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Evaluation of the Optimized Policies for Adaptive Control Strategy

Research, Development, and Technology
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FOREWORD

This report describes the results of three field tests of the Optimized Policies for Adaptive Control (OPAC) signal control logic which is designed to control isolated intersections. This report will be of interest to designers and operators of traffic control systems, particularly persons dealing with the control of isolated intersections.

The existing control strategy, max-out/gap-out which is used by full actuated controllers to control actuated signals, does not respond to the quantity of traffic awaiting service, only to the existence of traffic awaiting service. The OPAC strategy, on the other hand, responds directly to the quantity of traffic by making decisions on changes of signal phase based on minimization of vehicle delay.

The results of the research described in this report indicate that reductions in vehicle delay at signalized isolated intersections operated under OPAC control, as compared with actuated control, range from 3 percent to 20 percent, depending on vehicle demands (the higher the demand, the greater the improvement observed).

The research reported herein is a part of Nationally Coordinated Program (NCP) Area B.1, "Traffic Management Systems."

Sufficient copies of this report are being distributed to provide one copy to each regional and division office, and to selected transportation officials. A limited number of copies of this report are available from the Research, Development, and Technology Report Center (HRD-11), 6300 Georgetown Pike, McLean, Virginia 22101. When these copies are exhausted, copies of the report may be obtained from the National Technical Information Service (NTIS), 5285 Port Royal Road, Springfield, Virginia 22161. A charge will be imposed for each copy ordered from NTIS.

Jerry A. Reagan

by R. J. Betsold, Director
Office of Safety and Traffic
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16. Abstract

The OPAC strategy is an on-line traffic signal control algorithm designed to optimize the performance of traffic signals at isolated intersections using delay as the performance criterion. OPAC-RT is a traffic signal control system which implements the OPAC strategy in real time. The system uses traffic data collected from detectors located well upstream (400 to 600 ft) of the stop bar on all approaches to an intersection. Optimum signal timing is determined using minimum and maximum green constraints and does not require a fixed cycle length. This report describes three field tests of the on-line OPAC strategy. The results indicate that OPAC performs better than well timed actuated signals, particularly at greater demand levels.

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SI* (MODERN METRIC) CONVERSION FACTORS

APPROXIMATE CONVERSIONS TO SI UNITS

LENGTH

Symbol	When You Know	Multiply By	To Find	Symbol
in	inches	25.4	millimetres	mm
ft	feet	0.305	metres	m
yd	yards	0.914	metres	m
mi	miles	1.61	kilometres	km

AREA

Symbol	When You Know	Multiply By	To Find	Symbol
in^2	square inches	645.2	millimetres squared	mm^2
ft^2	square feet	0.093	metres squared	m^2
yd^2	square yards	0.836	metres squared	m^2
ac	acres	0.405	hectares	ha
mi^2	square miles	2.59	kilometres squared	km^2

VOLUME

Symbol	When You Know	Multiply By	To Find	Symbol
fl oz	fluid ounces	29.57	millilitres	mL
gal	gallons	3.785	litres	L
ft^3	cubic feet	0.028	metres cubed	m^3
yd^3	cubic yards	0.765	metres cubed	m^3

NOTE: Volumes greater than 1000 L shall be shown in m^3.

MASS

Symbol	When You Know	Multiply By	To Find	Symbol
oz	ounces	28.35	grams	g
lb	pounds	0.454	kilograms	kg
T	short tons (2000 lb)	0.907	megagrams	Mg

TEMPERATURE (exact)

Symbol	When You Know	Multiply By	To Find	Symbol
°F	Fahrenheit temperature	5(F-32)/9	Celcius temperature	°C

APPROXIMATE CONVERSIONS FROM SI UNITS

LENGTH

Symbol	When You Know	Multiply By	To Find	Symbol
mm	millimetres	0.039	inches	in
m	metres	3.28	feet	ft
m	metres	1.09	yards	yd
km	kilometres	0.621	miles	mi

AREA

Symbol	When You Know	Multiply By	To Find	Symbol
mm^2	millimetres squared	0.0016	square inches	in^2
m^2	metres squared	10.764	square feet	ft^2
ha	hectares	2.47	acres	ac
km^2	kilometres squared	0.386	square miles	mi^2

VOLUME

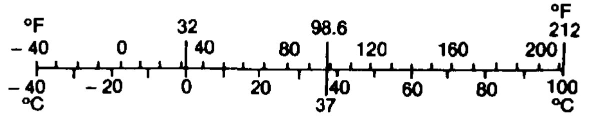
Symbol	When You Know	Multiply By	To Find	Symbol
mL	millilitres	0.034	fluid ounces	fl oz
L	litres	0.264	gallons	gal
m^3	metres cubed	35.315	cubic feet	ft^3
m^3	metres cubed	1.308	cubic yards	yd^3

MASS

Symbol	When You Know	Multiply By	To Find	Symbol
g	grams	0.035	ounces	oz
kg	kilograms	2.205	pounds	lb
Mg	megagrams	1.102	short tons (2000 lb)	T

TEMPERATURE (exact)

Symbol	When You Know	Multiply By	To Find	Symbol
°C	Celcius temperature	1.8C + 32	Fahrenheit temperature	°F



* SI is the symbol for the International System of Measurement

(Revised April 1989)

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INTRODUCTION

1. Background

On-going traffic control research includes the development of strategies for networks, arterials, and isolated intersections. This research includes off-line strategies in which manually collected data is processed using batch computer programs to produce signal timing plans. It also includes on-line strategies that use detector inputs to calculate signal timing for immediate implementation.

Significant progress has been made in the development of off-line signal timing plan generation programs. Programs such as SIGOP, TRANSYT, MAXBAND, PASSER, SOAP, and S-STOP, which have been under development since the late 1960's, are used routinely throughout the world for calculating signal timing for arterials, networks, and isolated intersections. With the rapid advancements in digital computer technology, hardware has become smaller, faster, and less costly. In keeping with the developments in hardware, off-line signal timing strategies have become increasingly sophisticated in their computational procedures and are continuously being refined to improve their capabilities and ease of use.

Significant progress has also been made with the development of on-line strategies. The earliest of these were developed during the 1950's by signal equipment manufacturers for actuated traffic signals. These strategies included techniques such as volume-density control and diamond intersection control to reduce delays at isolated intersections. More recent innovations within the United States for the control of isolated intersections have been characterized by the development of new features for conventional actuated controllers such as:

- Phase skipping - in which certain phases can be skipped as a function of traffic conditions or time of day.
- Variable coordinated phase - which changes the coordinated (nonactuated) phase as a function of time-of-day to permit the coordinated control of differing approaches as traffic patterns change.
- Variable length yield (permissive) period - a technique that permits the controller to yield to actuated phases over an extended time period.
- Multiple permissive periods - a feature which controls multiple controller phases using YIELDs instead of FORCE OFFs.
- Dual Ring Control - a phase relationship in which phases which are not conflicting can be timed independently.

Many strategies have also been developed for on-line control of coordinated signal systems. The research leading to the development of these strategies took place at the Transport and Road Research Laboratory (TRRL) in the United Kingdom, in Toronto, Canada, and at the Federal Highway Administration (FHWA) in the United States.

As the population in urban areas increases, the need for traffic responsive control strategies becomes greater. On-line traffic control strategies have a much greater potential for being truly traffic responsive than do off-line methods of signal timing. The design of modern signal controllers incorporating microprocessor components offers an opportunity for the implementation of distributed strategies which minimize the need for large central installations. Distributed strategies also provide the opportunity to use improved optimization techniques which do not use cycle length, split, and offset in the conventional sense.

The Optimized Policies for Adaptive Control (OPAC) Strategy is an on-line traffic signal timing optimization algorithm that represents the most recent development in traffic control research. The OPAC strategy is a distributed strategy featuring a dynamic optimization algorithm which provides the computation of signal timing without requiring a fixed cycle time. Signal timing is calculated to minimize vehicle delays and is constrained only by minimum and maximum green times.

2. Problem Statement

The successful implementation of the OPAC strategy offers the potential for significantly improving the control strategies used at isolated intersections. The exhaustive search procedures, which consider vehicle demand on all approaches, are likely to produce signal timing that is superior to that of existing actuated equipment. The problem, therefore, was to implement the OPAC strategy in a real-time environment and determine whether it represents a viable alternative to actuated control at an isolated intersection.

To this end, the FHWA contracted for the design, implementation, testing, and field evaluation of an on-line traffic control system for isolated intersections utilizing the OPAC strategy. The resulting system and the field evaluation of the real-time OPAC strategy are the subjects of this report.

3. Definition of Study Objectives

The objectives of this study were:

- To develop a system consisting of the existing OPAC algorithm and the hardware and software which would enable the real-time OPAC program to interface with a full actuated modern solid-state controller such that the signal phase times would be determined by the OPAC optimization algorithm.

- To determine, in terms of traffic performance, how effectively the OPAC control algorithm controls traffic at isolated intersections as compared with full actuated control.
- To make recommendations, based on the observed performance of the existing OPAC control algorithm, for improvements and enhancements. Upon approval by the contractor, incorporate modifications into the OPAC algorithm which would improve its effectiveness.
- To estimate the cost effectiveness of using OPAC instead of full actuated control at isolated intersections.
- To produce a strategy that can be offered to the signal industry for commercial implementation.
- To develop features that will minimize the amount of fine tuning required by local traffic engineering personnel.

4. Scope of Work

The work required to meet the objectives stated above consisted of:

- Software development, modification, and testing of both the OPAC control algorithm itself and the software which enables OPAC to interface with a full actuated controller.
- Hardware application for an OPAC field evaluation, including detection hardware (detectors, cable, etc.), a microcomputer to execute the OPAC software, and other hardware required to interface the computer executing OPAC with the full actuated controller.

- Development of a field test work plan followed by field data collection, reduction, and analysis.
- Rewriting and revision of software documentation.
- Economic Analysis.

A summary of the tasks undertaken to meet the objectives of the study is provided in appendix A.

5. Summary of Study Results

Three field tests of the real-time OPAC traffic signal control system developed during the study were conducted. The first two field tests were directed at the evaluation of the first version of the OPAC system which was limited to the control of two phase intersections. Based on the observed performance of this first version, various enhancements were identified both to increase the effectiveness of the system and to permit installation of OPAC for control of a broad range of controller phasing configurations. After making the required modifications, this second version of the system was evaluated during the third field test conducted at a site operating with an eight phase dual ring controller.

The principle measures of effectiveness selected for comparison of the performance of an actuated controller and the OPAC systems were delay and percentage of vehicles forced to stop. During the first field test both delay and the percentage of stops were decreased when the intersection was under the control of the OPAC system. The improvements were modest: for data aggregated over intervals of approximately 10 minutes delay was decreased on the average by 3.9 percent and stops were decreased by 1.6 percent. However, the observed volumes during this field test were extremely low. More definitive statements regarding the performance of the OPAC system would require more analysis of stops and delay at higher volumes.

During the second field test delay was greatly reduced under OPAC system control. On the average delay was reduced by 15.9 percent despite an increase of 4 percent in average volume. The percentage of vehicles forced to stop, on the other hand, were increased on the average by 3.9 percent. Since stops were not an OPAC measure of effectiveness in the first version of the system, and since there was also an increase in volume during OPAC operation, this increase in stops is to be expected and represents a minor degradation in the performance of the OPAC algorithm with respect to the actuated controller.

During the third field test delay was decreased on the average by 7.7 percent at an eight phase intersection. Also, despite the inclusion of stops in the OPAC system's signal timing optimization function, the percentage of stopped vehicles was increased by an average of 9.5 percent.

The first version of the OPAC system is limited by numerous constraints. Despite these limitations, this version of the real-time OPAC traffic control system has demonstrated a potential for greatly increasing intersection performance as measured by delay and percentage of stopping vehicles. Also, despite the increase in stops, the results of the third field test indicate that the enhanced OPAC system has the potential for greatly improving the operation of isolated intersections. The second version of the OPAC system incorporates numerous user-input smoothing factors and parameters. It is expected that further calibration of these values will further increase the benefits of the real-time OPAC system.

THE OPAC STRATEGY

1. Strategy Development: OPAC-1

The OPAC strategy evaluated in this study is the culmination of a research effort that included the development of three optimization algorithms.(1) The first, designated OPAC-1, was developed to serve as the basis for future OPAC strategy development. OPAC-1 incorporates Dynamic Programming techniques in the solution of the traffic control problem. Dynamic Programming is a general approach to the mathematical solution of multistage decision processes.

Dynamic Programming is characterized by the following:(2)

- The problem is divided into n stages, n = 1, . . ., N, with a policy decision at each stage.
- Each stage is characterized by the following:
    1) An input state, I, that gives all relevant information about the system at the beginning of the stage.
    2) An output state, O, that gives all relevant information about the system at the end of the stage.
    3) A decision variable, x, that controls the operation of the stage.
    4) A stage return, r, that is a performance measure of the utility or disutility contributed by the stage.
- The effect of the policy decision at each stage is to transform the current input state into a state associated with the next stage.
- Given the current state, an optimal policy for the remaining stages is independent of the policy adopted in previous stages.

- A recursive relationship that identifies the optimal policy for each input state at stage n, given the optimal policy for each input state at stage n+1.

- Given this recursive relationship, the solution procedure moves backward stage by stage, each time finding the optimal policy for each input state of that stage, until it finds the optimal policy when starting at the initial stage.

- When the optimal policies have been determined for the initial stage, the problem is solved. The entire optimal policy is then retraced moving forward from stage 1 to stage N.

When applying the Dynamic Programming method to the traffic control problem, the following assumptions were made:(1)

- The isolated intersection has four approaches labelled N, S, E, and W. The intersection is controlled by a two-phase light providing green alternately to the N-S (phase 1) and E-W (phase 2) approaches.

- Time is divided into intervals of 5 seconds. All calculations are carried out for the interval as a unit, regardless of variations that might occur within the unit. Signals may change only at the boundary between the units.

- Traffic is assumed to be homogeneous. It is assumed that arrival rates on all approaches are known and traffic patters are specified by integer number of vehicles in each interval.

- Signal phases are composed of effective greens and effective reds only. There must always be an all red interval following a decision to switch lights. This period is assumed to include that part of the amber which is effectively red as well as the lost time at the start of the green.

- When the signal is green, the maximum discharge rate on an approach is 2 vehicles per interval.
- No constraints are imposed on the minimum or maximum length of the green periods.

Each interval of time is designated a stage. For each stage, the initial state is defined by the initial queues on each approach and the signal status. The initial signal status for each approach is either green (0) or red (1). The input decision variable for each approach is either 0 (no signal change) or 1 (change). The output of the algorithm for each stage and specific set of initial queues and signal indications are new queues and signal indications for each approach. The performance measure is delay, calculated to be the sum of the minimum delay associated with the corresponding intersection state at the succeeding interval (which has already been calculated since the procedure moves backwards), the initial queues, and the arrivals for the stage minus the departures.

The dynamic programming procedure as applied to the traffic control problem is as follows:

1) Select an intersection state at interval i. That is, select a specific queue length and signal status within the valid ranges for each approach.
2) Calculate the total delay for intervals i to n (the last in the stage) for each input decision (i.e., calculate the delay assuming the signal changes in interval i and recalculate the delay assuming there is no change).
3) Choose the policy for interval i to be 'change' or 'no change' based on which produced the least total delay.
4) Repeat steps 2 and 3 for all valid input states at interval i.

The procedure is complete when interval 1 has been reached and yields values for the optimum policy and minimum total delay for each initial intersection state.

While this procedure assures globally optimum solutions, it requires complete knowledge of arrivals over the entire control period. Also, it is not suitable for real-time implementation because of the processing involved. Much of the output from the program is never used because optimum policies are generated for all combinations of initial conditions at each stage of the control period. If an 'entire optimum policy' is defined to be the complete sequence of optimum policies throughout the control period which corresponds to a particular initial state at interval 1, then, depending on the valid ranges for initial input variables, the algorithm could produce hundreds of entire optimum policies. In practice, since only one initial state at interval 1 will be true in reality, only one entire optimum policy would be implemented. Hence, OPAC-1 is useful only for the evaluation of the relative effectiveness of other strategies.

2. Strategy Development: OPAC-2

The second optimization algorithm, designated OPAC-2, is a simplification of the OPAC-1 algorithm. It was designed to serve as a building block in the development of a distributed on-line strategy. OPAC-2 has the following features:

- The control period is divided into stages T seconds long. T is typically approximately equal to the cycle length, although it could be longer.
- Each stage is divided into an integral number of intervals 's' seconds long. For development of the algorithm, s = 5 seconds.
- During each stage there must be at least one signal phase change and there may be as many

as three. The phase change (switching) times are measured from the start of the stage in s (5) second time units.

- For any given switching sequence at stage n, the performance function for each approach is defined to be the sum over all intervals in the stage of the initial queue plus the arrivals during each interval minus the departures during each interval.

For OPAC-2, the optimization problem is stated as follows:

> For each stage, given the initial queues on each approach and the arrivals for each interval of the stage, determine the switching times, in terms of intervals, which yield the least delay to vehicles over the whole stage.

The procedure used for solving the problem is an optimal sequential constrained search (OSCO) method. It is an exhaustive search of all possible combinations of valid switching times to determine the optimum set. Valid switching times are constrained by minimum and maximum phase durations. Since there are allowed to be up to three switching times within the stage, the optimization process is divided into three steps.

The algorithm first assumes there will be three switches within the stage. Based on the minimum and maximum constraints, a range is determined for each switching time. An exhaustive search is made of all possible switch combinations and the one which results in the least delay is saved. The process is repeated with the assumption of two switches within the stage and then a single change. At the end of this step, the optimum set of switching times, be there one, two, or three switches, has been identified.

3. The Rolling Horizon Approach

While OPAC-2 is an optimization procedure which lends itself more readily to operation in real-time than does OPAC-1, it still requires knowledge of arrivals over the whole stage. Depending on minimum phase durations, the stage might need to be 1 or 2 minutes long. Obtaining actual arrivals over this length of time might be difficult. However, OPAC-2 could be implemented with a traffic prediction model which predicts the traffic pattern over the entire stage. While using a prediction model might simplify the optimization, past research and experimentation with predictors has shown that they are less effective than historical data as estimators of traffic arrival patterns. This research has explored as many as 15 different prediction techniques, none of which provided an acceptable level of performance. Failure to develop an effective prediction algorithm has been the result of inherent characteristics of traffic data. Among observations of volume there exists a high degree of variability (i.e., volume data is noisy) and successive samples of traffic volumes are independent. In other words, it is difficult to predict what will happen during the next cycle based on what happened during this cycle.

In order to use only available flow data without degrading the performance of the optimization procedures, a 'rolling horizon concept' was applied to the OPAC-2 algorithm. This version is called ROPAC.(1) In this version the stage length consists of k intervals. The stage is called the Projection or Project Horizon (or simply horizon) because it is the period over which traffic patterns are projected and optimum phase change information is required. The horizon is typically approximately equal to the cycle length. With intervals of 4 seconds and an average cycle length of 60 seconds, the horizon would be approximately 15 intervals.

From detectors placed upstream of each approach actual arrival data for r intervals can be obtained for the beginning, or head, portion of the horizon. For the remaining k-r intervals, the tail of the horizon, flow data may be obtained from a model. An optimal switching policy of one, two, or three switches is calculated for the whole horizon, but only those changes which occur within the head portion are implemented.

It is important that the detectors be placed well upstream (10 to 15 seconds) of the intersection in order to obtain actual arrival information over the head period. As indicated earlier, traffic prediction models have proven unacceptable in determining optimum signal timing. Knowing actual arrivals, however, allows for the exact calculation of delay based on particular phase change decisions. Hence, it is important to have actual arrival data over the period for which phase changes will be implemented.

At the conclusion of the current head period, a new project horizon containing new head and tail periods is defined with the new horizon beginning at (rolled to) the termination of the old head period. The calculations are then repeated for the new project horizon. Figure 1 is an illustration of the procedure.

The roll period is a multiple number of steps. For the development of the ROPAC algorithm, the roll period was equal to the head period. In reality, the roll period could be independent of the head period and could be as small as one step. By having several steps of actual arrival information and performing the signal timing optimization every step, the ROPAC algorithm is further optimized.

