. This is done by suspending execution of SUPER, if it is running, to INTER each 0.1 seconds. Any time unused by programs assigned a higher priority is made available to lower priority data analysis programs.

Data Acquisition Programs

Although these programs have been described under Data Acquisition Computer Hardware, there are several interesting points to be made. All data could be collected under the scan method, as in DSCAN, every second. All data could also be collected by the random interrupt method, as in RANDM. However, a large number of random interrupts of high priority might cause INTER or some other scheduled program to miss an execution. For this reason, the random interrupt type data collection technique cannot be used for large systems. Considering the number of drawbacks in order to gain higher efficiency, exclusive use of the random method would not be worthwhile.

Volume data are stored into lists by location of the data. Each minute SUPER sets all previous volume data locations to zero, then begins to accumulate and store volume counts for the next 60 seconds.

Intersection Programs INTER and TRAFF

The signal driver program INTER is executed immediately following DSCAN. A general flow diagram is exhibited in Figure 6. The control status of each intersection may be off, monitoring, or on and accepting new variables from TRAFF. If control is off, the control line releases the field controller from digital control.

When monitoring a signal, program INTER observes green confirms and drum advances described earlier. The cycle and interval lengths and the cycle starting times are recorded. Table 3 describes the progressive interval at each intersection. These progressive intervals are the intervals at each intersection where new offsets and interval lengths may be installed to change progression patterns. The offset is defined as the time from the progressive interval at some base intersection to the progressive interval at the intersection where the offset is being calculated. The control center display is updated each time a confirm in the field is detected so that the display exhibits the present field control status.

If the control status is on, the display is driven in parallel with the field controllers. At first, control is exactly as it was in the field before digital control. The offsets, cycle lengths, and interval lengths are measured and set to the traffic analysis program TRAFF. Every six minutes, TRAFF provides INTER with new offsets, interval lengths, cycle lengths, and adjusted progressive interval lengths.