ROPAC, as well as OPAC-1 and OPAC-2, was really designed to respond to platoons in the traffic stream. If many vehicles suddenly arrive at the intersection on a particular phase, the

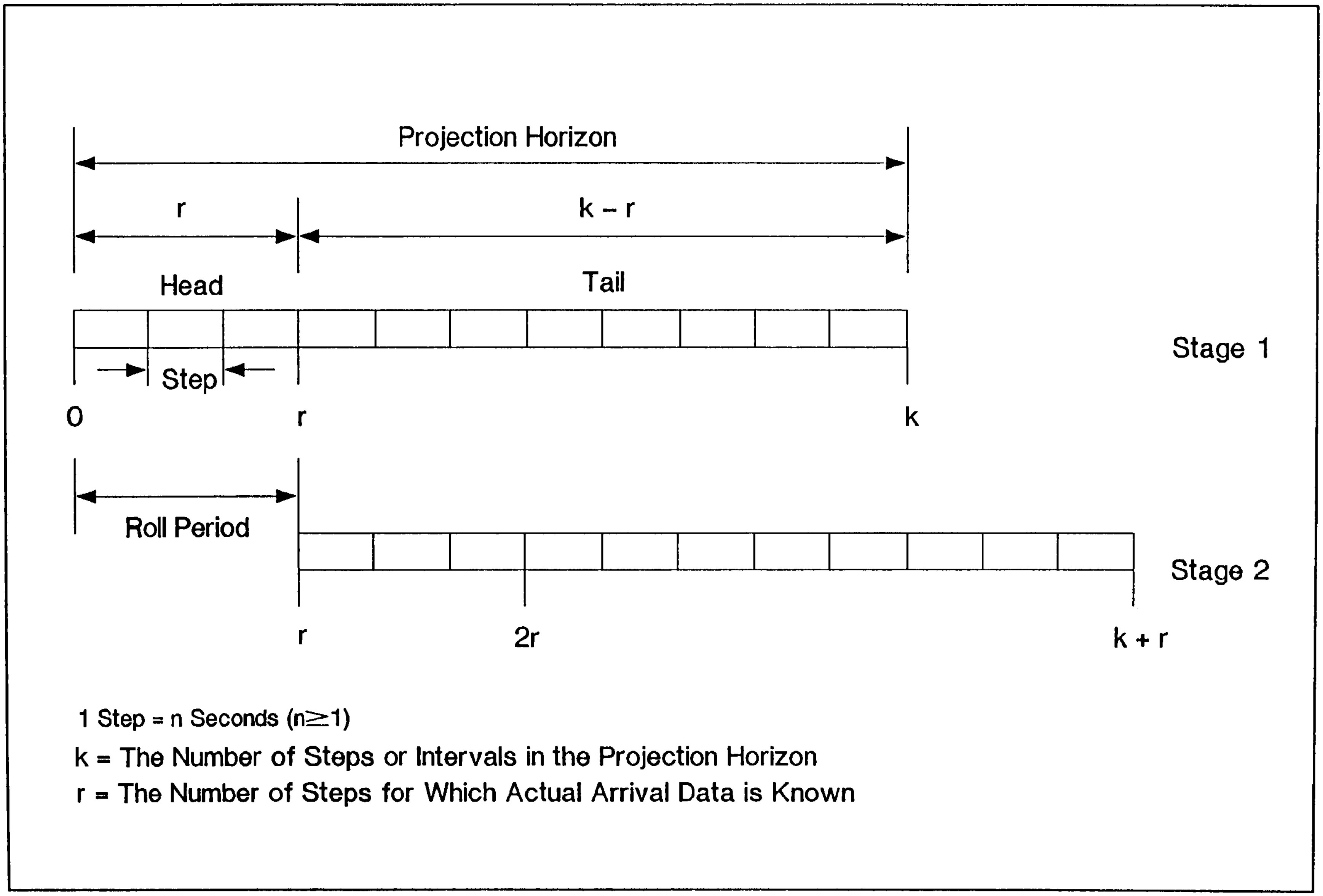


Figure 1. OPAC Algorithm rolling horizon concept.

delay which would be incurred if they were forced to stop causes the algorithm to terminate other phases or extend the current phase in order to service them and minimize intersection delay.

A REAL-TIME DEMAND RESPONSIVE TRAFFIC SIGNAL CONTROL SYSTEM

The rolling horizon OPAC algorithm, ROPAC, described in chapter 2 was integrated into an off-line program designated OPAC9. The real-time traffic control system developed under this study uses the OPAC9 software as the signal timing optimization algorithm. Other hardware and software elements of the real-time system, including the controller hardware and software interface and the detector processing software, were designed based on signal and detector information required by the optimization algorithm. The system developed for this study is designated the Real-Time OPAC Traffic Signal Control System (OPAC-RT).

There are two versions of the OPAC-RT Traffic Signal Control System. The first, Version 1.0, uses the OPAC9 software with no modifications or enhancements which would affect its phase change decisions. This version is described in detail below in 'OPAC-RT Version 1.0: Two Phase Operation.'

Based on the observed performance of Version 1.0, various enhancements were identified which were expected to increase its effectiveness and make it more generalized in terms of the locations for which the system could be used. These enhancements were incorporated and the resulting system is designated Version 2.0. This version is described in detail below in 'OPAC-RT Version 2.0: Dual Ring, Eight Phase Operation.'

1. <u>OPAC-RT Version 1.0: Two Phase Operation</u>

The primary objective of Version 1.0 of the OPAC-RT system is to effectively control the signal timing at a two phase, fully actuated, isolated intersection. The system collects vehicle arrival information from upstream detectors as well as signal indications which are supplied as inputs to a modified version of the ROPAC strategy (see chapter 2 for a summary of the strategy). The system then implements the switching decisions output by the optimization algorithm.

The system also stores system conditions throughout the control period. This information includes phase returns, signal switch times, walk requests, the time of the occurrence of any errors, and arrival patterns.

a. Relationship to the OPAC Strategies

As indicated in the introduction to this chapter, Version 1.0 of the OPAC-RT system uses OPAC9, a FORTRAN version of the rolling horizon OPAC algorithm, as its signal timing optimization function. The main body of the OPAC9 software is a subset of the OPAC-RT system whose major function is to determine the set of optimum switching policy decisions for the current stage or project horizon. Input and output functions of the OPAC9 software were modified or deleted for use in the real-time system. Other modifications to the OPAC9 software designed to increase its suitability for real-time applications included:

- Restructuring of the OPAC9 program to increase its modularity.
- Removal of the triple switch optimization to increase the speed of the optimization (i.e., at least one and no more than two signal changes are allowed within a single horizon). The removal of the triple switch optimization had no practical effect on the performance of the algorithm. In executing the OPAC9 program a triple switch was almost never selected as the optimum because, in general, the horizon length was too short to accommodate three phase changes, given minimum phase duration constraints.
- Deletion of the global optimization policy option. The system does not consider the

delay at downstream intersections as a result of a particular switching policy.

- Deletion of tail calculations which are not applicable to on-line control.
- Addition of a fixed tail algorithm which calculates arrivals for the tail of the horizon during on-line control.

Also, minor modifications were made to the horizons in OPAC9 in order to distinguish the 'roll period' from the 'head period.' In OPAC9 these terms referred to the same thing. Actual arrivals were known for some number of intervals at the head of the horizon. The remainder of the arrival pattern for the tail of the horizon was filled in by a tail routine. After the optimum switching policy was determined for the horizon, it was shifted, or rolled, to the end of the head portion and the calculations were repeated.

In OPAC-RT, the roll period is the number of intervals or steps to roll the horizon before the next optimization begins. The head period is the number of steps for which actual arrival data is available. Since it is required that the detector processing, hardware interface, and optimization software execute within one interval, there is no reason to require that the roll period and the head period be the same in length. At most, the optimization may be performed once per step. Actual arrival data may be available for several steps, depending on the step size and the travel time from the upstream OPAC detectors to the intersection stop line.

b. System Configuration and Operating Environment

The OPAC-RT system is composed of 3 major subsystems, the Processor subsystem, the Data Acquisition and Control (DAC) subsystem, and the Traffic Signal subsystem. They are interlinked by various signal and control lines. Figure 2 is an overview of the OPAC-RT system and its operating environment.

The Processor Subsystem consists of an IBM-AT microcomputer running at 8-Mhz. It requires a minimum configuration of 640K of main memory, at least 1 disk drive with a minimum of 600K available storage, and at least 2 available expansion slots. A standard keyboard and monochrome monitor are also required. The disk drive may be either fixed or floppy, however, if a fixed drive is used there must be at least 600K available space for the OPAC-RT program plus additional storage space for accumulated statistical data.

The processor incorporates three counter/timer units used for periodic interrupt generation. The interrupts generated by these units control the execution of the real-time OPAC-RT software shown in figure 2.

The Data Acquisition and Control (DAC) Subsystem performs two functions in the OPAC-RT system. The first is to provide an interface between the processor and the signal controller and the second is to collect traffic flow information for use by the processor in executing the optimization algorithm.

The Traffic Signal Subsystem includes a signal controller configured so that both phase 1 and phase 2 operate in the nonactuated mode with both phases in vehicle recall. In this state an external signal applied to the HOLD input will cause the controller to remain in the current phase without regard to any external vehicle or pedestrian inputs. Application of a FORCE-OFF pulse will then cause the controller to terminate the current phase and then proceed to the next phase where it will remain until the next FORCE-OFF is applied. In this manner, the HOLD and FORCE-OFF are used to implement the phase changes dictated by the OPAC optimization algorithm.

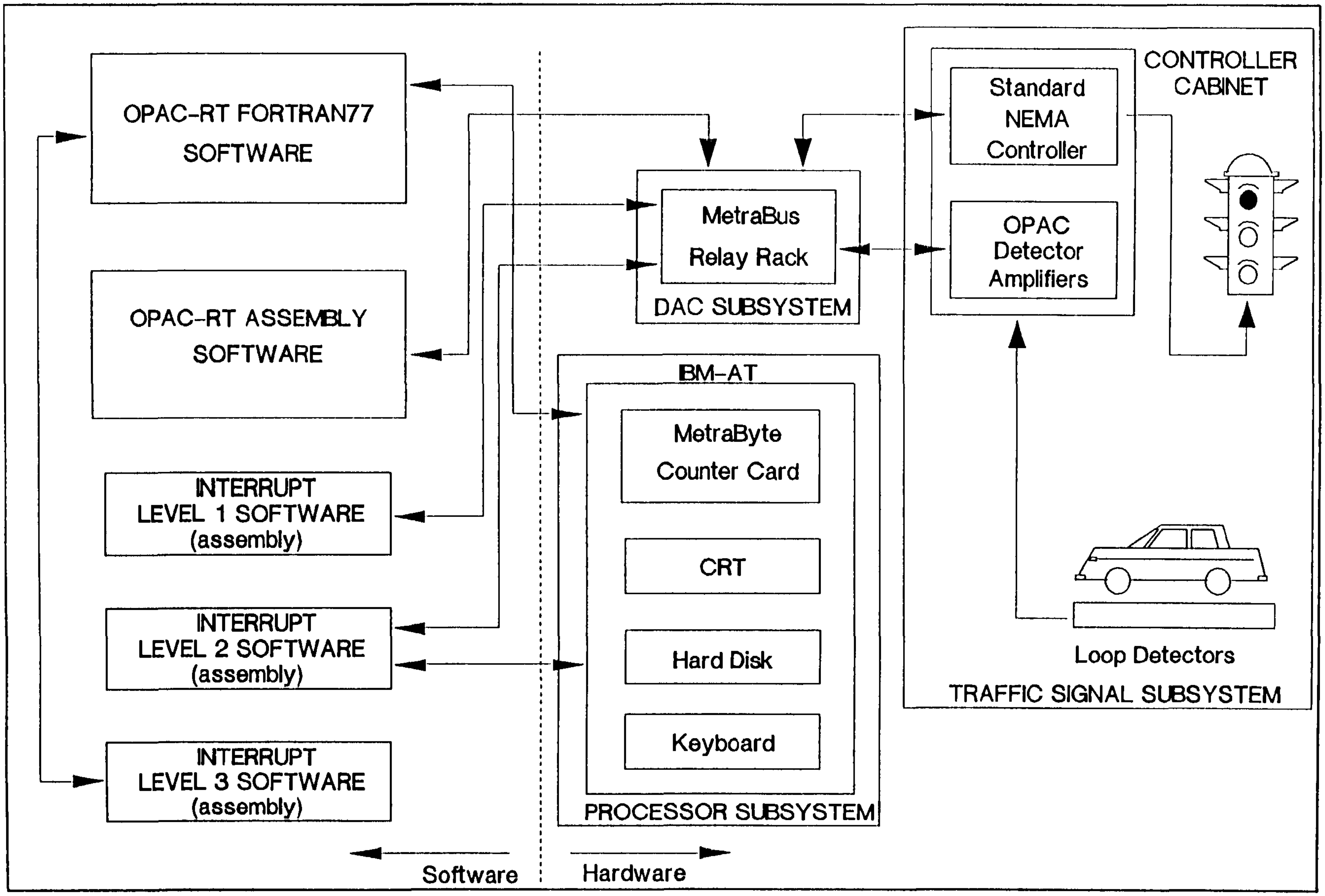


Figure 2. OPAC-RT operating environment.

At any time the HOLD signal is removed, the controller will return to local actuated mode. However, since permanent vehicle calls are applied to both phases, the controller will effectively operate as a pretimed controller until either the HOLD is reapplied or the permanent vehicle calls are removed.

The vehicle detection component consists of inductive loops installed at the intersection approaches. The loops are connected to vehicle detector amplifiers whose outputs are relay contact closures when vehicles are detected.

The Support Software required to run and maintain the OPAC-RT Version 1.0 software includes the following:

- Version 2.0 or later of the MS-DOS or PC-DOS operating system.
- Version 3.31 or later of the MicroSoft FORTRAN77 compiler.
- Version 4.0 or later of MicroSoft Macro Assembler.
- Version 3.05 or later of MicroSoft 8086 Object linker. (An overlay linker should not be used.)
- Any text editor which produces standard DOS text file format.

c. Summary of Processing Logic

The OPAC-RT software performs three primary functions. These are: system set up, optimization/implementation, and system shut down.

(1) Primary System Functions. The system set up function consists of reading user input data, checking for errors, and setting up the interface hardware. The optimization/

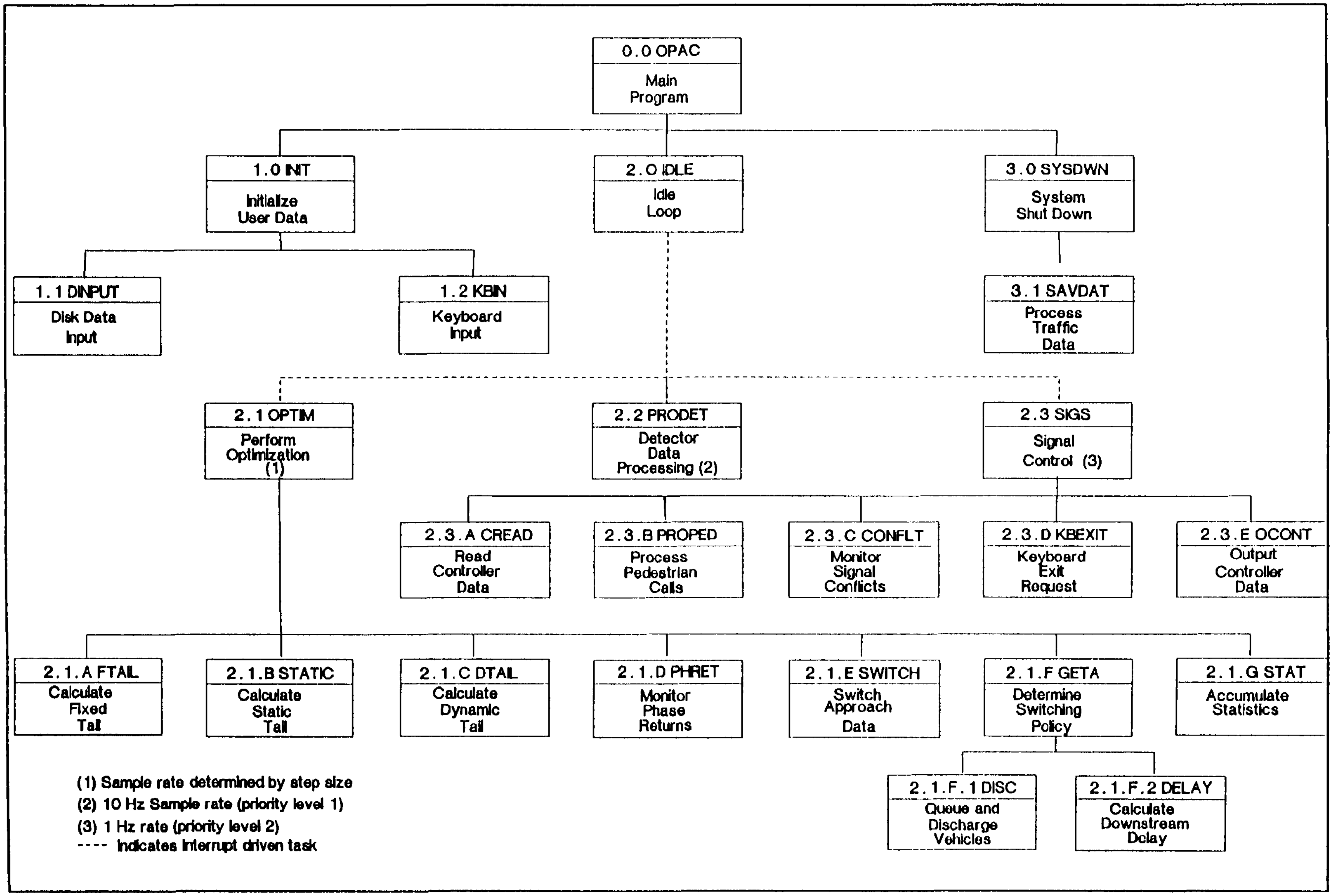
implementation function consists of polling vehicle detectors, calculating switching decisions, and implementing the switching decisions through the controller. The system shut down function consists of disabling the interface hardware and saving operational data on the disk.

(2) Software Organization. The functions of the OPAC-RT software package are organized into three priority levels. The most time critical functions are performed at the highest priority level (Priority Level 1). The least time critical functions are performed at the lowest priority level (Priority Level 3). Modules which have no priority level are background tasks which execute when no other task is executing.

An overview of the organization of the OPAC-RT functions according to priority level is shown in figure 3. As shown, Priority Level 1, the PRODET module, consists of the detector processing algorithm. Priority Level 2, the SIGS module and its associated submodules, includes controller command and monitoring routines. Priority Level 3, the OPTIM module and its associated submodules, includes the optimization routines which determine the most optimal signal timing.

The Priority Level 1 module, detector processing (PRODET), is activated 10 times a second by an interrupt invoked by the external timer card. Any computations being performed at other priority levels are interrupted and suspended when Priority Level 1 is activated. Lower priority level computations are resumed after Priority Level 1 execution has completed.

The detector processing module updates the system time in tenths of seconds and the number of steps since the system was started. Then the module polls each OPAC-RT detector for each of the four approaches to determine if a vehicle has passed over it. Vehicles are added to the appropriate element of an arrival pattern



(1) Sample rate determined by step size
(2) 10 Hz Sample rate (priority level 1)
(3) 1 Hz rate (priority level 2)
---- Indicates interrupt driven task

Figure 3. OPAC-RT Version 1.0 program structure.

array based on the user-input travel time from the OPAC-RT detectors to the stop line. The Priority Level 2 module, controller signal reading and command (SIGS), is executed once per second by an interrupt invoked by the external timer card. Once again, any computations being performed at a lower priority level are interrupted and suspended when Priority Level 2 is activated. The SIGS module reads the current status of various controller signals, including phase green, phase red, and pedestrian walk service, checks the current phase returns against what the software expects them to be, manipulates internal minimum greens and horizon lengths based on pedestrian returns, and sets and clears the HOLD and FORCE-OFF as specified by the optimization algorithm.

In the event that a pedestrian actuation is identified, the SIGS module temporarily changes minimum greens and the horizon length (used by the optimization module) according to user-identified values. The user specifies in the input data file a green extension to be used in the event the controller times a pedestrian phase. It is intended that the user supply values such that the extended internal minimum greens will be equal to or greater than the sum of the WALK and pedestrian clearance intervals. This is done to avoid issuing a FORCE OFF before the controller has timed the WALK and pedestrian clearance intervals. The controller will ignore the FORCE OFF if it is issued before the end of the pedestrian clearance interval; however, phase returns from the controller will not match what the software expects them to be and the OPAC-RT system will automatically shut down, returning the intersection to local actuated control.

The Priority Level 3 module, optimization (OPTIM), is activated every n seconds, where n is a multiple of the user-specified step size. Priority Level 3 is performed when Priority Level 1 and 2 modules are not executing. The optimization module consists of the OPAC9 software modified as specified in 'a. Relationship to the OPAC Strategies' above. The optimization performs an exhaustive search for the optimal switching times assuming both a double and single signal switch occurs within the current project horizon. A count down timer is updated for the SIGS module which will issue the FORCE-OFF command.

The background task executes when none of the Priority Level modules are executing. This task consists of an idle loop which consistently checks whether or not to exit and shut down the system.

2. OPAC-RT Version 2.0: Dual Ring, Eight Phase Operation

The primary objective of Version 2.0 of the OPAC-RT system is to effectively control the signal timing at an isolated intersection controlled by a dual ring, eight phase controller. Only the major phases, typically the through phases, are actually controlled by the system. The minor phases, typically the left turn phases, are treated by OPAC as part of the intergreen period. The minor phases are controlled by the usual gap out/max out strategy.

The system collects vehicle arrival information from upstream detectors as well as signal indications which are supplied as inputs to a modified version of the ROPAC strategy (see chapter 2 for a summary of the strategy). The system then implements the switching decisions output by the optimization algorithm.

The system also stores system conditions throughout the control period. This information includes phase returns, HOLD release times, walk requests, the time of the occurrence of any errors, detector occupancies, and arrival patterns.

a. Relationship to the OPAC Strategies

The optimization software for Version 2.0 of the OPAC-RT system was adapted from that developed for Version 1.0. While the functions of most routines remained unchanged, all the code required rewriting to accommodate the following enhancements:

- Dual ring and single ring multiphase control.
- Independent minimum and maximum greens among phases.
- Vehicle stops as part of the optimization function.
- Occupancy as a measure of congestion.
- Step size independent of green, yellow, and all red interval durations.
- Elimination of the unnecessary servicing of side streets given call-only detectors are present on all phases. It is important that call-only detectors be present because the OPAC detectors are placed so far upstream. Without call detectors, vehicles entering the traffic stream from driveways and shopping centers downstream of the OPAC detectors will not be detected. In very light traffic, the system might not know they were there and would not service them. Without call detectors, the system must assume there are vehicles on opposing phases and service them, sometimes unnecessarily.

The function of the optimization software in Version 2.0 is essentially the same as that for Version 1.0: using current signal and arrival information, determine the optimum ending point for the current phase. Version 2.0 of OPAC-RT controls at most four phases of an eight phase controller. Normally, these are the through phases. If none of the major phases are timing, the optimization is bypassed. More details regarding the processing logic are provided in 'c. Summary of Processing Logic' below.

In Version 1.0, the user is allowed to specify the roll period, or the rate, in intervals or steps, at which the optimization is to be performed. In practice, performing the optimization less than once per step (e.g., every two or three steps) only degrades the performance of the optimization algorithm. Hence, in Version 2.0, the optimization is performed once per step and cannot be changed by the operator.

In Version 2.0, the optimization function was modified to include stops. As indicated in earlier chapters describing the OPAC strategies, each time the optimization function is executed, an exhaustive search of all possible switching decisions for single and double phase changes within the horizon is conducted. For each iteration of the search, estimates of both delay and stops are calculated. Stops are defined to be the sum of the maximum queues on all phases expected to develop over the horizon as a result of the switching decision. The user specifies proportionality factors for both delay and stops to indicate the relative importance of each for determining signal timing. The proportionality constants are equivalent to the 'k' factor used in the TRANSYT traffic simulation and optimization program.

b. System Configuration and Operating Environment

The OPAC-RT Version 2.0 system configuration is essentially the same as that of Version 1.0.

- The Processor Subsystem of the Version 2.0 system, like that of Version 1.0, consists of an IBM-AT microcomputer running at 8-Mhz and includes a minimum of 640K of main memory, at least 1 disk drive with a minimum of 600K available storage, and at least 2 available expansion slots.

- The Data Acquisition and Control (DAC) Subsystem has been expanded to accommodate the expanded control requirements of the dual ring controller.
- The Traffic Signal Subsystem has been modified to include a NEMA certified Eight Phase Dual Ring Digital Controller Unit, a NEMA certified Conflict Monitor, and other equipment normally used in a typical cabinet setup.

The NEMA controller can be configured in the dual-ring mode with leading or lagging turn movements as required at the intersection. OPAC-RT only controls the major phases (normally the through movements) of an intersection; the minor phases are directly controlled by the controller. To avoid the necessity of servicing the side street when there is no traffic, OPAC-RT requires call-only detectors for all phases in use. If this is not possible, then the major phases which do not have call-only detectors should be in vehicle recall.

The controller HOLD inputs are manipulated by the OPAC-RT software to control the operation of the intersection. In this state an external signal applied to the HOLD input of a particular phase will cause the controller to remain in that phase without regard to any external vehicle or pedestrian inputs. Signals to the HOLD inputs are applied on a per ring basis so that it is possible for phase changes to occur in one ring while the other ring is dwelling in a particular phase because of an applied hold.

With the exception of the HOLD inputs applied by OPAC-RT, the controller will time and operate in a normal fashion. Its phase timing will only be modified when the HOLDS are active. Refer to any of various descriptions on eight phase Dual-Ring NEMA controllers for more information.

The Support Software required to run and maintain the OPAC-RT Version 2.0 is the same as that required for Version 1.0 with the exception that Version 4.01 or later of the MicroSoft FORTRAN77 compiler is required in order to optimize the code.

c. Summary of Processing Logic

The OPAC-RT software performs three primary functions. These are: system set up, optimization/implementation, and system shut down.

(1) System Set Up. The system set up function consists of reading user input data, checking for errors, and setting up the interface hardware. During system set up an external to internal phase map is developed. The OPAC-RT system may be used to control any phase configuration from simple two phase operation to any combination of leading and lagging turns in an eight phase configuration.

The eight phase, dual ring controller may by summarized by figure 4. For the OPAC-RT system to control the intersection, at least two and at most four phases may be optimized. The other phases may be skipped or used for minor (e.g., left turning) phases.

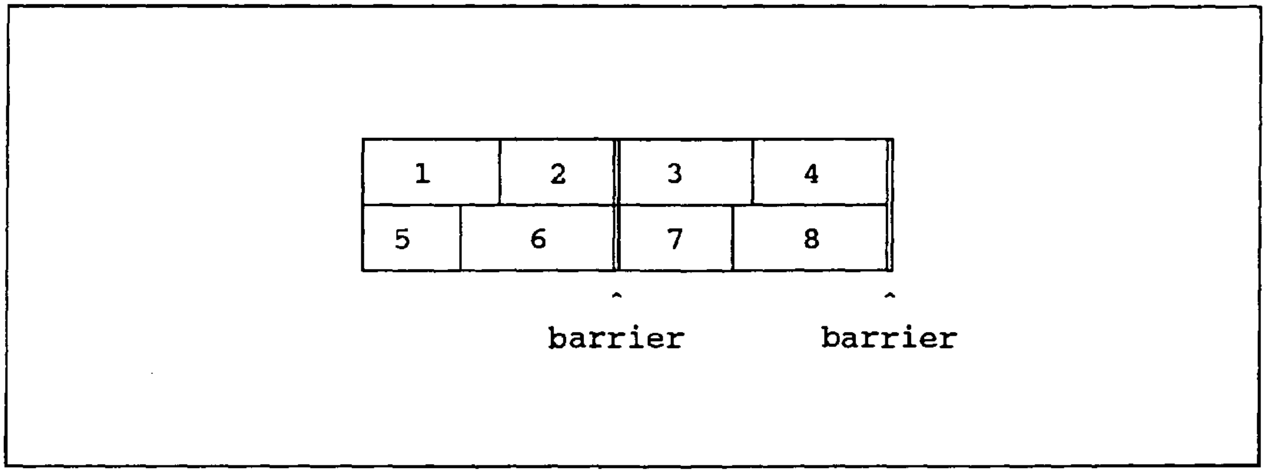


Figure 4. Representation of eight phase, dual ring controller.

In order for the system to be used with all combinations of leading and lagging turns, the OPAC-RT system uses a generalized twelve-phase configuration illustrated in figure 5. With respect to the OPAC-RT system, the user-specified phase configuration is termed 'external' and the generalized representation used by the system is called 'internal.'

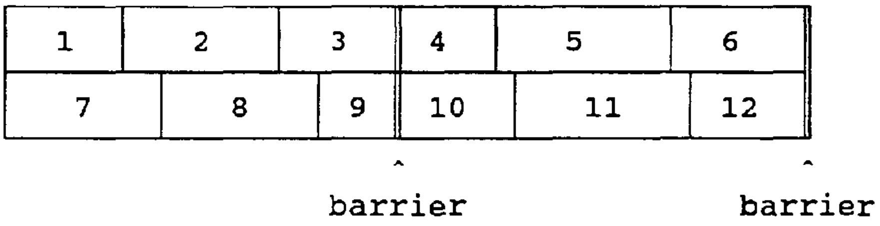
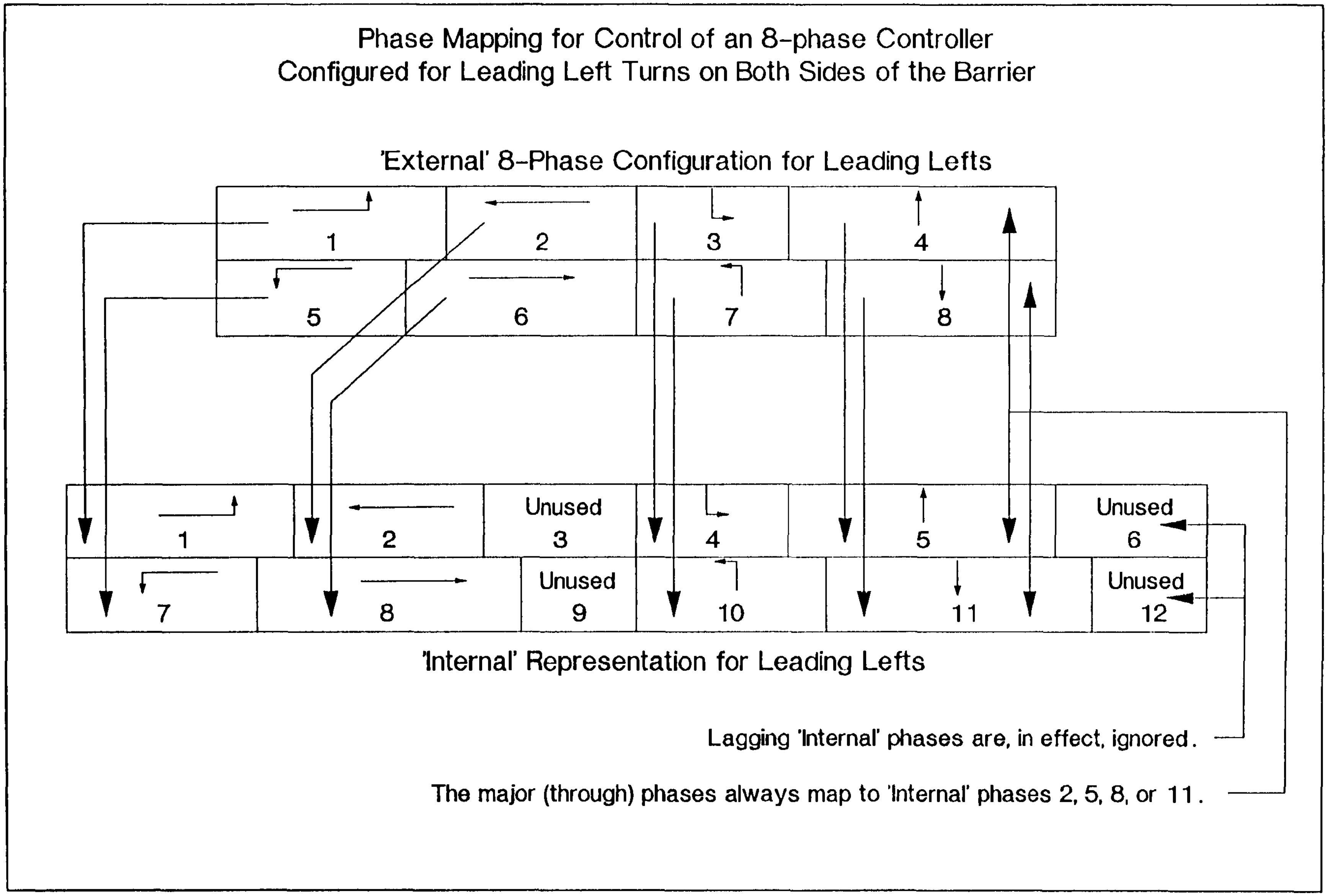


Figure 5. OPAC-RT generalized phase configuration.

Internal phases 2, 5, 8, and 11 are the major phases controlled by the OPAC-RT optimization algorithm. The user defines the external eight phase configuration in terms of major, minor, or unused phases and the order in which they are timed. For example, for two phase operation, the user would specify external phases 1 or 2 and 3 or 4 as major and the remainder as unused. Using this information, an external to internal phase map is generated for processing signal timing information.

For example, an 8-phase configuration with leading lefts on both sides of the barrier would be mapped to the generalized 12-phase configuration as indicated in figure 6. External phases 2, 4, 6, and 8 would be specified as major and external phases 1, 3, 5, and 7 as minor, assuming the operator wishes to control the through phases. All parameters associated with internal phases



Phase Mapping for Control of an 8-phase Controller
Configured for Leading Left Turns on Both Sides of the Barrier

'External' 8-Phase Configuration for Leading Lefts

'Internal' Representation for Leading Lefts

Lagging 'Internal' phases are, in effect, ignored.

The major (through) phases always map to 'Internal' phases 2, 5, 8, or 11.

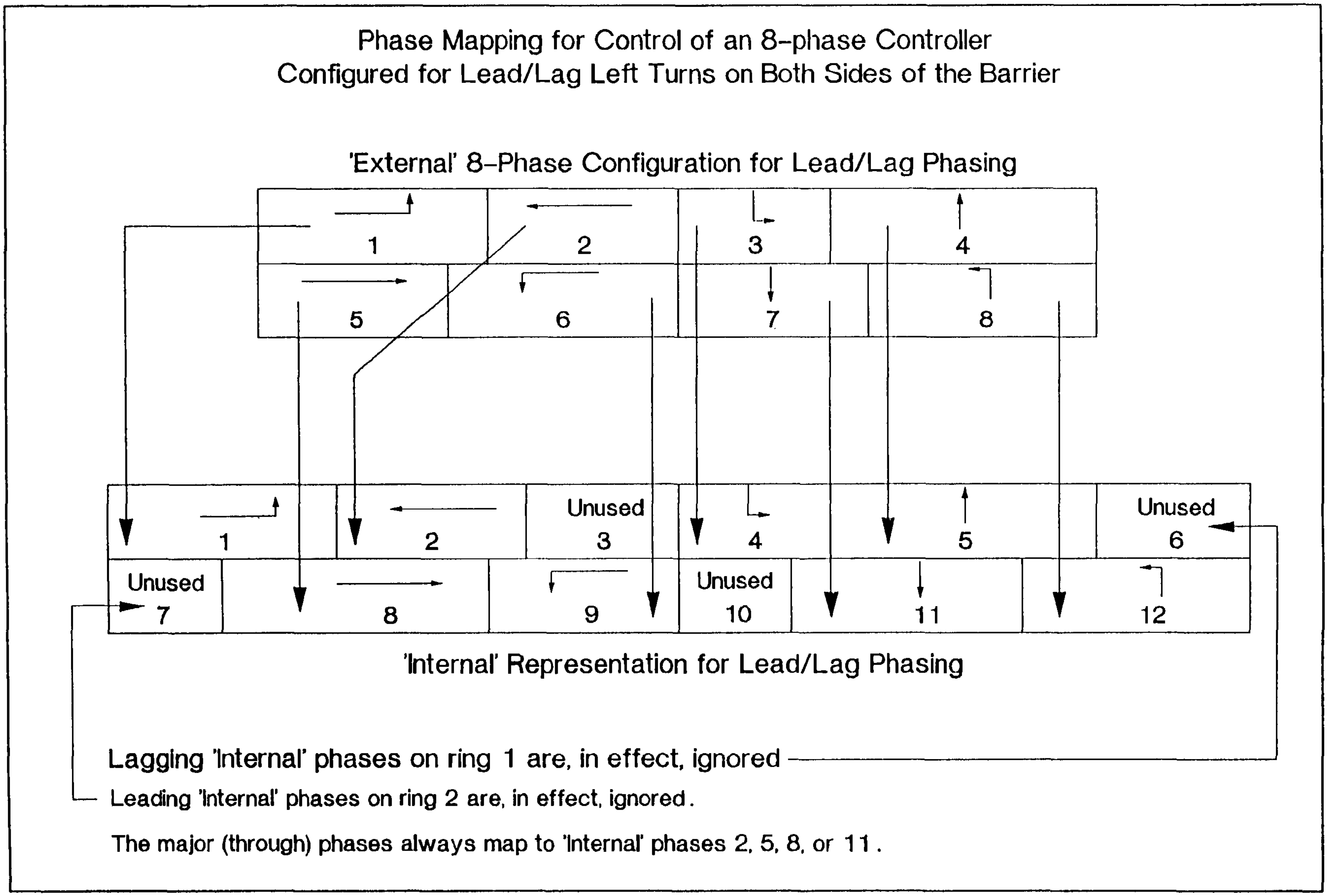
Figure 6. Representing leading left phasing in OPAC-RT Version 2.0.

3, 6, 9, and 12 are set such that the phases are, in effect, ignored.

As another example, an eight phase configuration with lead-lag phasing on both sides of the barrier would be mapped to the internal configuration as indicated in figure 7. External phases 2, 4, 5, and 7 would be specified as major and external phases 1, 3, 6, and 8 as minor, assuming the operator wishes to control the through phases. Internal phases 3, 6, 7, and 10 are, in effect, ignored.

(2) <u>Optimization/Implementation</u>. The optimization/ implementation function consists of polling vehicle detectors; maintaining such timing variables as expected phase durations, cycle length, and the time since the last barrier; accumulating vehicle counts and occupancy measures for calculating smoothed traffic characteristics including volume in vehicles per hour, occupancy, and average speed in miles per hour; calculating switching decisions; and implementing the switching decisions through the controller.

The optimization algorithm of Version 2.0 of the system incorporates many more features than does Version 1.0. One feature of the algorithm is that all timing variables, including minimum and maximum greens, vehicle clearance, pedestrian clearance, etc., are specified independently by phase. In Version 1.0, minimum and maximum greens were the same for both phases. Another feature is that the step size is independent of all minimum green, vehicle clearance, and all red interval durations. In Version 1.0, the cycle was divided into effective green and effective red intervals and minimum and maximum greens and vehicle clearance intervals were all defined in terms of steps.



Phase Mapping for Control of an 8-phase Controller
Configured for Lead/Lag Left Turns on Both Sides of the Barrier

'External' 8-Phase Configuration for Lead/Lag Phasing

'Internal' Representation for Lead/Lag Phasing

Lagging 'Internal' phases on ring 1 are, in effect, ignored

Leading 'Internal' phases on ring 2 are, in effect, ignored.

The major (through) phases always map to 'Internal' phases 2, 5, 8, or 11.

Figure 7. Representing lead/lag phasing in OPAC-RT Version 2.0.

Another feature of the optimization/implementation function is its determination of the duration of the minor phases. The minor, typically left turning, phases are treated by OPAC-RT as part of the intergreen period. Hence, the software must have an approximate, if not exact, duration for each minor phase. Since the exact duration of the minor phases depends on the demand, the software maintains an exponentially smoothed value for the duration of each minor phase. These values are used by the optimization algorithm as the current expected minor phase durations in determining the optimum termination points for the major phases.

Another feature of the software is its approximation of the number of left turning vehicles. Because the OPAC detectors are 400 to 600 ft (120 to 180 m) upstream of the intersection, left turning volumes must be modelled by the software. To do this a smoothed, expected duration for each minor phase is maintained as described above. Based on the current expected phase durations and user-input discharge rates, estimated volumes for each minor phase are calculated. The calculated volumes are assigned to the minor phases and the total volumes, adjusted for the vehicles expected to turn left, are assigned to the major phases.

Another feature of Version 2.0 is that the requirement for mandatory servicing of the minor street has been eliminated. If call-only detectors have been installed for all phases, the logic will permit the controller to rest in the current phase when there are no calls on opposing phases and no opposing phase is in recall. If the current phase(s) has timed its maximum and there are no calls on any opposing phase, the switching decision is ignored and the current phase is allowed to remain green. In this regard, the signal operates like and eight phase controller which dwells in green in the absence of opposing calls.