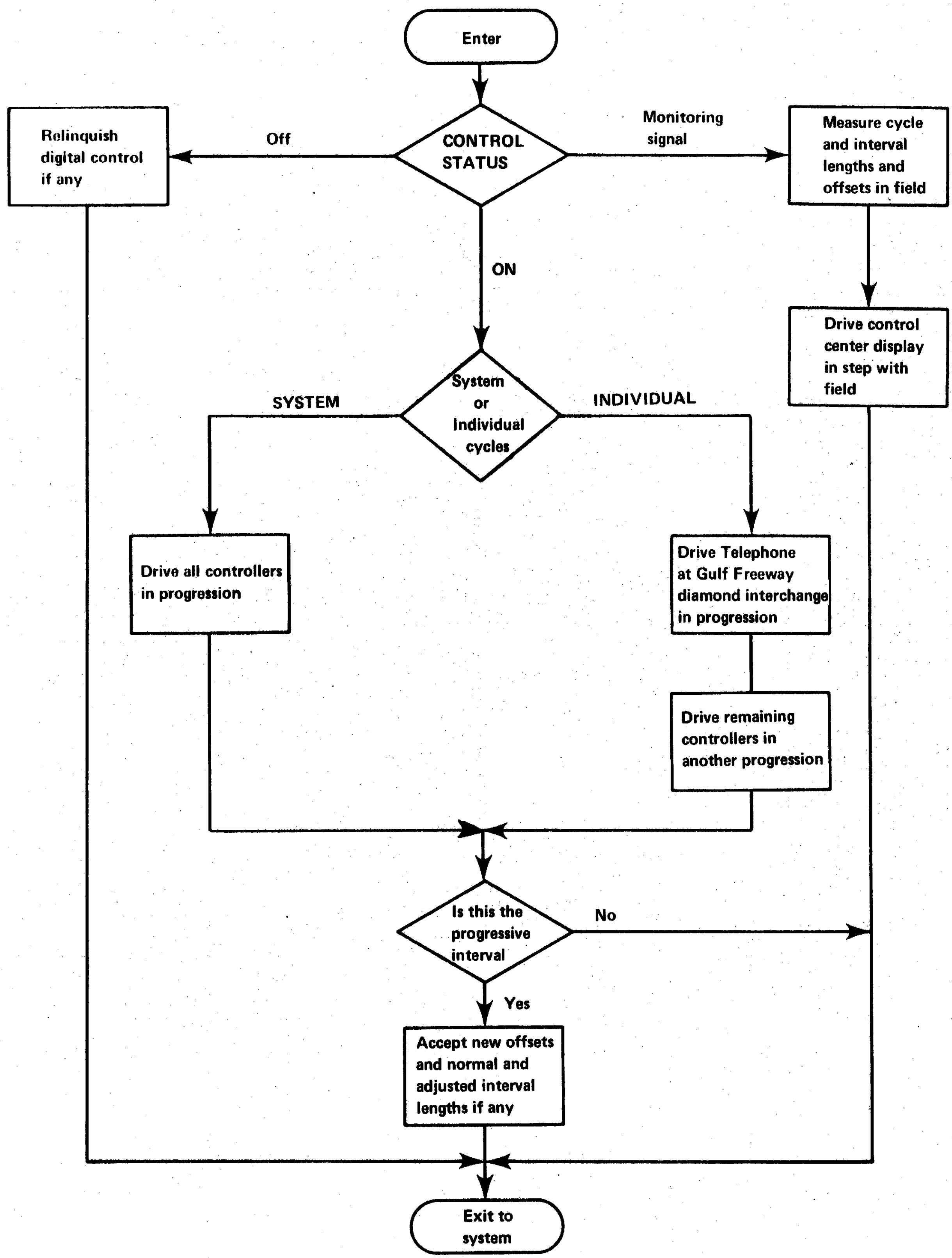

FIG. 6 — GENERAL FLOWCHART OF SIGNAL DRIVER PROGRAM INTER

Table 3

Progressive Intervals at
Intersections Controlled in the Wayside-Telephone Network

Number	Intersection	Progressive Interval
1	G-Way. East	Way. Thru
2	G-Way. West	Way. Left Turn
3	Way-Tel.	Way. Thru
4	OST-Wheeler	O.S.T. Thru
5	G-Tel. West	Tel. Left Turn
6	G-Tel. East	Tele. Thru

The new offsets, 0_{new}, for each intersection are installed by making a one time adjustment to the new progressive interval lengths, L_{new} (computed from Equation 1) so that the progressive interval will end with the signal phase in step with the newly computed progressive pattern. These adjusted interval lengths, L_{adj}, are computed from

$$L_{adj} = L_{new} + WBASE + 0_{new} - TOD \qquad (9)$$

where WBASE is the actual clock time of the beginning of the Wayside progressive green (number 1 in Table 3), the clock time of the network's master base signal, and TOD is the actual clock time of the first beginning of a given main street green's progressive interval following the measurement of WBASE. Due to the simplicity of the network, the progression offsets were preselected based on travel time runs through the system. Offsets for AM, PM, and Offpeak conditions were determined.

SUPER

Data used by TRAFF are stored each minute on a disk file by program SUPER. SUPER places control information on this file and sets time of day indicators and monitors other variables for action to be taken, such as printing. Last of all, SUPER tests for detector failures and incident conditions by comparing volumes of neighboring detectors and by testing measured volumes against critical values.

START

Volumes and occupancies are set to zero at the start of the operational program by START. START also initialized control variables to normal conditions for a particular time of day. During a restart of the computer system, which occurs following severe software errors, recovery conditions are set to those of the previous minute, as recorded on disk.

STUDY RESULTS

Initial testing of the traffic control system by computer simulation of traffic flow and field controller operations was conducted from September, 1971, until February, 1972. Signal control output was evaluated by driving the control center display board and manually checking the computed control variables of cycle length, splits, and offsets as listed on the computer printer.

Existing pretimed control was duplicated and implemented by the computer control system from February until May of 1972. A progressive pretimed signal pattern based on new manually collected traffic flow data was implemented and operated from June until September. Traffic responsive progressive control began in September and was run on a nearly continuous basis until February of 1973. No information was given to the public regarding these control studies to minimize the possibility of influencing study results.

Data Collection

The performances of the three types of control, existing pretimed, progressive pretimed, and progressive traffic responsive, were evaluated from data collected on vehicle travel times and the general volume levels for three conditions of operation. These three operating conditions were the A.M. peak from 7 - 8 a.m., the off-peak from 2 - 3 p.m., and the P.M. peak from 4:30 - 5:30 p.m.

Volume counts were made during each study period on Wayside Drive between the Gulf Freeway and Telephone Road. Manual counts were made initially but were automated as the traffic detection system became operational.