The optimization algorithm may also be disabled in the presence of congestion as defined by a user-specified occupancy threshold This 'congestion override' capability is provided because:

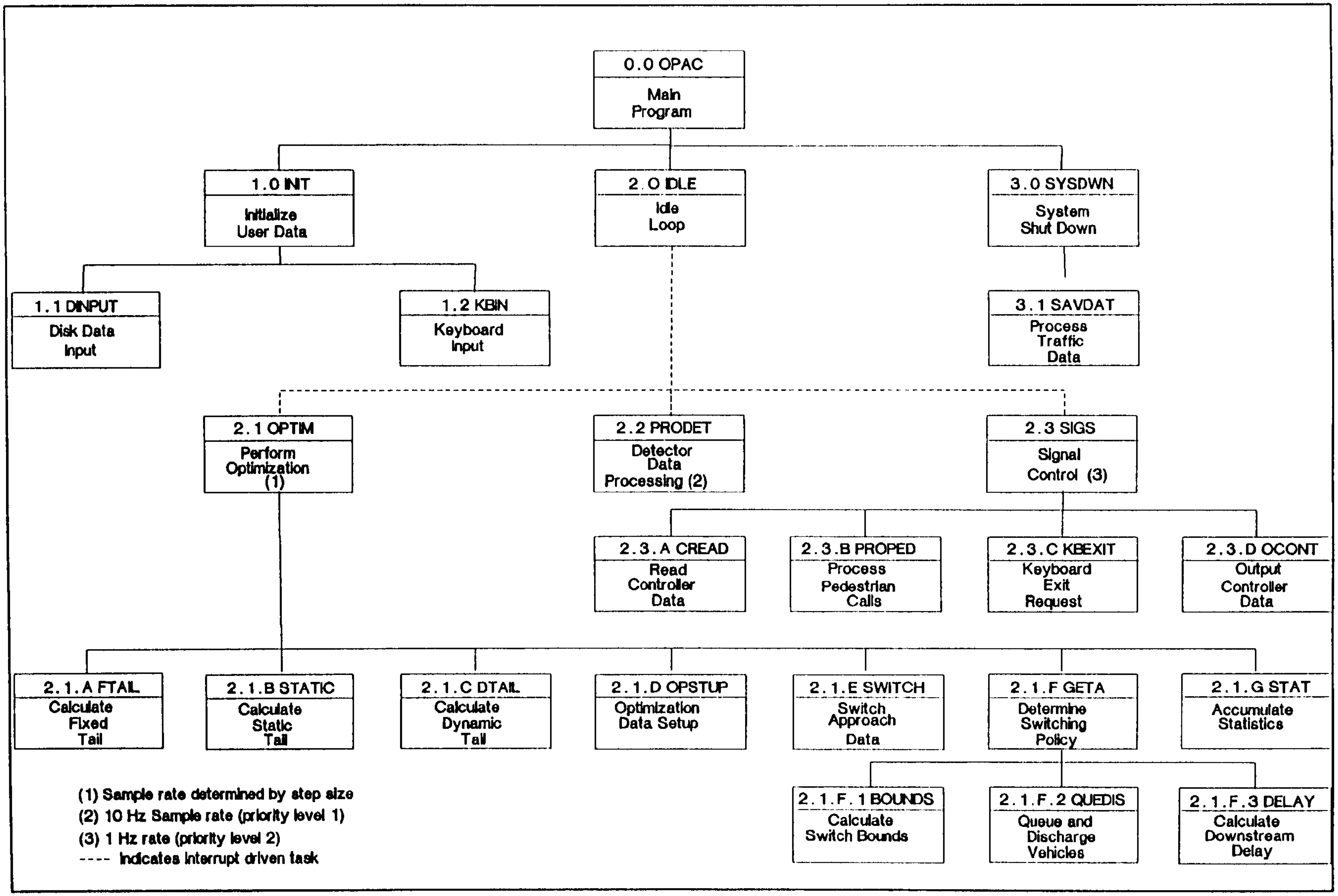
- The OPAC optimization is intended for operation under normal (undersaturated) conditions. During periods of congestion, measures of effectiveness such as queue length might be preferable to stops and delay.
- During periods of congestion, queues may become extremely long, extending over the upstream detectors. As a result, traffic demand will not be accurately measured by OPAC.

Smoothed occupancies for each OPAC detector are calculated during system operation. If the occupancy of the OPAC detectors associated with one of the major phases exceeds the threshold, the switching decision for that phase is ignored and the phase is allowed to time to its maximum. When the occupancies for that phase fall below the threshold, the switching decisions from the optimization algorithm are implemented.

(3) System Shut Down. The system shut down function is performed by disabling the interface hardware and saving operational data on the disk.

(4) Software Organization. As with Version 1.0, the functions of the OPAC-RT Version 2.0 software package are organized into three priority levels. The most time critical functions are performed at the highest priority level (Priority Level 1). The least time critical functions are performed at the lowest priority level (Priority Level 3). Modules which have no priority level are background tasks which execute when no other task is executing.

An overview of the organization of the OPAC-RT Version 2.0 functions according to priority level is shown in figure 8. As shown, Priority Level 1, the PRODET module, consists of the detector processing algorithm. Priority Level 2, the SIGS module and its associated submodules, includes controller command and monitoring routines. Priority Level 3, the OPTIM module and its associated submodules, includes the optimization routines which determine the most optimal signal timing. The execution frequencies of the three priority levels are the same as those for Version 1.0.



(1) Sample rate determined by step size
(2) 10 Hz Sample rate (priority level 1)
(3) 1 Hz rate (priority level 2)
---- Indicates interrupt driven task

Figure 8. OPAC-RT Version 2.0 program structure.

EVALUATION OF THE REAL-TIME OPAC STRATEGY

1. Evaluation Criteria

Two measures of effectiveness were selected for comparing the operation of the intersection under full actuated and OPAC-RT control. These were delay, defined as vehicle-seconds of delay per vehicle, and percentage of stopped vehicles. Average cycle lengths under both modes of operation were also recorded and compared.

2. The Test Plan

For each field test, the plan for testing the on-line OPAC algorithm consisted of two phases. In the first phase, the values of three parameters required by the algorithm were fine tuned. This phase was performed to identify the parameter values which yielded the best OPAC-RT algorithm performance. The parameters included in this process were:

- Saturation flow per approach (Field Tests 1 and 2) or phase (Field Test 3).
- Travel time in seconds from the OPAC-RT detectors to the stop line.
- Horizon length.

The horizon is the time period over which the OPAC-RT optimization algorithm calculates its switching decisions. It consists of a head and a tail portion. In the head portion of the horizon, the algorithm has available real-time vehicle arrival patterns. In the tail portion, the arrival patterns are estimated from historical data. This estimation requires a 'smoothing factor' which was calibrated prior to any field tests. Details of the procedures for the calibration of the smoothing factor and the parameters listed above are provided in appendix B. The actual values used in each field test are provided in the descriptions of the field test sites.

The second phase of the test plan was performed as a 'Before/After' study. In the before study, the actuated controller was in control of the intersection. The test plan called for the collection of volume counts, stops, and delay data on each of 3 days for approximately 3 hours each day. Data were to be collected in 25-minute segments, yielding 18 sets of observations. An observation consisted of volume counts, stops, and delay by approach per cycle. Delay was calculated by recording the number of stopped vehicles on each intersection approach at a fixed data collection time interval and multiplying this number by the time interval.

The 'After' study was conducted in the same manner with the OPAC-RT algorithm in control of the intersection. The plan specified that the 'Before' and 'After' data collection would be conducted on the same days of the week. For example, if the 'Before' data was collected on Tuesday, Wednesday, and Thursday of the first week, the 'After' data would be collected on Tuesday, Wednesday, and Thursday of the second week. Allowances were made for adverse conditions such as bad weather so that a particular field test could be completed in 2 weeks, even if the 'Before' and 'After' data were not collected on the same days of the week. For a more detailed discussion of the field procedures refer to appendix C.

3. Data Reduction Procedures

Although data was collected on a per cycle basis, it was necessary to normalize this data to account for the different cycle lengths. For each cycle, volume was converted to a measure of flow in vehicles per hour. Total delay was divided by the number of vehicles entering the intersection to obtain the more meaningful delay measure of vehicle-seconds per vehicle. The number of stops per cycle was divided by the number of vehicles to obtain percent stops.

In evaluating OPAC-RT system, a simple comparison of the observations of delay and percent stops under full actuated and OPAC-RT control was determined to be inadequate to develop a full understanding of the algorithm's operation. It was postulated that the performance of the OPAC-RT algorithm would be better understood if measured as a function of volume conditions on the major and minor streets. This approach to the evaluation was based on some constraints of both Version 1.0 of the algorithm and the actuated controller. Version 1.0 requires at least one phase change per horizon. Thus, even if there are no calls from the side street, OPAC-RT will service the side street once per horizon and cause delay to the major street. The actuated controller will not change phases unless there is a call from the side street, thus there is no delay to the major street when there is no volume on the side street.

On the other hand, the actuated controller cannot distinguish one call on the minor street from many calls on the major street. In other words, if volumes on the major street are high and volumes on the minor street low, the actuated controller may cause delay to the major street because it assigns the same worth to the one vehicle on the minor street as it assigns the many vehicles on the major street. The OPAC-RT algorithm has counted the many vehicles and considers them more important (i.e., there would be more delay if they were stopped) than the one vehicle on the minor street.

Thus, it seems plausible that the relative performance of the OPAC-RT algorithm would depend upon the different volume conditions on the major and minor streets. Therefore, it was proposed that the delay and percent stops data be stratified by categories of low, medium, and high volumes. Using vehicles per hour as the definition of flow, an average flow and standard deviation in flow at each intersection during the testing period were calculated. Statistically, for a normal distribution, 30 percent of the data lies less than one half a standard deviation below the mean and 30 percent lies greater than one half a standard deviation above the mean. For large samples (greater than 100-200 cases) from infinite or very large (relative to the sample size) populations, sample distributions may be approximated by a normal distribution, even if the population distribution is not normal.(4) Therefore, the categories of low, medium and high volumes were defined as follows:

Low: $\text{Flow} < \text{Mean} - (1/2 * \text{STD})$
Medium: $\text{Mean} - (1/2 * \text{STD}) \leq \text{Flow} \leq \text{Mean} + (1/2 * \text{STD})$
High: $\text{Flow} > \text{Mean} + 1/2 * \text{STD}$

where: Flow = measured flow for individual observations.
Mean = the mean flow over all data for a particular field study.
STD = the standard deviation in flow over all data for the field study.

Table 1 summarizes the nine volume conditions or classes on the major and minor streets which result from this stratification. The numbers in the cells of the table are labels for the various volume classes. Further references to these classes will be made in terms of the corresponding numbers.

For each field study the per cycle observations of delay and percent stops were sorted into appropriate cells based on volume conditions and intersection control. Those cycles during which

Table 1. Field test data volume class definitions.

		Major Street		
		Low	Medium	High
Minor Street	Low	1	4	7
	Medium	2	5	8
	High	3	6	9

disruptive events such as pedestrian calls, the presence of oversized or stalled vehicles, or the passage of emergency vehicles occurred were deleted, leaving a total of 1208 observations available for analysis. The reasons for deleting observations during which vehicles stalled, emergency vehicles passed, or oversized vehicles disrupted traffic seem intuitively obvious: these events disrupt traffic flow and associated data are therefore not representative of operation under ideal conditions. The reasons for deleting cycles during which pedestrian calls are serviced may not seem so obvious.

Servicing pedestrians may also disrupt traffic; the right lane of traffic may be stopped to allow the pedestrians to cross the street. However, even if pedestrians did not affect traffic, it might not be possible to implement the optimum phase durations calculated by the OPAC-RT signal timing optimization algorithm since they might violate walk and pedestrian clearance requirements. Since operation under OPAC-RT might be less than optimum during cycles where pedestrian calls are serviced, these cycles were also deleted.

While an appropriate analysis of this stratified data would yield an indication of the volume conditions under which the OPAC-RT system might perform better or worse than the actuated controller, the results using per cycle data must be considered with care. Basically, on a per cycle basis, traffic data is very erratic and does not say much about overall traffic or intersection performance. However, accumulated over some period of time, the data begins to be more representative of overall intersection performance.

In determining a way to evaluate the intersection, the problem becomes finding an appropriate time period over which to accumulate the data. A typical period for collecting volume counts is 15 minutes. During the field studies, particularly the second and third studies, it was very difficult to find 15 minutes of consecutive data (that is, 15 minutes during which no cycles were deleted because of pedestrians or other disruptive events). However, it was possible to accumulate the data into several 10-minute periods of consecutive data. Accumulated over smaller time periods, the data appeared to still be erratic. Hence, in addition to stratifying the per cycle delay and stops data by volume classes, both delay and stops were aggregated into time units of approximately 10 minutes or 600 seconds. These data were used to determine the more average performance of the intersection under OPAC-RT control as compared with that under actuated control.

4. Analysis Procedures

The analysis procedures described below were applied to the data from individual field studies and to the data combined from Field Tests 1 and 2 since at both sites the intersection was two phase.

a. Per Cycle Data

The optimization algorithm in Version 1.0 uses delay as its measure of effectiveness. Version 2.0 uses a function of both delay and stops as its measure of effectiveness. Stratification of the per cycle field test data - both delay and percent stops - as defined in '3. Data Reduction Procedures' above lends itself to a two-way analysis of variance. The analysis of variance would determine whether there was any interaction between the two factors of intersection control (actuated or OPAC-RT system control) and volume class, whether there was any difference in operation of the intersection under full actuated or OPAC-RT system control as measured by delay and percent stops, and whether there were any differences in delay or percent stops among the volume classes.

While the analysis of variance is a powerful tool in hypothesis testing, it has as one of its assumptions that the observations are taken from normal populations. While in many cases this assumption is acceptable, it may or may not be so in the case of delay measures. The Kruskal-Wallis test is a nonparametric analysis used to test the hypothesis that k (in this case two) independent samples are from identical populations. It is an alternative to a one-way analysis of variance and does not require the assumption of normal populations.

Hence, in order to avoid the unnecessary assumption of normal populations, the nonparametric Kruskal-Wallis test was performed on the delay data for each volume class as defined in '3. Data Reduction Procedures' above. While this test does not yield any measure of the interaction between the mode of intersection control and volume class, it does determine if intersection performance was significantly different between the full actuated or OPAC-RT system modes of intersection control.

The other measure of effectiveness was percent stops. This data was also stratified by volume conditions on the major and minor street. Again, nonparametric Kruskal-Wallis tests comparing percent stops under actuated and OPAC-RT system control for each volume class were used to analyze the data.

As indicated in '3. Data Reduction Procedures' above, per cycle traffic data tends to be very erratic. The analysis of this data as described above proved to be inconclusive. For the most part, there appeared to be no difference in the performance of the intersection under OPAC-RT and actuated control. A regression analysis of the per cycle data designed to determine a linear relationship, if any, between volume and delay proved completely inadequate. For these reasons, the analysis of the per cycle data was abandoned in favor of the aggregated data.

b. Aggregated Data

For each method of intersection control - actuated and OPAC-RT - a relationship between delay and volume was sought. Various models were analyzed using regression and Analysis of Variance tests to determine a best fit to the data. Other descriptive parameters, including mean, variance and standard deviation, were calculated to determine the relative performance of the intersection under OPAC-RT and actuated control. Since the analysis of the per cycle data proved inconclusive, the analysis of the aggregated data is the basis on which the conclusions regarding the performance of the OPAC-RT system are made.

5. Field Test 1

a. The Test Site

The location chosen for the first field test, the initial testing of the on-line OPAC strategy, was the intersection of North George Mason Drive and North 16th Street in Arlington, Virginia. This particular intersection was chosen in accordance with the requirements of the project. It is a two phase full actuated intersection with one phase serving two multilane approaches. The intersection also offers low to moderate volume levels.

Figure 9 illustrates the physical layout of the intersection. Detectors supplying information to the OPAC-RT system were located approximately 600 ft (180 m) from the stop lines. Call-only detectors at the stop line in each lane were 6 ft by 50 ft (1.8 m by 15 m). The intersection currently operates under loop/occupancy control by stopbar detectors.

Critical OPAC-RT input parameters were calibrated as specified by the test plan. The saturation flows used were:

- Northbound George Mason - 6480 veh/hr.
- Southbound George Mason - 5220 veh/hr.
- Eastbound 16th Street - 3150 veh/hr.
- Westbound 16th Street - 2250 veh/hr.

Travel times from the OPAC-RT detectors to the stop lines were all 12 seconds. The horizon length was 12 steps or 48 seconds. The step size was 4 seconds. The head period of the projection horizon was 3 steps. Table 2 summarizes the controller settings while the OPAC-RT system was on-line. Under actuated control, the settings were the same, except that vehicle recall was set to OFF for both phases.

b. Deviations from the Test Plan

Due to some adverse weather conditions, the 'Before' and 'After' data collections could not be performed on the same days of the week. The 'Before' data was collected on Tuesday, Wednesday, and Thursday, June 9, 10, and 11, 1987 and on Monday, June 15. The

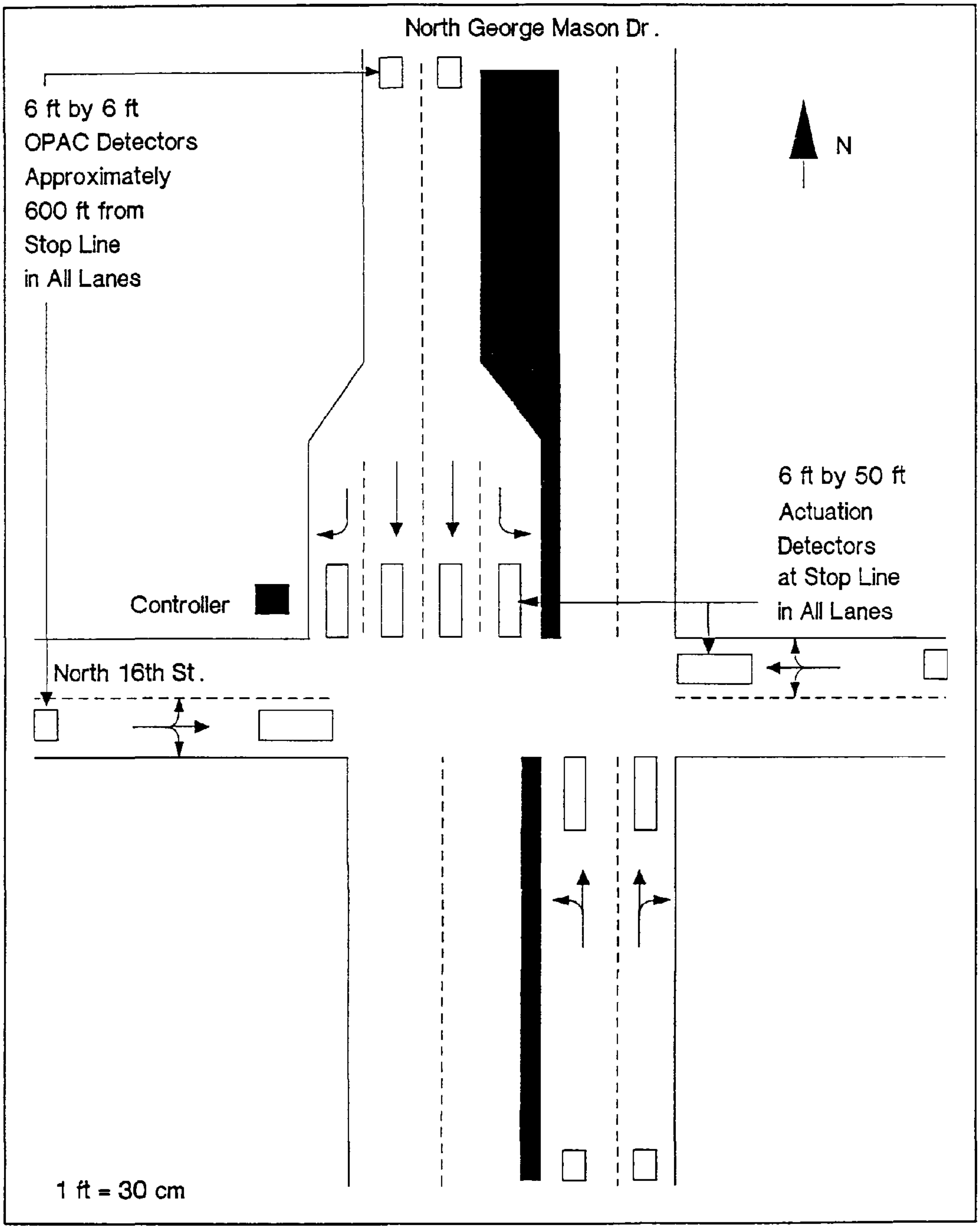


Figure 9. Field Test 1 test site - Arlington County, Virginia.

Table 2. Field Test 1 controller settings.

THUMBWHEEL SWITCH SETTINGS			
		PHASE 1	PHASE 2
MIN GRN	-	5	5
PASSAGE	-	2	2
YELLOW	-	4	4
RED CLEAR	-	0	0
MAX I	-	40	30
MAX II	-	40	30
WALK	-	7	10
PED CLEAR	-	8	20
SEC/ACT	-	0	0
TIME TO REDUCE	-	0	0
BEFORE REDUCTION	-	0	0
MIN GAP	-	0	0
TOGGLE SWITCH SETTINGS			
PED RECALL	-	OFF	OFF
WALK	-	STEADY	STEADY
RECALL	-	EXT	EXT
MEMORY	-	OFF	OFF

'After' study was conducted on Tuesday, Wednesday, and Thursday, June 16, 17, and 18, 1987.

c. The Test Results

The per cycle observations of delay and stops were sorted by mode of intersection control (actuated or OPAC-RT). Those cycles during which disruptive events such as pedestrian calls, the presence of oversized or stalled vehicles, or the passage of emergency vehicles occurred were deleted from the analysis. The remaining observations were then aggregated over periods of approximately 600 seconds.

(1) Delay. Figures 10 and 11 are scatter plots of the aggregated data under actuated and OPAC-RT control, respectively. Of several linear and nonlinear models, a hyperbolic model yielded the best results from the regression analysis. Figure 12 illustrates both sets of data and the regression models. The regression results, summarized in table 3, indicate that the model is very poor. The main reason for this is probably because of the small range in values for the independent variable, flow. This data was combined with that from Field Test 2 and the resulting regression equation proved much more satisfactory. See '7. Field Tests 1 and 2 Combined' for a discussion of the results.

The average delay for the aggregated data under actuated control was 6.29 seconds. Under OPAC-RT system control, the average delay was 6.04 seconds. On the average, then, OPAC-RT yielded a 3.9 percent reduction in delay to vehicles.

The results of the first field test indicate that the OPAC-RT Version 1.0 system has the potential for improving the operation of isolated intersections. At the lower volumes at this intersection, the average delay under actuated and OPAC-RT system control were essentially identical. At the higher volumes, however, the difference became larger. Thus it appears that at lower volumes the intersection performs better under full

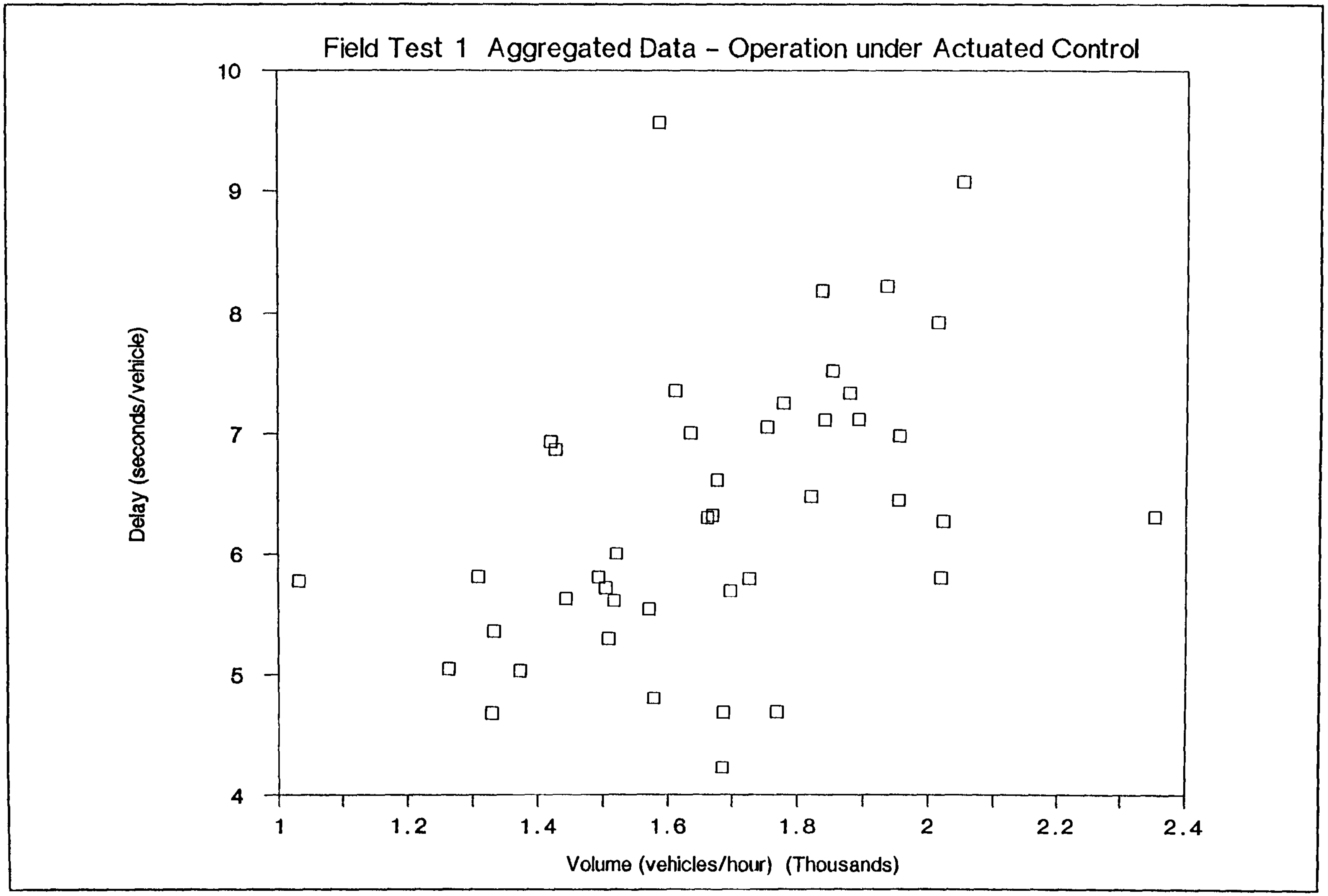


Figure 10. Scatter plot of Field Test 1 aggregated delay data - actuated control.

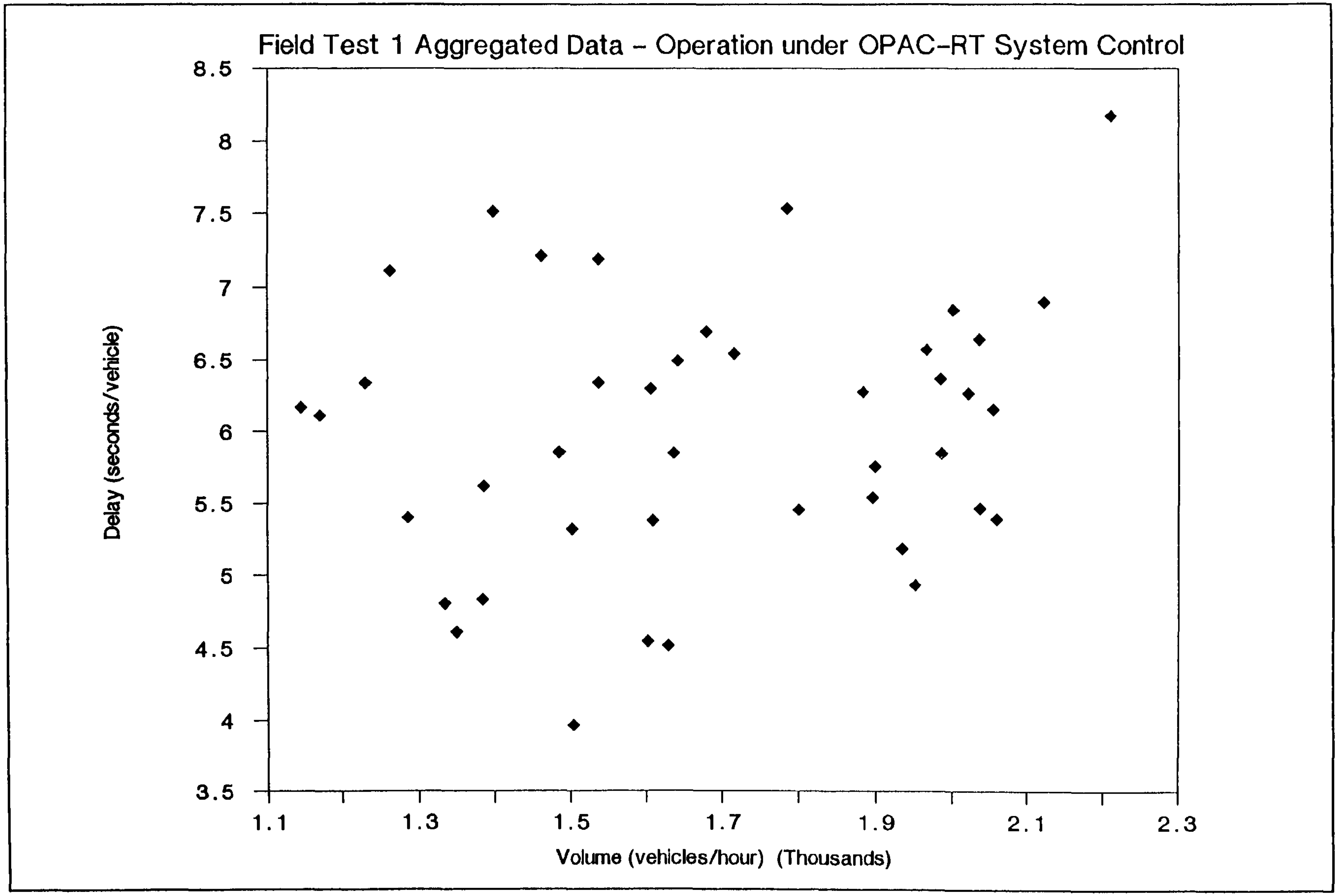


Figure 11. Scatter Plot of Field Test 1 aggregated delay data - OPAC-RT system control.

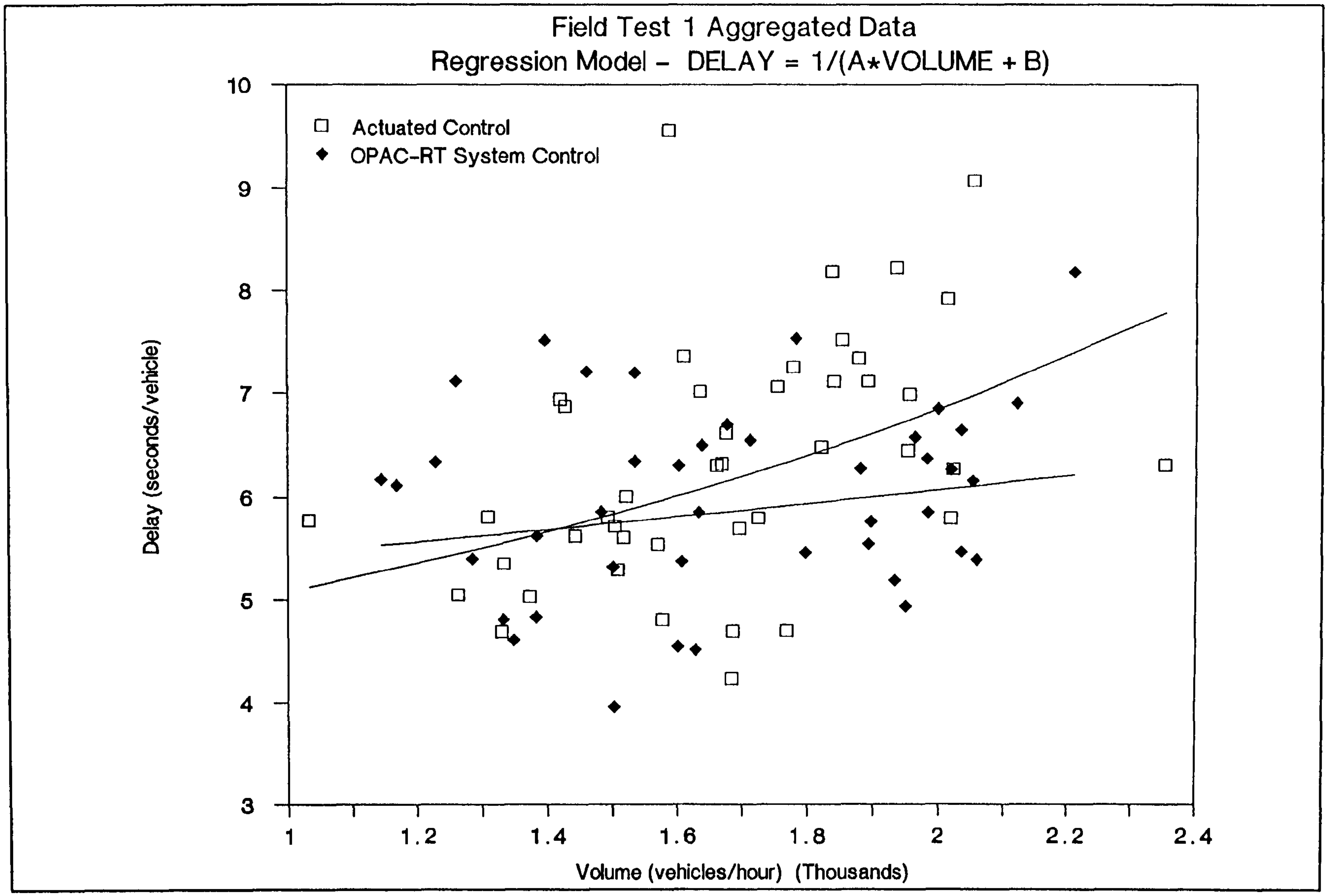


Figure 12. Field Test 1 aggregated delay data - regression results.

Table 3. Summary of regression results for delay - Field Test 1.

NONLINEAR (HYPERBOLIC) REGRESSION – $\text{DELAY} = (A_0 * \text{VOLUME} + A_1)^{-1}$

REGRESSION COEFFICIENTS

VARIABLE	ACTUATED CONTROL	OPAC-RT CONTROL
Volume (A_0)	-0.00005	-0.00001
Constant (A_1)	0.2427	0.2018

OTHER STATISTICS

	ACTUATED CONTROL	OPAC-RT CONTROL
R SQUARED	0.1916	0.0386
SAMPLE SIZE	43	42

actuated control, but at higher volumes performance is better under OPAC-RT Version 1.0 system control.

It must be recognized, however, that the OPAC-RT Version 1.0 requirement that the minor side street be serviced even though there were no vehicle calls significantly degraded OPAC's performance at the low traffic volumes. To make more definitive statements regarding the viability of the OPAC-RT system, an analysis of an intersection with a wider range in flows - particularly higher flows - is required. This was taken into consideration in selecting the second field test site.

(2) Percent Stops. In a manner similar to the delay data, the stops data (total vehicles and stopping vehicles) was aggregated into time periods of approximately 600 seconds. Despite the fact that Version 1.0 of the OPAC-RT does not optimize for stops, the percentage of stopping vehicles was decreased under OPAC-RT control on the average of 1.6 percent. This decrease is almost insignificant but may be due, in part, to the slightly higher average cycle length observed under OPAC-RT system control. In general, past research has shown that shorter cycle lengths increase stopping percentages.

(3) Cycle Length. On the average, the cycle lengths under actuated and OPAC-RT control were similar. Under actuated control, the average cycle length was 40 seconds. Under OPAC-RT system control, the average cycle length was 44 seconds. Despite the slightly higher average cycle length, both delay and stops were decreased on the average under OPAC-RT system control. While the improvements in performance were modest, it must again be recognized that several requirements of the Version 1.0 system, including required servicing of the minor side street and equal minimum and maximum greens for each phase, degrade the performance of the OPAC algorithm, particularly at low volumes.

6. Field Test 2

a. The Test Site

The location chosen for the second field test was the intersection of Flowing Wells Road and Prince Road in Tucson, Arizona. At the time of the second field test it was a two phase semi-actuated intersection with both phases serving multi-lane approaches. The intersection also offers moderate volume levels. Part of a computer controlled network, this intersection was placed off-line while the field study data collection team collected data for operation under OPAC-RT and actuated control.

Figure 13 illustrates the physical layout of the intersection. Call-only and OPAC detectors and their locations with respect to the stop lines at the intersection are shown in the figure.

Critical OPAC-RT input parameters were calibrated according to the test plan. The saturation flows used were:

- Northbound Flowing Wells - 4320 veh/hr.
- Southbound Flowing Wells - 4320 veh/hr.
- Eastbound Prince Street - 4860 veh/hr.
- Westbound Prince Street - 5130 veh/hr.

Travel times from the OPAC-RT detectors to the stop lines were all 12 seconds. The horizon length was 15 steps or 60 seconds. The step size was 4 seconds. The head period of the projection horizon was 3 steps. Table 4 summarizes the controller settings while the OPAC-RT system was on-line. Under actuated control, the settings were the same, except that vehicle recall was set to OFF for phase 2.

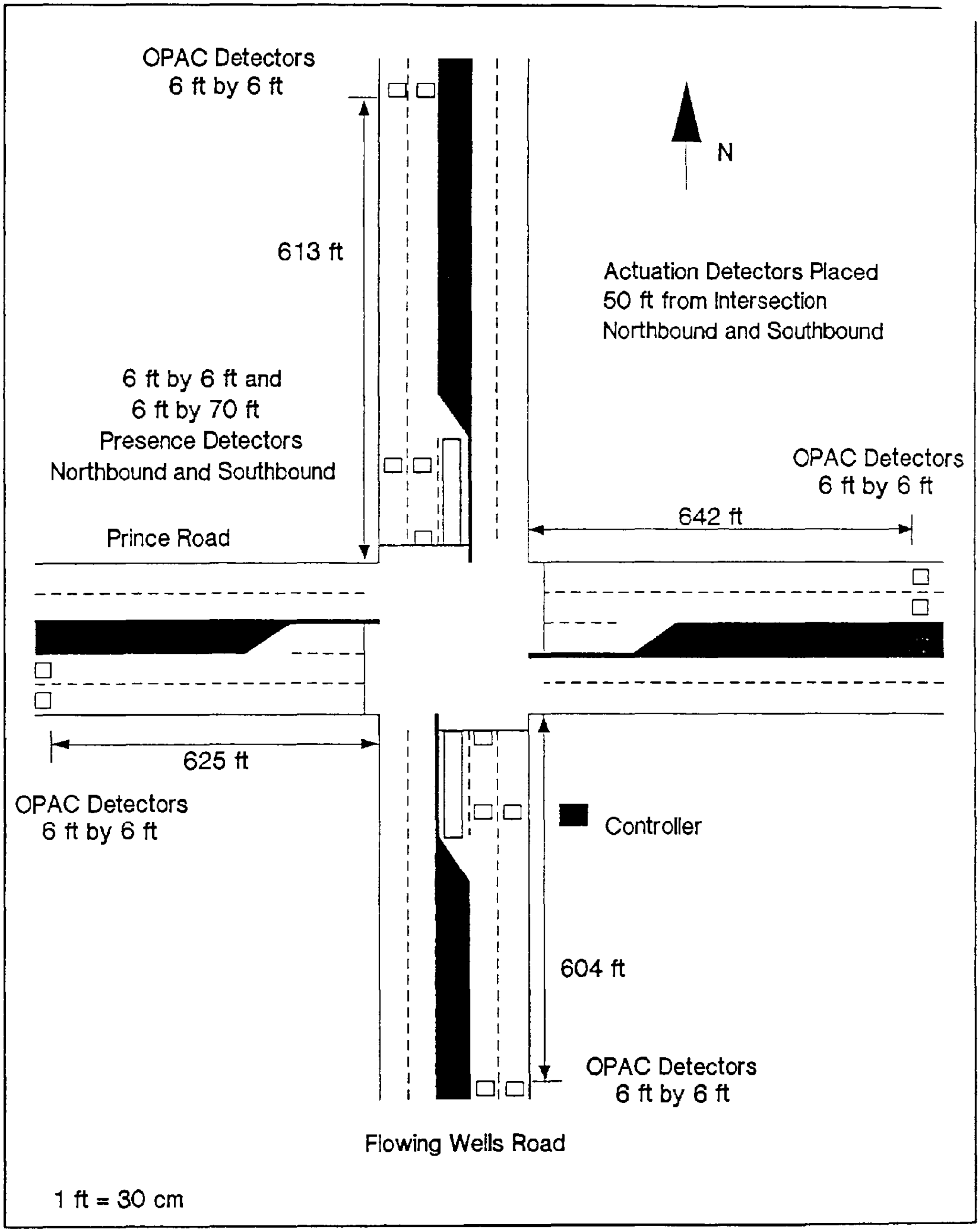


Figure 13. Field Test 2 test site - Tucson, Arizona.

Table 4. Field Test 2 controller settings.

THUMBWHEEL SWITCH SETTINGS			
		PHASE 1	PHASE 2
MIN GRN	-	15	10
PASSAGE	-	2	2
YELLOW	-	3	3
RED CLEAR	-	1	1
MAX I	-	40	35
MAX II	-	40	60
WALK	-	7	7
PED CLEAR	-	14	13
SEC/ACT	-	0	0
TIME TO REDUCE	-	0	0
BEFORE REDUCTION	-	0	0
MIN GAP	-	0	0
TOGGLE SWITCH SETTINGS			
PED RECALL	-	OFF	OFF
WALK	-	STEADY	STEADY
RECALL	-	EXT	EXT
MEMORY	-	OFF	OFF

b. Deviations from the Test Plan

The field test was originally scheduled for the weeks of November 8 and November 15, 1987. Due to problems with both equipment and personnel, the field test did not begin until November 16, 1987. The data for which the intersection was under actuated control was collected on Monday, Tuesday, and Wednesday of the week of 15 November. Parameter calibration was conducted on Thursday, 19 November and the second part of the study was conducted on 20, 23, and 24 November, 1987.

c. The Test Results

The per cycle observations of delay and stops were sorted by mode of intersection control (actuated or OPAC-RT). Those cycles during which disruptive events such as pedestrian calls, the presence of oversized or stalled vehicles, or the passage of emergency vehicles occurred were deleted from the analysis. The remaining observations were then aggregated over periods of approximately 600 seconds.