Travel times were collected using the average car technique by recording the actual travel times required to travel between designated system boundary points along both Wayside Drive and Telephone Road. Approximately 15 travel times were recorded for each direction of flow, route, and time period. Some additional travel times were made by portable microwave television surveillance when it became available late in the study.

The manually collected data, particularly the travel time data, were collected on a sampling basis due to manpower limitations over approximately a two-month period for each type of control. No data were collected until each newly installed type of control was operating satisfactorily and traffic flow conditions had stabilized.

Volume Results

Volume counts were made for the three types of control to determine primarily if the same levels of demand existed during the study. Significant changes in the hourly volume levels were not expected to result due to changes in control. Improvements in performance were expected to occur, however, in reductions in travel times experienced by motorists driving through the network. Table 4 shows that no significant change in the volume levels occurred during each type of control and that acceptable comparisons could be made between travel times. Any sizable reductions in travel times can therefore be assumed to be due to improvements in control performance and not the result of reduction in volume or demand.

Table 4

Average Hourly Traffic Flow on Wayside Drive for Three Types of Intersection Control During A.M. Peak, Off-peak, and P.M. Peak Flow Conditions

Type of Control[a]	A.M. Peak 7-8 a.m.	Off-Peak 2-3 p.m.	P.M. Peak 4:30-5:30 p.m.
Existing Pretimed	1979	1431	1952
Progressive Pretimed	1975	1396	1939
Progressive Traffic Responsive	1940	1433	1917

[a]All types of control implemented by computer control.

Travel Time Results

The travel time study results are summarized in Table 5 for the three types of control and three time periods of control. Progressive pretimed control shows a considerable improvement over the existing non-progressive pretimed control as indicated by the reduction in average travel times. Some of this reduction in travel time can be attributed to improvements in green splits based on more recent traffic flow data. The remainder of the travel time reduction is due to the improvements in flow provided by the progression that was implemented.

The progressive traffic responsive control showed further improvements over the progressive pretimed control. For the A.M., off-peak, and P.M. time periods, reductions in average travel times of 12, 8, and 2 seconds or 18, 13 and 3 percent, respectively, were obtained

Table 5

Average Travel Times in Seconds for Wayside Drive and Telephone Road by Type of Control and Time of Day

Time of Day	Route Name	Existing Pretime	Progressive Pretimed	Progressive Traffic Responsive
A.M. Peak 7-8 a.m.	Way. W.	46	47	47
	Way. E.	92	71	49
	Tele. S.	75	71	58
	Tele. N.	138	77	66
	Average	88	67	55
Off-Peak 2-3 p.m.	Way. W.	44	46	44
	Way. E.	90	69	46
	Tele. S.	82	64	63
	Tele. N.	93	63	65
	Average	77	60	52
P.M. Peak 4:30-5:30 p.m.	Way. W.	63	45	42
	Way. E.	92	68	65
	Tele. S.	125	73	69
	Tele. N.	103	68	70
	Average	96	64	62

for an average overall reduction of 11 percent. The progressive traffic responsive control system showed a 28 percent average overall reduction in travel time compared to the existing pretimed control operation.

These data and results reflect the operations of the two main traffic arteries within the network. The operations of the cross streets, the frontage roads in this network, are also important to system operations and performance. Subjective evaluation of the frontage road operation based on visual observations made by television surveillance indicated that the operations on the frontage roads generally showed slight improvements. Improvements in frontage road operation are not included in any improvement results.

Cost-Effectiveness Analysis

In this computer control study, as has been the case in other studies, the question has arisen as to the true benefits or level of effectiveness that was achieved as a direct result of computer control. There is little doubt in the opinion of the engineering staff associated with this study that the existing system could have been improved simply by retiming the signal phases to meet the changes in traffic patterns that had occurred over the past few years. On the other hand, there is little question that significant improvements in traffic operations were the result of the increased control capabilities provided by real-time computer control. First, complex interchanges can easily be controlled and interconnected to provide smooth flowing traffic with minimal delays. Second, "many" traffic patterns can be generated to meet long term changing traffic patterns.

Third, short term fluctuations in flow can be detected and responded to further reduce delay.