(1) Delay. Figures 14 and 15 are scatter plots of the aggregated data under actuated and OPAC-RT control, respectively. Of several linear and nonlinear models, a hyperbolic model yielded the best results from the regression analysis. Figure 16 illustrates both sets of data and the regression models. The regression results, summarized in table 5, indicate that the model is very poor. As with the data from Field Test 1, the main reason for this is probably because of the small range in values for the independent variable, flow. This data was combined with that from Field Test 1 and the resulting regression equation proved much more satisfactory. See '7. Field Tests 1 and 2 Combined' for a discussion of the results.

The average delay for the aggregated data under actuated control was 15.81 seconds. Under OPAC-RT system control, the average delay was 13.29 seconds. In addition, the volumes under OPAC-RT control were found to be higher by an average of 4.12 percent.

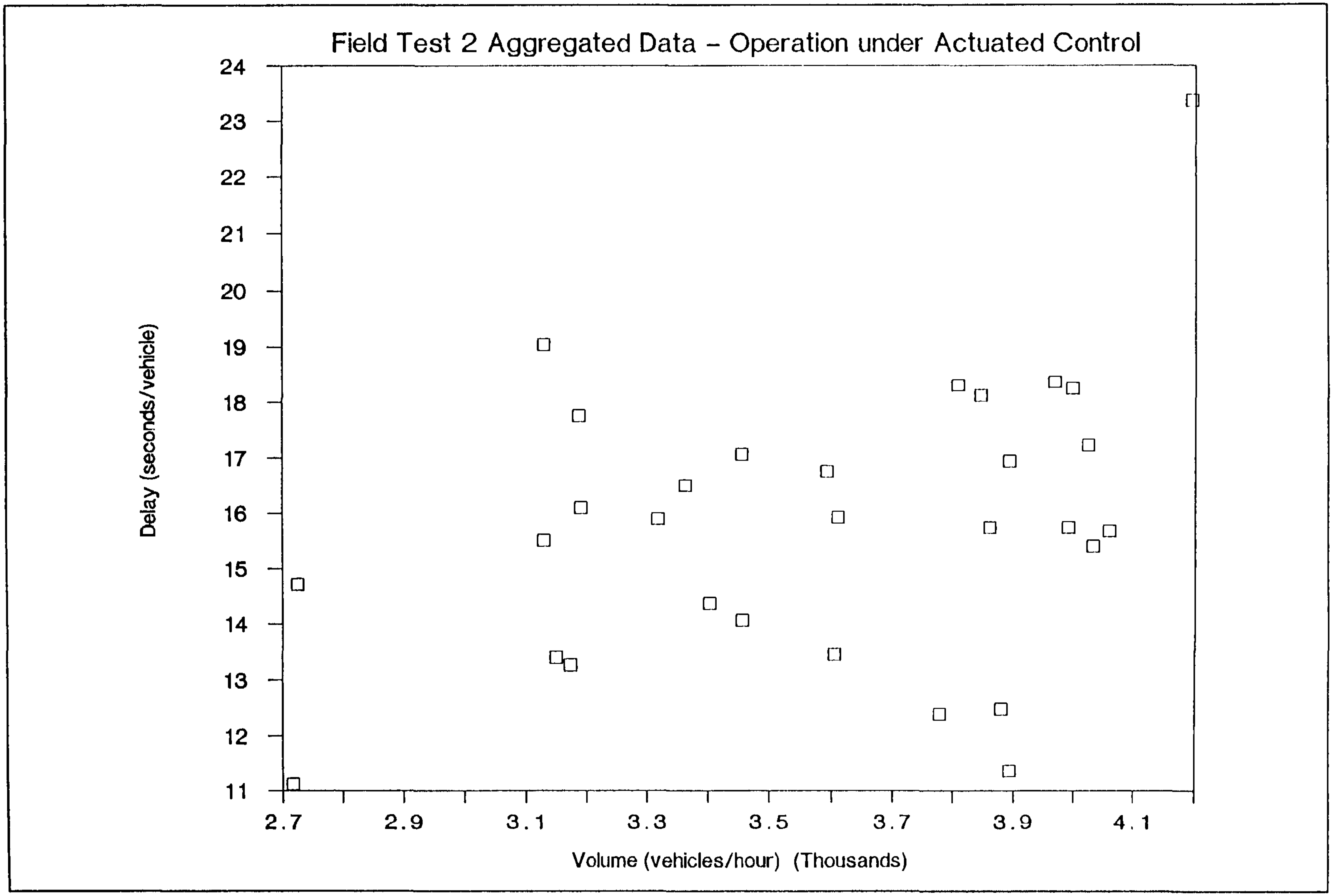


Figure 14. Scatter plot of Field Test 2 aggregated delay data - actuated control.

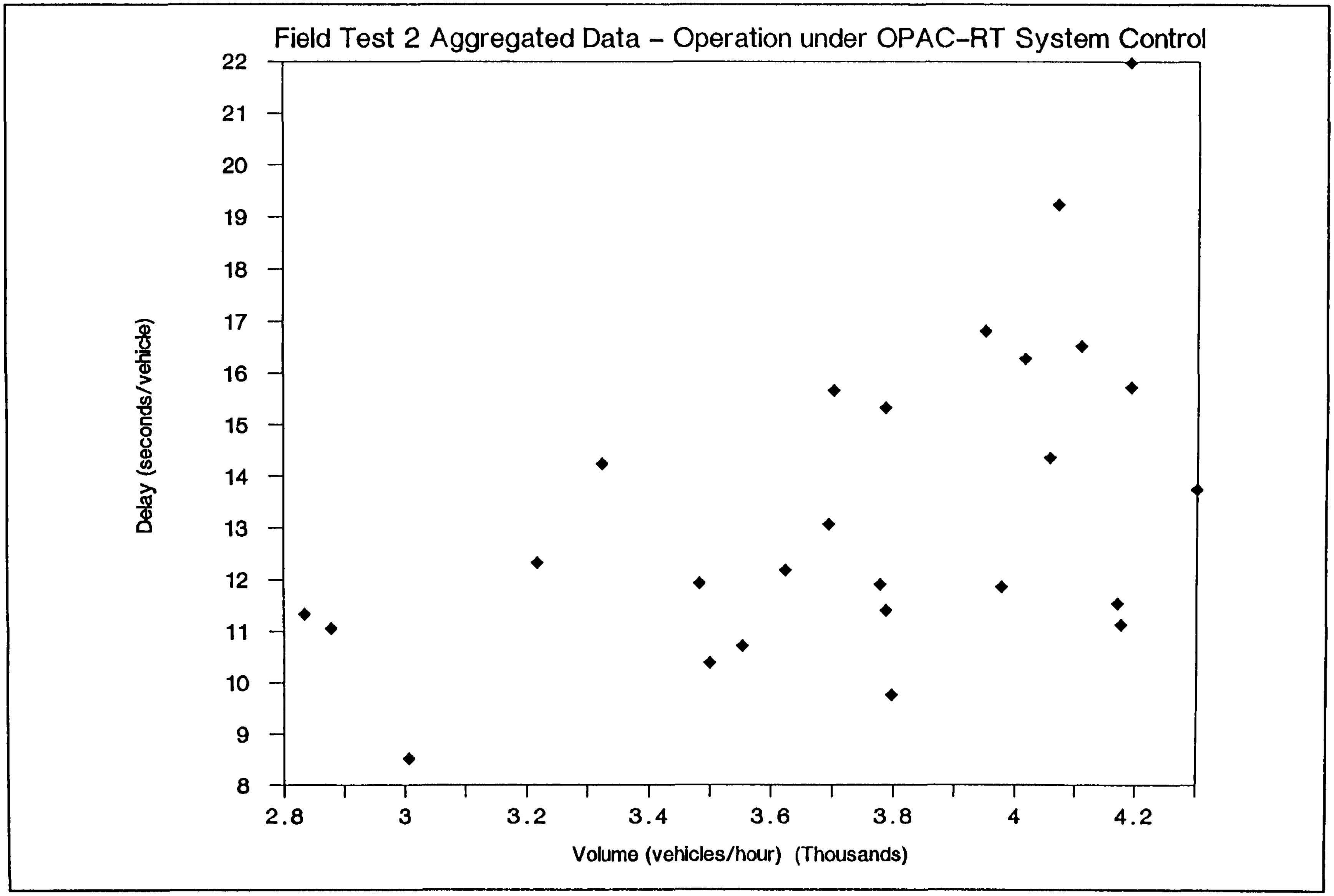


Figure 15. Scatter plot of Field Test 2 aggregated delay data - OPAC-RT system control.

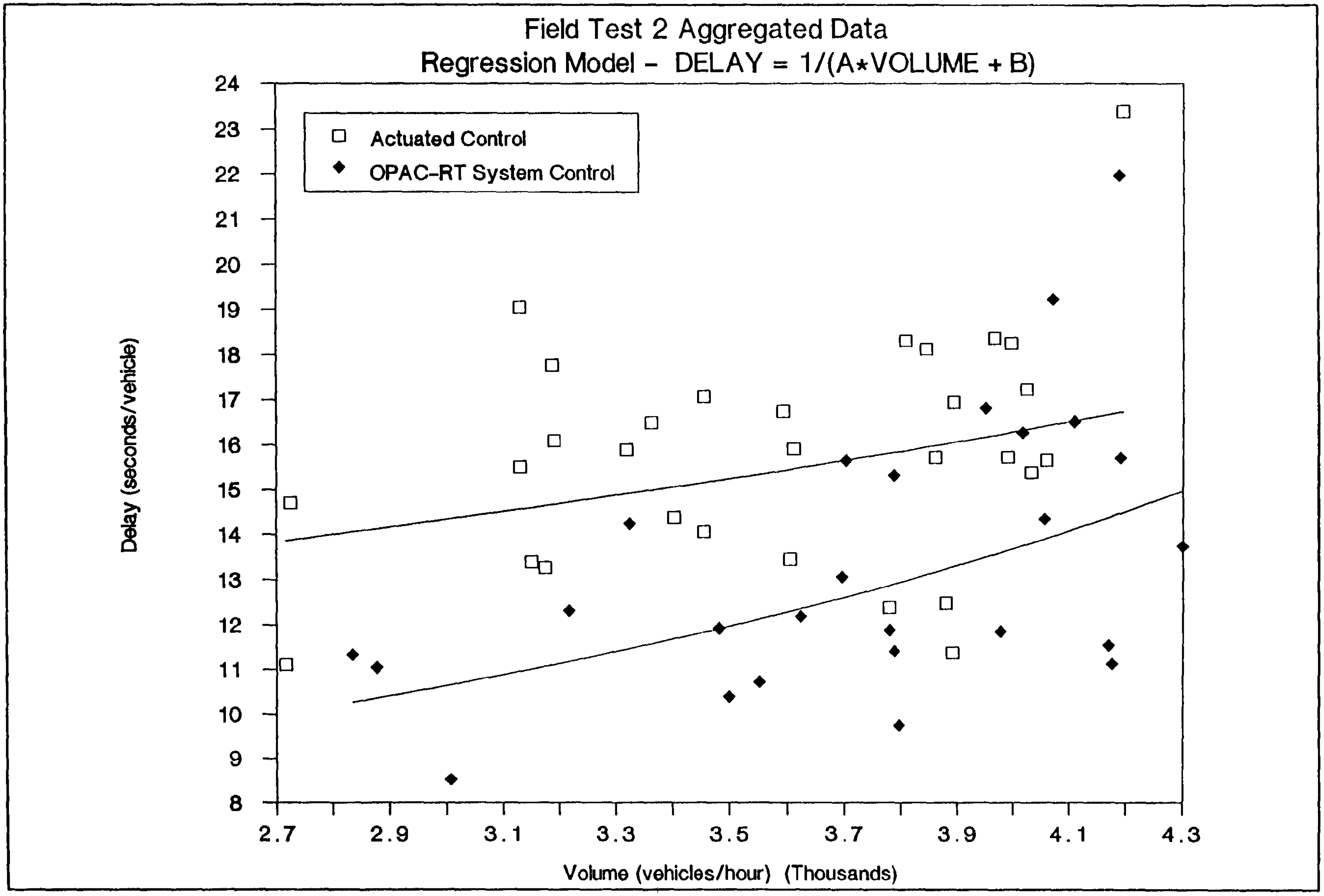


Figure 16. Field Test 2 aggregated delay data - regression results.

Table 5. Summary of regression results for delay - Field Test 2.

NONLINEAR (HYPERBOLIC) REGRESSION - $DELAY = (A_0 * VOLUME + A_1)^{-1}$

REGRESSION COEFFICIENTS

VARIABLE	ACTUATED CONTROL	OPAC-RT CONTROL
Volume (A_0)	-8.39×10^{-6}	-2.09×10^{-5}
Constant (A_1)	0.09494	0.1568

ANALYSIS OF VARIANCE - ACTUATED REGRESSION EQUATION

	SUM OF SQUARES	MEAN SQUARES	F	SIGNIFICANCE OF F
Regression	0.00033	0.00033	3.13238	0.0876
Residual	0.00299	0.00011		

ANALYSIS OF VARIANCE - OPAC-RT REGRESSION EQUATION

	SUM OF SQUARES	MEAN SQUARES	F	SIGNIFICANCE OF F
Regression	0.00188	0.00188	9.48554	0.0053
Residual	0.00456	0.00020		

OTHER STATISTICS

	ACTUATED CONTROL	OPAC-RT CONTROL
R SQUARED	0.1006	0.29199
SAMPLE SIZE	30	25

On the average, then, OPAC-RT yielded a 15.94 percent reduction in delay to vehicles despite an increase in volume.

As noted earlier, the intersection in Tucson is part of a computer controlled network and was placed off-line during the field study. Traffic patterns at the intersection were platooned because surrounding intersections were still on-line. The reduced delay under OPAC-RT control indicates the degree to which the OPAC strategy responds to platooned traffic.

The results of the second field test support the findings from the first field test and indicate that the OPAC-RT Version 1.0 system has a great potential for improving the operation of isolated intersections. It must be recognized, however, that the OPAC-RT Version 1.0 requirement that the minor side street be serviced even though there were no vehicle calls degraded OPAC's performance. Despite the great improvement in performance with respect to delay, it was postulated that the OPAC-RT system could do much better if certain constraints on the algorithm were removed. Some of these constraints were removed and the resulting system evaluated in Field Test 3. See '8. Field Test 3' for a discussion of the results.

(2) Percent Stops. In a fashion similar to that used with the per cycle delay data, the per cycle stops data (total and stopping vehicles) were aggregated into periods of approximately 600 seconds. Using this aggregated data, and despite increased volumes and the fact that the Version 1.0 signal optimization algorithm does not optimize stops, OPAC-RT increased percent stops per cycle by only 3.9 percent. The increase in stops may be due, in part, to the significantly shorter cycle length under OPAC-RT control. In general, past research has shown that shorter cycle lengths increase stopping percentages.(3)

(3) Cycle Length. On the average, the cycle lengths under actuated and OPAC-RT control were very different. Under actuated control, the average cycle length was 86 seconds. Under OPAC-RT system control, the average cycle length was 55 seconds. This difference in cycle length was expected as the OPAC algorithm forces the termination of a phase at the calculated optimum time by issuing a FORCE OFF command to the controller. The actuated controller may dwell in a particular phase if there is sufficient demand; the variable green interval will be extended by the passage for each vehicle detected.

7. Field Tests 1 and 2 Combined

Additional analysis was conducted on the delay data combined from the first and second field tests. Figure 17 shows the aggregated data and the resulting regression equations using hyperbolic models. Table 6 summarizes the regression results. As indicated by the table, the hyperbolic regression equations were adequate models of the relationship between volume and delay. These models provide a much better fit to the combined data than do the regression models for the individual field tests. This is due primarily to the greater number of data points and the wider range of the independent variable, flow, represented by the data.

The average delay under actuated control for the combined data was 8.13 seconds. The average delay under OPAC-RT control for the combined data was 7.41 seconds. On the average, there was a 9 percent decrease in delay under OPAC-RT control.

The combined analysis supports the conclusions from the first and second field tests that the real-time OPAC system has the potential for decreasing delay at isolated intersections. As expected, under low volume conditions the benefits of the OPAC-RT system over the actuated controller are negligible; however, the

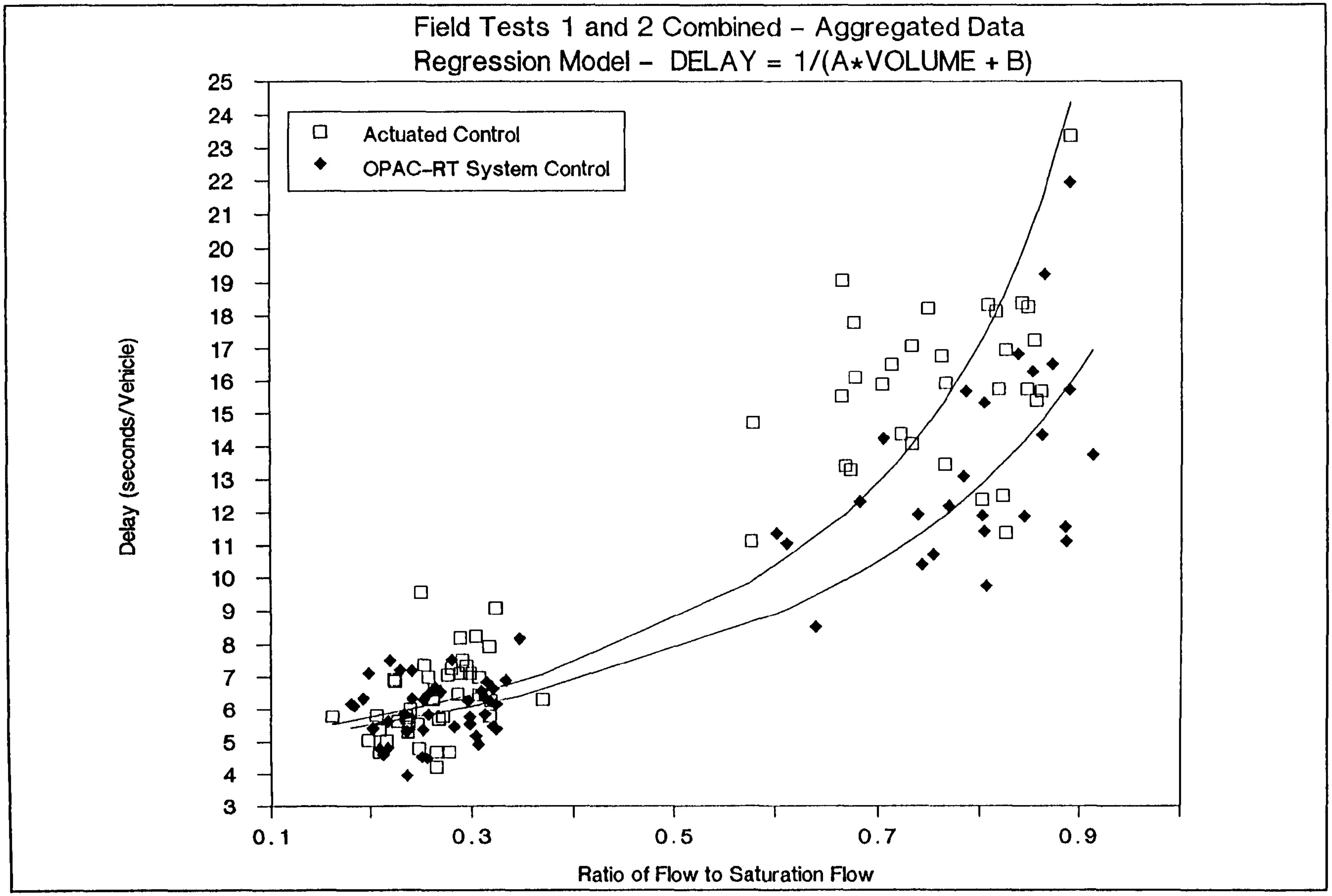


Figure 17. Aggregated delay data for Field Tests 1 and 2 combined - regression results.

Table 6. Summary of regression results for delay - Field Tests 1 and 2 combined.

NON-LINEAR (HYPERBOLIC) REGRESSION: $\text{DELAY} = (A_0 * \text{VOLUME} + A_1)^{-1}$

REGRESSION COEFFICIENTS

VARIABLE	ACTUATED CONTROL	OPAC-RT CONTROL
Volume (A_0)	-4.87×10^{-5}	-4.17×10^{-5}
Constant (A_1)	0.2427	0.2378

ANALYSIS OF VARIANCE - ACTUATED REGRESSION EQUATION

	SUM OF SQUARES	MEAN SQUARES	F	SIGNIFICANCE OF F
Regression	0.16964	0.16964	293.3791	0.0000
Residual	0.04047	0.00058		

ANALYSIS OF VARIANCE - OPAC-RT REGRESSION EQUATION

	SUM OF SQUARES	MEAN SQUARES	F	SIGNIFICANCE OF F
Regression	0.1268	0.1268	219.3086	0.0000
Residual	0.0370	0.00058		

OTHER STATISTICS

	ACTUATED CONTROL	OPAC-RT CONTROL
R SQUARED	0.8074	0.7741
SAMPLE SIZE	72	66

benefits of OPAC-RT with respect to delay to drivers increases with increased volume.

8. Field Test 3

a. The Test Site

The location for the third field test was the intersection of Flowing Wells Road and Prince Road in Tucson, Arizona. This intersection was chosen for the third field test because it was being converted to eight-phase, dual ring operation and the OPAC detectors required for the OPAC-RT system were already in place. As indicated in the discussion of the second field test, this intersection is part of a computer controlled network and was placed off-line during the field study.

Figure 18 illustrates the physical layout of the intersection. The intersection was eight phase with lagging left turns on all approaches. The left turn phases are treated by OPAC-RT as part of the intergreen period. The logic maintains an exponentially smoothed average duration for each minor (typically left turning) phase for use in calculating the optimum durations of the major (typically through) phases. Call-only and OPAC detectors and their locations with respect to the stop lines at the intersection are shown in the figure.

Saturation flows were recalculated for the third field test. Because left turning vehicles were permitted during the through phases, it was impossible to determine saturation flows for the turning phases according to the procedures of the test plan. Saturation flows of 1800 vehicles per hour were assumed for these minor phases. The saturation flows used were:

- Phase 1 (Left turns, Westbound Prince) - 1800 veh/hr.

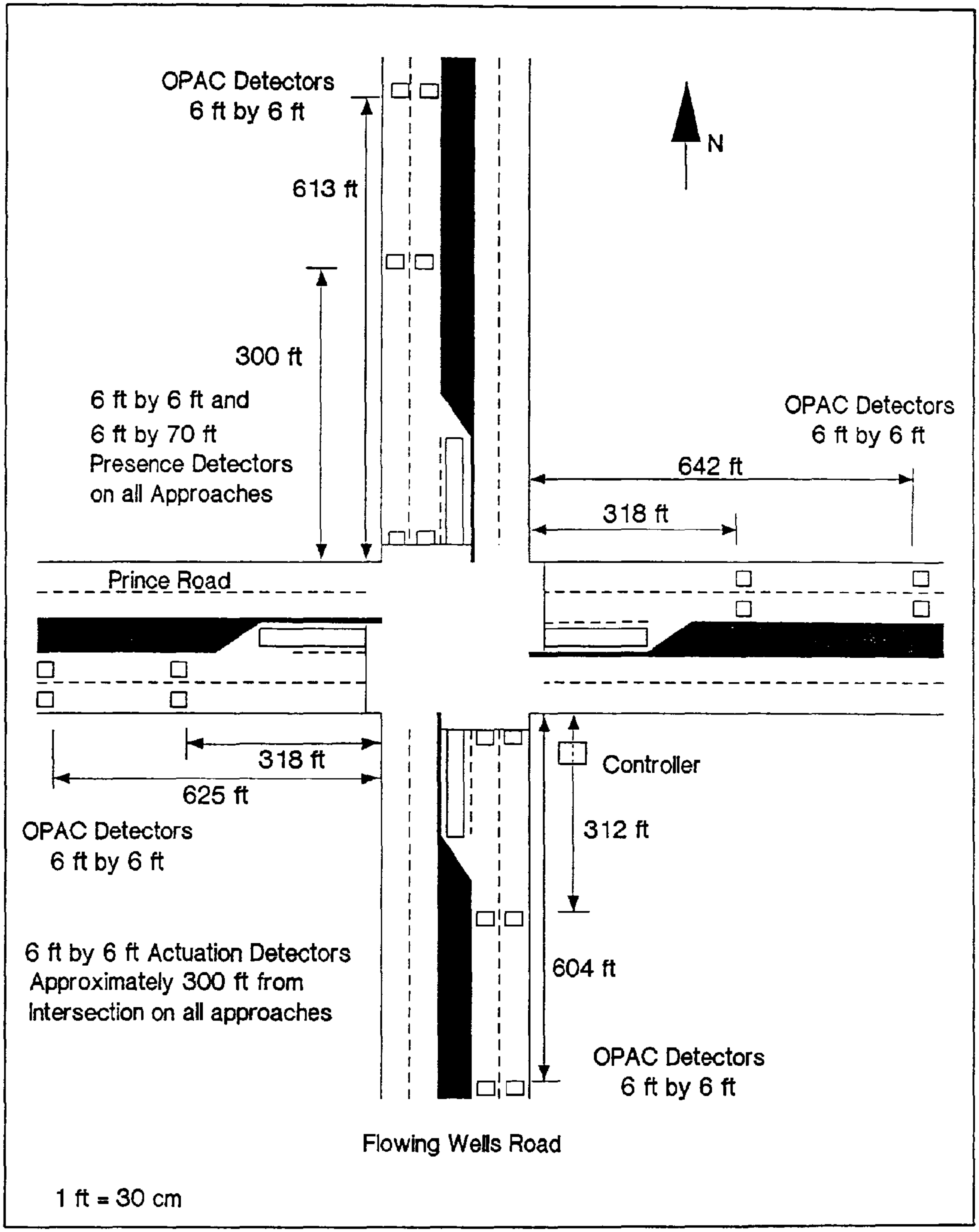


Figure 18. Field Test 3 test site - Tucson, Arizona.

- Phase 2 (Through, Eastbound Prince) - 4908 veh/hr.
- Phase 3 (Left turns, Northbound Prince) - 1800 veh/hr.
- Phase 4 (Through, Southbound Prince) - 4695 veh/hr.
- Phase 5 (Left turns, Eastbound Prince) - 1800 veh/hr.
- Phase 6 (Through, Westbound Prince) - 5473 veh/hr.
- Phase 7 (Left turns, Southbound Prince) - 1800 veh/hr.
- Phase 8 (Through, Northbound Prince) - 4643 veh/hr.

Travel times from the OPAC-RT detectors to the stop lines were all 12 seconds. In order to accommodate the new phasing, the horizon length was increased to 20 steps or 100 seconds. The step size was 5 seconds. The head period of the projection horizon was 3 steps. Table 7 summarizes the controller settings while the OPAC-RT system was on-line. Under actuated control, the settings were the same, except that vehicle recall was set to recall to minimum green for phases 2 and 6. Also, the passage time for the through phases was 5 seconds under actuated control.

As indicated in figure 18, the 5 second passage time was applied to approach detectors located approximately 300 ft (90 m) from the stop line for all through approaches. Undoubtedly, this value of passage time was selected to avoid situations in which the signal would prematurely 'gap out' causing sudden stops for high-speed approach traffic. Call-only detectors were also installed on Flowing Wells Road to detect traffic exiting from a shopping plaza driveway.

b. Test Conditions

Saturation flows were recalculated for this field test due to the change in phase configuration. Travel times remained as determined by the calibration during Field Test 2. The horizon length was extended to accommodate the new eight phase configuration.

Table 7. Field Test 3 controller settings.

THUMBWHEEL SWITCH SETTINGS								
	PHASES							
	1	2	3	4	5	6	7	8
MIN GRN	2	15	2	10	2	15	2	10
PASSAGE	2	0	2	0	2	0	2	0
YELLOW	2	3.5	2	4	2	3.5	2	4
RED CLEAR	1	2	1	2	1	2	1	2
MAX I	25	60	25	45	25	60	25	45
WALK	0	7	0	7	0	7	0	7
PED CLEAR	0	17	0	16	0	17	0	16
SEC/ACT	0	0	0	0	0	0	0	0
TIME TO REDUCE	0	0	0	0	0	0	0	0
BEFORE REDUCTION	0	0	0	0	0	0	0	0
MIN GAP	0	0	0	0	0	0	0	0
TOGGLE SWITCH SETTINGS								
PED RECALL	OFF	OFF	OFF	OFF	OFF	OFF	OFF	OFF
WALK	STDY	STDY	STDY	STDY	STDY	STDY	STDY	STDY
RECALL	OFF	OFF	OFF	OFF	OFF	OFF	OFF	OFF
MEMORY	OFF	OFF	OFF	OFF	OFF	OFF	OFF	OFF

Version 2.0 of the OPAC-RT system incorporates several user-input smoothing and proportionality factors. In particular, the optimization function includes weighted stops and delay. For Field Test 3, the weighting of stops, relative to delay, was 1.

The field test was originally scheduled for the weeks of December 4 and December 11, 1988. The OPAC-RT data was to be collected on Tuesday, Wednesday, and Thursday, December 6, 7, and 8. Because of personnel, equipment, and weather problems, this data was collected on Wednesday, Thursday, and Friday, December 7, 8, and 9, and on Monday, December 12. The actuated data was collected as scheduled on December 13, 14, and 15.

c. The Test Results

The per cycle observations of delay and percent stops were combined according to modes of intersection control (actuated versus OPAC-RT). Those cycles during which disruptive events such as pedestrian calls, the presence of oversized or stalled vehicles, or the passage of emergency vehicles occurred were deleted from the analysis. The remaining data were then aggregated into time periods of approximately 600 seconds.

(1) Delay. Figure 19 illustrates the aggregated field test data and the hyperbolic curves resulting from the regression analysis. Table 8 summarizes the regression and analysis of variance results. As indicated by the table, the hyperbolic equations are poor models of the relationship between volume and delay. As with both Field Tests 1 and 2, this is probably due to the limited range of volume data observed during the field test.

The average delay under OPAC-RT control was 19.23 seconds. The average delay under actuated control was 20.83 seconds. Operation under OPAC-RT yielded a 7.7 percent reduction in delay overall. The reduction in delay under OPAC-RT control indicates the responsiveness of the algorithm to platooned traffic. As indicated earlier, the intersection is part of a system. While this intersection was off-line during the field study, the surrounding intersections remained on-line, producing platooned

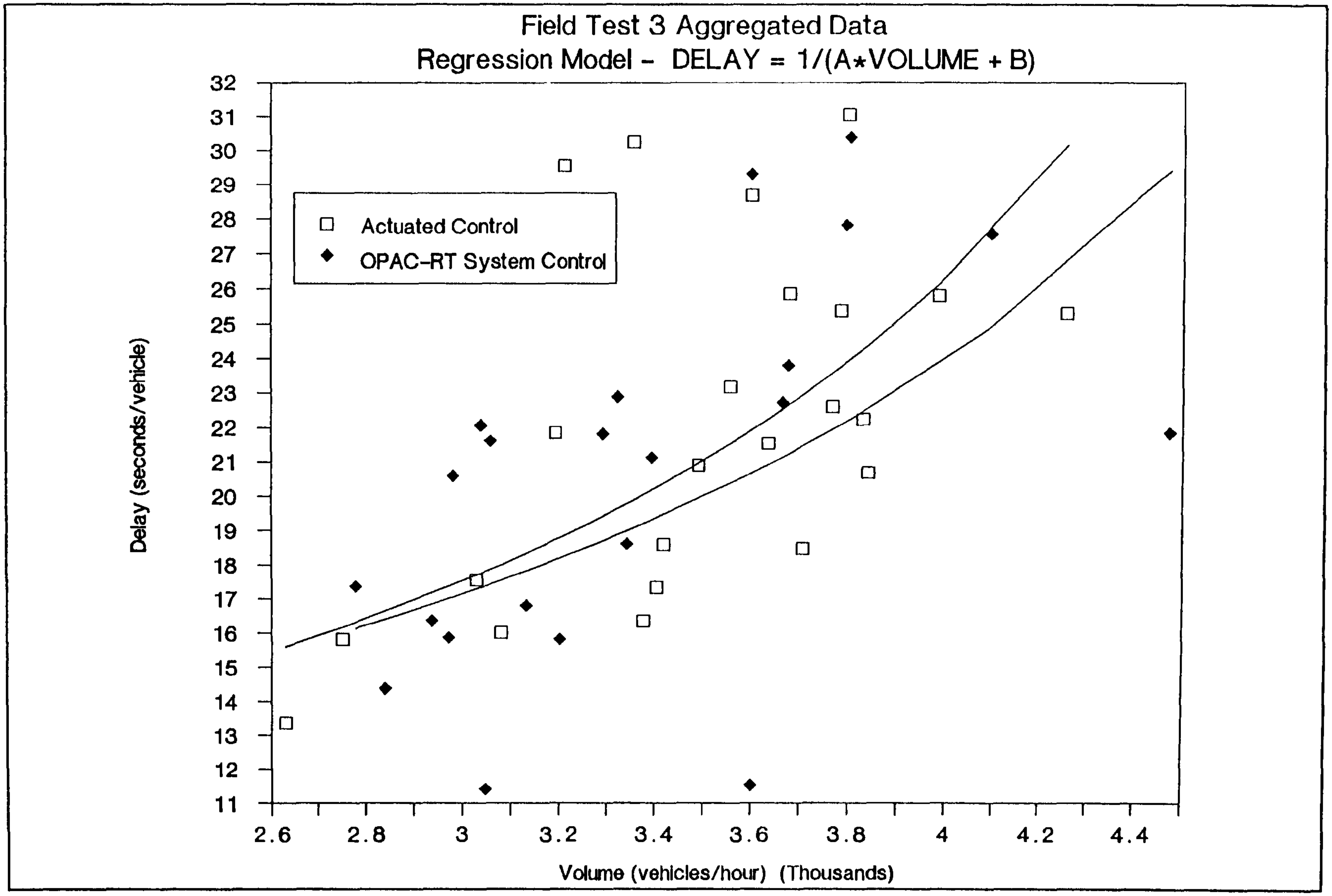


Figure 19. Field Test 3 aggregated delay data - regression results.

Table 8. Summary of regression results for delay - Field Test 3.

NON-LINEAR (HYPERBOLIC) REGRESSION: $DELAY = (A_0 * VOLUME + A_1)^{-1}$

REGRESSION COEFFICIENTS

VARIABLE	ACTUATED CONTROL	OPAC-RT CONTROL
Volume (A_0)	-1.90×10^{-5}	-1.65×10^{-5}
Constant (A_1)	0.11397	0.10787

ANALYSIS OF VARIANCE - ACTUATED REGRESSION EQUATION

	SUM OF SQUARES	MEAN SQUARES	F	SIGNIFICANCE OF F
Regression	0.00121	0.00121	15.9983	0.0007
Residual	0.00159	0.00008		

ANALYSIS OF VARIANCE - OPAC-RT REGRESSION EQUATION

	SUM OF SQUARES	MEAN SQUARES	F	SIGNIFICANCE OF F
Regression	0.00108	0.00108	5.81276	0.0256
Residual	0.00372	0.00019		

OTHER STATISTICS

	ACTUATED CONTROL	OPAC-RT CONTROL
R SQUARED	0.4324	0.2252
SAMPLE SIZE	23	22

traffic at the intersection of Prince Street and Flowing Wells Street.

The benefits of OPAC-RT, with respect to delay, do not appear to be as nearly as impressive as observed during Field Test 2. However, the results do indicate that the enhanced OPAC algorithm has the potential for improving the operation of isolated intersections. As indicated earlier, Version 2.0 uses several averaging functions for information required by the signal timing optimization function. For example, the minor (typically left turning) phases are treated as part of the intergreen period. Hence, the algorithm must have estimates of the durations of these phases in order to perform its optimization. The estimates of these phases are made via an exponential smoothing function utilizing a user-input smoothing factor. Errors in these estimates could greatly degrade the performance of the intersection under OPAC-RT control. It is expected that further calibration of the many new user-input parameters and smoothing values will further increase the benefits of the OPAC-RT system.

(2) Percent Stops. Despite the inclusion of stops in the optimization function, OPAC-RT increased percent stops by an average of 9.5 percent. For the field test, the weighting of stops, relative to delay, was 1. In reality, this weighting favors delay. A weighting of stops, relative to delay, of say 4 or 5 might have caused a decrease in stops. If the trends observed during the three field tests are to be taken as valid, then shorter cycle lengths reduce delay and increase stops while longer cycle lengths increase delay and reduce stops. For some combination of weighting factors for delay and stops, both will be optimized.

Another factor affecting the performance of the algorithm with respect to stops is the estimation of minor phase (left turning) volumes. The estimation process is rather involved. The logic uses the exponentially smoothed durations for the minor phases and user-input discharge rates to determine an estimate of the number of vehicles turning. Errors in the minor phase durations will cause errors in estimates of minor phase volumes, which in turn will cause errors in the algorithm's estimate of queues on all phases, which are used to define stops. It is expected that further calibration of the optimization function and other user inputs will further optimize the performance of the intersection with respect to both delay and stops.

(3) Cycle Length. Again, for the third field test, the cycle lengths under actuated and OPAC-RT control were very dissimilar. Under actuated control, the average cycle length was 110 seconds. The average cycle length under OPAC-RT control was 80 seconds. This difference was not unexpected, given the results of the second field test. As indicated earlier, past research has indicated that shorter cycle lengths decrease delay and increase stops while the opposite tends to increase delay and decrease stops.(3) As indicated above the weighting of stops relative to delay during this field test favored delay, hence it was expected that the average cycle length under OPAC-RT control would be shorter.

ECONOMIC ANALYSIS

The OPAC method of intersection control provides distinct advantages in traffic flow efficiency for a typical intersection over that afforded by an actuated controller. However, since up to this time OPAC has been only a research study, additional development is required to produce an OPAC controller for use at a typical intersection. This OPAC standardization development will include modification of the OPAC algorithm for use in an actual controller. The OPAC controller itself will require modifying an existing controller design, modifying a commercially available processor or custom developing a new controller.

The 170 type traffic controller is a commercially available, microprocessor based controller which is capable of implementing a traffic control strategy as given in the microcode within its EPROM. However, the implementation of OPAC within a standard 170 controller will not be possible without several modifications to the controller and to the OPAC algorithm.

A standard 170 controller has a maximum nonvolatile storage space (EPROM) of 8192 (8k) bytes. This space must be split between the existing 170 software and the new software associated with the OPAC algorithm. This 8k of space is not large enough to accommodate the OPAC code. In addition, a 170 controller has a processor machine cycle time of 1.302 microseconds. This is more than 13 times slower than the IBM-AT originally used by OPAC. Since a worst case of 4.0 seconds for the algorithm processing time was observed on the IBM-AT, this will result in a 170 processing time of more than 52 seconds. If it is assumed that the 170 processor spends 50 percent of its time performing the normal 170 functions, then the time required to execute the optimization algorithm is doubled to 104 seconds. The IBM-AT also made use of a math coprocessor which greatly decreased the time required to processes the large number of floating point operations required by the OPAC algorithm. In the absence of a coprocessor within the 170, this time of 104 seconds will be even greater.

For these reasons it is infeasible to implement OPAC using a standard 170 controller or its successor the type 179 controller. There are, however, two possible approaches to implementing the OPAC algorithm in a functional system.

The first approach would be to modify a standard 170 controller (or other microprocessor based controller) to accommodate the OPAC requirements. These modifications would include a new processor, such as an Intel 80286 or a Motorola 68020, at least 640 kilobytes of processor RAM, at least 640 kilobytes of EPROM or EEPROM which could be overlayed onto the system RAM if necessary, and a system clock that will provide a processor cycle time of 0.1 microsecond or less. A math coprocessor would also be required unless the processor speed or efficiency is increased to compensate for the lack of the coprocessor.

The second approach would be to design a new processor or adapt an existing processor to meet the requirements of OPAC as well as the requirements associated with the normal traffic control functions provided by a standard NEMA controller (such as the 170). The new processor would have to meet the OPAC requirements set forth above. However, since several NEMA signal manufacturers are introducing new controllers with processor capabilities equivalent to that of the 80286, it is likely that the first approach would be preferable.

The standardization of the OPAC system would require an initial development period to define the required hardware, adapt and refine the OPAC algorithm, and to integrate the OPAC algorithm with the normal NEMA traffic control functions. The result of this development effort would be a hardware specification and an OPAC microcode module which would be burned into EPROMS and plugged into the new OPAC controller.

This development effort would be a one time cost, the majority of which will be the modification and integration of the OPAC system with the standard NEMA traffic control functions. The work required essentially duplicates that conducted under the current contract. Therefore, it is anticipated that this effort will cost approximately $200,000. When this effort is completed, the cost of equipping an individual intersection with the new OPAC controller would be slightly higher than the cost of equipping the intersection with a 170 type controller. This is due to the slightly higher cost that the OPAC controller likely would be over the 170 type controller.

The largest additional cost of an operational version of OPAC would be the installation of the OPAC vehicle loop detectors. The installation costs in both Arlington, Virginia and Tucson, Arizona were approximately $25,000, a cost that significantly exceeds that of an actuated controller.

The most significant increase in the cost associated with the implementation of an OPAC controlled system, is that of the of the loop detector installation. The loop installation in both Arlington, Virginia and Tucson, Arizona cost approximately $25,000. This cost was relatively constant, in spite of the difference in the number of detectors installed, because the loop lead in cable length was the same in both cases, and this aspect of the installation was responsible for the majority of the cost.