However, the question remains, "should a computer control system have been installed?" One test that might be required is that the benefits received by the motoring public exceed the costs of providing the computer control. The second test might be that the level of performance must exceed a certain pre-established performance level regardless of the differences in benefits and costs. The third test might be that the initial capital expenditures required to install the system not exceed a pre-established maximum or that the system not be so complex that the operating agency cannot operate the system. The results of this study indicate that all of the previously listed test criteria are affirmative except for the size of the initial capital expenditure required--which can only be answered by the local operating agency.

The benefits of progressive traffic responsive control will not be compared against the existing pretimed system, but rather against the control results of the progressive pretimed system as might have existed using an interconnected 3-dial system timed with recent traffic flow data. From Table 5, therefore, reductions in travel time of 12, 8 and 2 seconds for the A.M. peak, off-peak, and P.M. peak control periods would have resulted. Using available traffic volume data for Wayside Drive and Telephone Road, the net travel time savings per day are estimated to be 100 vehicle hours per day. Using a conservative value of travel time of $2 per vehicle hour, a net benefit of $52,000 per year results, or $13,000 per intersection per year.

The cost of installing a computer traffic control system depends heavily on the system design. A detailed system design is beyond the scope of this report. However, a fully traffic responsive progressive computerized traffic control system using detectors on all approach movements, local minicomputers, and a network master minicomputer with the associated data transmission system could cost $25,000 per intersection. This value assumes existing signals in place which could be adapted for control. The annual control hardware cost over a 10-year period at 6% interest would be $3,400 per year per intersection. Incremental maintenance and operation of the system and programming staff operating costs are estimated to run $3,000 per year per intersection. Thus, the average annual cost per intersection would be about $6,400. Even at these costs, the resulting benefit/cost ratio would be $13,000/$6,400, or 2.03. This is a very favorable result.

Frontage Road Diversion Control

Major incidents on the freeway and closure of freeway entrance ramps cause heavy diversion to the frontage road. When this diversion occurs, it is desirable to have a progressive movement on the frontage road. Computer control of the two diamond interchanges has allowed frontage road diversion to take place without major congestion at these interchanges. For several months, key freeway entrance ramps were closed during portions of the morning peak period. This provided improved freeway flow. By controlling the Wayside network, it was possible to give progression and more green time to the inbound frontage road during the critical closure periods, thereby reducing frontage road congestion. Major research work will be conducted in the future on this phase of signal control as changeable message signs being installed on the Gulf Freeway become operational.

FINDINGS AND RECOMMENDATIONS

Findings

The real-time computer control of a small network of traffic signals has been successfully accomplished with the cooperation and support provided the Texas Transportation Institute by the Texas Highway Department and the City of Houston. The technology for the coordinated computer control of complex diamond interchanges has been developed and implemented. More specific findings are:

1) The average overall travel time was reduced 28 percent by using the progressive traffic responsive computer control system as compared to the existing pretimed control system.

2) The progressive traffic responsive computer control system showed an 11 percent reduction in overall travel time when compared with progressive pretimed control using recent traffic data. A favorable benefit-cost ratio of 2.03 would result.

3) Real-time traffic responsive computer control under heavy volume conditions requires an accurate measure of the true demand existing on each intersection approach if excessive delays are to be avoided.

4) Diamond interchanges can be interconnected and controlled to favor and progress frontage road traffic.

Recommendations

Based on the successful operational results of this Wayside-

Telephone network computer control system and recognizing the need for highly efficient traffic control at other diamond interchanges along the Gulf Freeway, it is recommended that other diamond interchanges along the Gulf Freeway be brought under centralized traffic responsive computer control. In general, it is further recommended that serious consideration be given to providing frontage road progression capabilities for all diamond interchanges having continuous one-way frontage roads in urban areas.

Other more specific recommendations are offered based on the results of this study:

1) The diamond interchanges and their adjacent intersections along the Gulf Freeway at Scott, Cullen, Griggs and Woodridge should be controlled by a digital minicomputer traffic control system. Those at Woodridge and Griggs should be interconnected with those at Wayside and Telephone.
2) The effectiveness of lane occupancy as opposed to vehicle count for measuring demand under all loading conditions should be investigated.
3) Studies should be conducted to determine how rapidly existing traffic flow conditions should be updated in real-time.

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PREVIOUS REPORTS OF STUDY

Research Report 165-1, "A Study of Accident Investigation Sites on the Gulf Freeway," by Mary Ann Pittman and Roy C. Loutzenheiser.

Research Report 165-2, "Evaluation of the Datamate Model D-16 as a Traffic Controller," by Gene P. Ritch.