A comparison of likely OPAC costs with typical conventional NEMA controller costs was developed for both two phase and eight phase control. Table 9 summarizes the results of this comparison.

Table 9. Comparison of intersection costs.

	2-Phase Control			8-Phase Control		
Item	NEMA (1)	OPAC-RT	NEMA (2)	NEMA (1)	OPAC-RT	NEMA (2)
Controller	$2,100	$3,000	$2,100	$2,100	$3,000	$2,100
Detector Amplifiers	240	720	240	480	960	480
Loop Installation	8,400	11,100	2,800	8,400	11,100	2,800
Loop Lead-in	1,700	25,700	14,400	1,700	25,700	14,400
Total Cost	$12,440	$40,520	$19,520	$16,780	$44,960	$23,980
Incremental OPAC Cost	$28,080		$20,980	$28,180		$20,980

The $\text{NEMA}_{(1)}$ control options assume 50 ft by 6 ft (15 m by 1.8 m) loops installed in all lanes at the intersection stop line. The $\text{NEMA}_{(2)}$ control options assume dilemma zone detectorization with 6 ft by 6 ft (1.8 m by 1.8 m) square loops installed 300 ft (90 m) upstream from the stop line. It is also assumed that all approaches are two lanes, and that the eight phase control includes exclusive left turn lanes. This comparison also assumes that the OPAC detectors are installed approximately 500 ft (150 m) from the stop line.

Obviously, there is a significant variation in the costs of controllers and detectors that is a function of the intersection design, quantities purchased, and local construction costs. The following assumptions were used for the development of this table:

- NEMA controller costs are representative of small controller quantities. The controller costs might be reduced by as much as 30% for large quantities.
- The OPAC controller costs were estimated based on the cost of an existing NEMA controller, upgraded to include a more powerful processor, and the additional memory described above.
- Detector and lead-in costs assumed $8 per foot for saw cuts and loop cable, splice boxes at $150 each, and lead in cable at $12 per foot installed.

Thus, on the basis of these installed costs, the OPAC control algorithm must provide benefits in excess of $28,000 annually for the $\text{NEMA}_{(1)}$ alternative and $20,000 annually for the $\text{NEMA}_{(2)}$ alternative in order for its installation to be justified. An equivalent annual cost can be calculated for this incremental cost to estimate the annual benefits that must be provided by OPAC. Assuming a 10-year installation life and a 10-percent cost of money, the equivalent annual cost of the OPAC installation over that of the $\text{NEMA}_{(1)}$ and $\text{NEMA}_{(2)}$ installations are $4,560 and $3,420 respectively. Thus the annual benefits to motorists must be greater than these values.

The effectiveness of the OPAC-RT system is measured by its performance with respect to decreasing delay and stops. The intersection used for the second and third field tests is representative of the kind of intersection where the OPAC-RT system might be installed. At this intersection average daily volumes of 3,600 vehicles per hour were observed. A modest estimate of the reduction in delay per vehicle which would be expected is 1 second per vehicle. During the second and third field tests the reduction in delay was closer to 2 seconds. If an estimated 1 second per vehicle of delay is gained under the OPAC-RT system and the average volume is 3,600 vehicles per hour, an average of 8,760 hours of delay per year will be saved at a single intersection.

While this modest improvement in vehicle delays (1 second per vehicle), is negligible from the motorist's point of view, a more widespread installation of OPAC would provide cumulative benefits to the motorist that are likely to be noticeable. In addition, it must be recognized that the 1-second delay reduction is intended to serve as an average value applicable to an entire 24-hour day. The actual reductions in delay during the peak period are likely to be much greater.

Using the annual savings of 8,760 hours of delay, and an average value of delay cost of $4.00 per hour, the benefits to motorists served by an OPAC intersection will be approximately $35,000 per year. Thus, the payback for the OPAC controlled intersection will be less than 1 year.

Although stops were increased during the third field test, it is expected that further calibration will cause a decrease in percent stops. With fewer vehicles stopping, fuel consumption and fuel emissions will also be reduced.

Based on these calculations, it appears that the OPAC configuration described in this section is cost effective for installation by local government agencies. It is likely, however, that because of the capital cost and maintenance cost associated with this installation, it will initially be implemented at problem intersections experiencing high levels of congestion.

Future consideration should also be given to the possibility of an OPAC configuration in which the loop detectors are replaced with the video detection technology (Wide Area Detection System - WADS) whose development is being sponsored by the FHWA. This technology offers the potential of replacing the high installation and maintenance costs associated with the loop detector. Other detection technologies such as the self-powered vehicle detector might also offer the potential for eliminating the high lead-in costs.

CONCLUSIONS

It must be emphasized that the results presented in this report were achieved with only minimal fine tuning of OPAC's operating parameters. These parameters include travel time from the OPAC detectors to the stop lines, horizon length, step size, and stops weighting factor. In spite of this fact, substantial improvements in intersection performance were measured.

The results of the first and second field tests indicate that the OPAC-RT Version 1.0 system has the potential for improving the operation of isolated, two phase intersections. At lower volumes the average delay under actuated and OPAC-RT system control were about the same and perhaps higher under OPAC-RT control. At the higher volumes, however, the difference became larger. During Field Test 2, average volumes were increased by 4 percent under OPAC-RT control yet delay was decreased by about 16 percent. Thus it appears that at lower volumes the intersection performs better under full actuated control, but at higher volumes performance is better under OPAC-RT Version 1.0 system control.

In addition, the decrease in delay under OPAC-RT control observed during Field Test 2 indicates the algorithm's positive response to platooned traffic. As part of a computer controlled network, the intersection of Prince Street and Flowing Wells Street was off-line during the field study but experienced platooned traffic from surrounding intersections.

Despite the improvement in delay and only minor increases in stopping percentages under OPAC-RT control, it must be recognized that the OPAC-RT Version 1.0 requirement that the minor side street be serviced even though there were no vehicle calls significantly degraded OPAC's performance, particularly at lower volumes.

The results of Field Test 3 support those of the first two field tests and indicate that Version 2.0 of the OPAC-RT system has the potential for improving the operation of isolated intersections. Again, the reduction in delay under OPAC-RT control indicates the responsiveness of the algorithm to platooned traffic. As indicated earlier, the intersection observed during Field Test 3 is part of a system. While this intersection was off-line during the field study, the surrounding intersections remained on-line, producing platooned traffic at the intersection of Prince Street and Flowing Wells Street.

From Field Test 3, the benefits of OPAC-RT, with respect to delay, do not appear to be as nearly as impressive as observed during Field Test 2. Version 2.0 uses several averaging functions for information required by the signal timing optimization function. For example, the minor (typically left turning) phases are treated as part of the intergreen period. Hence, the algorithm must have estimates of the durations of these phases in order to perform its optimization. The estimates of these phases are made via an exponential smoothing function utilizing a user-input smoothing factor. Errors in these estimates could greatly degrade the performance of the intersection under OPAC-RT control. It is expected that further calibration of the many new user-input parameters and smoothing values will further increase the benefits of the OPAC-RT system.

Together, the results of the field tests indicate that the real-time OPAC algorithm represents a viable alternative to actuated control at isolated intersections. In all cases the OPAC-RT system produced decreases in overall delay. While at lower volumes this decrease was minor, at higher volumes the improvement was as high as 16 percent. A conservative estimate of the reduction in delay to be expected would be 8 to 10 percent.

While the initial field test of Version 2.0 yielded an overall increase in stopped vehicles, the results of the third field test indicate that with further development and calibration of the many new user inputs the percentage of stops can be decreased under OPAC-RT control. The relative weighting of stops to delay was 1 during Field Test 3. Generally, shorter cycle lengths tend to decrease delay and increase stops while longer cycle lengths tend to increase delay and decrease stops. It is expected that some relative weighting of delay and stops will optimize both. With shorter cycle lengths and less stopped time, fuel consumption and emissions will also be decreased.

While the research on the OPAC strategy to date has concentrated on the isolated intersection, some research has been done on the implementation of the OPAC strategy in a network context. The results of Field Tests 2 and 3 have shown the positive response of the OPAC-RT system to platooned traffic, which is typical of arterial and network systems. With the positive results exhibited by the isolated intersection version, it is not unreasonable to expect that an arterial or network optimization algorithm could greatly reduce the delay to drivers.

At the present time, effort concentrated in further development of the OPAC controller for the control of isolated intersections would help facilitate a more efficient urban network. Arterial or network versions of the OPAC strategy have the potential for improving the movement of people, products, and services even more.

Thus, while this project has demonstrated both the feasibility and potential of the OPAC strategy, a significant amount of additional work is required to ensure that this strategy is operating in an effective manner. This work should include the integration of the latest version of OPAC-RT into a simulation program such as NETSIM for testing of new features and fine-tuning of parameters under controlled conditions. At a minimum, the relationship between OPAC performance and step size, horizon length, travel time and stops weighting should be evaluated during these tests under a wide range of traffic and geometric conditions.

The tests should also be used to determine the threshold value of congestion at which OPAC effectiveness is degraded relative to the effectiveness of pretimed or actuated control. The results of this evaluation will provide guidance to the practicing traffic engineer relative to the use of these threshold values.

The simulation should also be used to support the development of additional OPAC enhancements including:

- The automatic calculation of travel time as a function of measured vehicle speeds and detector locations. This capability would reduce the need for manual entry of this parameter.
- Improved techniques for estimating service times required by left turn movements that are one component of the approach traffic measured by the OPAC detectors. At the present time, the volumes associated with these movements are estimated using the duration of previous left turn phases. The time of the left turn phases are controlled using actuated controller logic.
- A sensitivity analysis should be performed that relates OPAC effectiveness to detector location. As indicated in the previous section, the OPAC detectors represent a significant element of the total system cost. If these detectors could be located closer to the controlled intersection without seriously degrading algorithm performance, these installation costs would be reduced.
- The operation of the OPAC algorithm should be evaluated under conditions with a variety of

> platooned arrivals. In this way, it will be possible to determine whether OPAC offers an alternative to existing Critical Intersection Control algorithms for coordinated signal systems. This work should include analysis of the impact of different estimation procedures for tail characteristics.

This project has conclusively demonstrated OPAC's promise as an effective alternative to actuated signal control. However, while the work described in this report has conclusively demonstrated the algorithm's potential, it is likely that significant further enhancements are possible. Because of the encouraging nature of these results, it is strongly recommended that future research be conducted that will improve the traffic engineering community's understanding of the conditions under which OPAC will provide effective control, provide guidance as to its installation and calibration, and extend its operation to a broader set of conditions.

APPENDIX A - SUMMARY OF STUDY TASKS

In order to meet the objectives of the OPAC evaluation, the work was organized into the following tasks:

Task A - Review Existing OPAC Software and Reports and Make Preliminary Determinations

A review of the existing OPAC documentation and program listing was performed in order to make the following determinations:

- The traffic input data required to execute OPAC reliably.
- The output provided by the OPAC software.
- How the OPAC/Microcomputer combination will control a traffic actuated controller using either HOLD/FORCE OFF or simulated vehicle actuations.

A more detailed description of the OPAC algorithm is given in chapter 2 of this report.

Task B - Determine the Appropriate Microcomputer Environment for OPAC

In order to make the appropriate choice for the microcomputer environment some technical requirements were defined. These included:

- Any modifications to the OPAC software would be limited to those which would improve computational efficiency while not affecting the results of the calculations.
- All software developed during the project would be in FORTRAN 77 unless otherwise authorized in writing by the Contracting Officer.

- Because the software was required to be in FORTRAN, the microcomputer selected for evaluation must have FORTRAN compiler software available.
- For the purposes of this study, 'real-time operation' was defined such that the OPAC/ Interface Software package would execute in less than one time step (equal to the sum of the yellow change and all red clearance intervals).
- The OPAC program and associated interface software developed to run the controller would have to execute in real-time in the microcomputer.

With the requirements described above, and based on manufacturers specifications, a microcomputer with sufficient computational power to execute the OPAC program and associated interface software in real-time was selected and purchased. Benchmark tests were performed to ensure that the selected computer would be capable of supporting real-time OPAC operation. Under consideration during the analysis of the results of the benchmark tests was the fact that the software to access detector data and process it in a form suitable for operating the OPAC algorithm would have to execute in real-time. A more detailed description of the operating environment for the OPAC program and associated interface software is given in chapter 3 of this report.

Task C - Select Initial Field Test Site

The objective of this task was the selection of a site suitable for the initial field test of the real-time version of the OPAC program. Included in the selection criterion were the following:

- Vehicle arrivals an all approaches should be essentially unaffected by upstream signals.
- Demand levels should not exceed capacity to an extent that might cause queues to back up

over detectors located 600 ft (180 m) upstream.

- The intersection should have four approaches, at least two of which should have two or more through lanes, and be currently operating in two phase control with no left turn phases.
- The existing controller should be a modern solid state controller.

The final site selection for the initial field test was an intersection in Arlington, Virginia. A detailed physical description of the intersection is given in chapter 4 of this report.

Task D - Develop Interface Software

Under this task it was required that a signal controller of the same type as was currently operating at the first test site in Arlington, Virginia be obtained. Following this acquisition the interface and detector data handling software required to operate the controller from the microcomputer were developed. A summary of this software is provided in the description of the system operating environment in chapter 3 of this report. A detailed description of the interface software is provided in 'OPAC-RT Traffic Control System: Hardware Interface and Detector Processing Software Documentation' as a separate volume to this report.

As a subtask the existing OPAC software was restructured to improve its modularity and computations were streamlined to ensure real-time operation. Also, the OPAC data entry system was modified so that data could be entered from the keyboard through an interactive input parameter file creation program.

Task E - Install Detector and Cable Connect

In accordance with applicable local ordinances and standards the necessary hardware was obtained and installed at the Arlington, Virginia site. Permanent detectors were installed, one in each lane on all four approaches of the intersection. Under the constraint that these detectors be located at a distance at least 10 seconds of travel time from the stop bars, they were placed approximately 600 ft (180 m) upstream of each approach. Also installed was the cable connect to the detector control boxes located at the intersection.

Task F - Test Software

The objective of this task was to perform off-line testing of the OPAC and interface software developed in Task D using the interconnected controller/microcomputer system developed in Tasks B and D. The tests were performed with detector data obtained with the detectors installed at the test site in Task E. Testing was designed to:

- Verify that the detector data handling software correctly transformed the raw detector data into the form required by the OPAC algorithm.
- Verify that the OPAC program computed phase times correctly.
- Verify that the interface software correctly commanded the controller in response to the phase times computed by OPAC.

Task G - Demonstrate Real-Time OPAC System

During this task, the OPAC-RT Traffic Control System was demonstrated to FHWA and local authorities. The demonstration utilized detector actuations from the detectors installed in Task E to operate the controller furnished in Task D. Detector data collected at the test site were used in an off-line demonstration to ensure that the OPAC predicted phase lengths agreed with the phase lengths as observed on the test controller.

Task H - Develop Field Test Work Plan

A data collection work plan was prepared and submitted for approval. The plan included a description of the data to be collected and the procedures for collecting it, as well as provisions for conducting calibration exercises in the field. The calibration studies consisted of the experimentation with different values of critical OPAC parameters with the objective of determining that combination of values which produced the best performance of the OPAC algorithm.

Task I - Conduct Initial Field Test

Using the approved field test work plan prepared in Task H, sensitivity studies were performed in the field to calibrate OPAC for optimal values of the saturation flow rate, travel time, and roll period parameters. Utilizing the optimal combination of parameter values, a 'Before' and 'After' Field Test of the OPAC control at the Arlington, Virginia intersection was conducted.

Task J - Analyze Results of Initial Field Test

Under this task the data collected in Task I was analyzed. The analysis included the following:

- The definition of the criterion on which the comparison of the operation of the test site under full actuated and OPAC control was to be based.
- The stratification of the data according to demand levels on the major and minor streets.

- A comparison of the measures of effectiveness according to the stratification mentioned above using appropriate statistical methods.
- Recommendations for improvements and enhancements to the OPAC algorithm.

A more detailed description of this analysis is given in chapter 4 of this report.

Task K - Conduct Second Field Test

Under this task, a second test site was selected for further evaluation of the real-time OPAC program. In addition to the requirements specified in Task C, the site was to have platooned arrivals on at least two of its four approaches. The selected site was in Tucson, Arizona. A detailed physical description of the intersection is given in chapter 4 of this report. The second field test was conducted following the same procedures developed and utilized in Tasks C, F, G, H, I, and J.

Task L - Identify and Implement Modifications for Improvements and Enhancements to the OPAC-RT Optimization Algorithm

Under this task, the following new features were incorporated into the real-time OPAC software developed under Tasks D and F:

- Dual ring and single ring multiphase control.
- Independent minimum and maximum greens among phases.
- Vehicle stops as part of the optimization function.
- Occupancy as a measure of congestion.
- Step size independent of green, yellow, and all red interval durations.

- Elimination of the unnecessary servicing of side streets given that call-only detectors at the stop line are present on all phases.

In order to adequately develop the enhancements listed above, the following activities were undertaken:

- The overall software structure of the real-time OPAC program developed and tested under Tasks D and F was reviewed to determine if modifications would be necessary. No major changes were required.
- The hardware configuration was expanded for interface with the dual ring, eight phase controller.
- All modifications were designed, coded, tested, and integrated into the OPAC software package.
- The strategy was then connected to an eight phase, dual ring controller and tested as a fully integrated system. The detector data simulator developed for software testing was modified for use with the new system and used to evaluate its operation. Pedestrian actuations were manually entered using push-button switches.

A more detailed description of the modified system, referred to as Version 2.0, and its operating environment is given in chapter 3 of this report.

Task M - Conduct Third Field Test

The second test site in Tucson, Arizona was used for the field test of the enhanced real-time OPAC software. Modifications made to the intersection by the City of Tucson made it suitable for the testing of OPAC with dual ring control. The field test was conducted following the data collection and analysis plan developed in Task H and used in Tasks I and K.

Task N - Perform an Economic Analysis

Based on the results of Tasks A through M, an economic analysis of the OPAC control program was performed. This analysis included:

- An estimate of the cost to complete development and testing of the OPAC software.
- The cost effectiveness of using a microcomputer based OPAC system instead of a full actuated controller at single intersections (assuming conventional loop detection).

The results of this analysis are described in detail in chapter 5 of this report.

APPENDIX B - CALIBRATION PROCEDURES FOR OPAC-RT PARAMETERS

1. Smoothing Factor, K, for Fixed Tail Routine

a. Introduction

The Optimization Policies for Adaptive Control (OPAC) computer program was developed to calculate demand-responsive optimum control policies for an adaptive-signal-controlled intersection.(1) A policy consists of the sequence of signal switching times that minimizes the total delay over the horizon being considered. A horizon can be any period for which flows (arrivals) to the intersection are known or can be predicted.

The generalized optimization technique for determining optimal switching policies requires future arrival information for the entire horizon, which is impossible in practice since the future is unknown. To reduce these requirements in such a way as to utilize only available flow data, yet preserve the performance of the computational procedure, OPAC utilizes a rolling horizon concept. For OPAC the horizon consists of n intervals of time, or steps. Actual arrival data for r steps at the head of the horizon can be obtained from upstream detectors. For the remaining n-r steps, the tail of the horizon, flow data is provided by some model. Optimal policies are calculated for the whole horizon, but only implemented for the head section of r steps. The horizon is then shifted x steps ahead, new flow data is obtained for the new head and tail portions of the horizon, and the optimization is repeated.

Figure 1 is an illustration of the procedure. The figure shows the roll period to be the same as the head period. In developing the algorithm, this was the case. In implementing the algorithm in real-time, having a roll period greater than 1 step degrades the performance of the algorithm. Hence, the real-time OPAC traffic control system utilizes a roll period of 1 step and a head period approximately equivalent to the travel time from the OPAC detectors to the intersection stopbar.

b. The FTAIL Model

Since signal switching policies are calculated based on the information in the whole horizon, the model used to predict the arrivals in the tail portion must be reliable. OPAC's prediction model is a routine called FTAIL. An initial guess at the number of arrivals per step is provided to the model. Actual arrivals are summed by approach for an arbitrary period of time. New weighted averages are calculated for each approach, after the arbitrary time period has expired, based on the following equation:

$$\text{NEWAVG} = \text{OLDAVG} + K^{*}\left[\frac{\text{SUM}}{L} - \text{OLDAVG}\right]$$

where: NEWAVG = New value used in tail of horizon.
OLDAVG = Old value used in tail of horizon.
SUM = Sum of arrivals for specified period.
L = Number of steps over which the arrivals were summed.
K = A smoothing factor.

The calculated new average is used in the tail of the horizon until the arbitrary time period has again expired and the averaging function is performed again.

The most important input to the equation is K, the smoothing factor. Its value must be specified when initializing the procedure and remains unchanged.

c. Methodology

Real arrival data for the calibration of the smoothing factor were collected at the intersection of North George Mason Drive and North 16th Street in Arlington, Virginia. Loop detectors on each approach were used to count the vehicles for four consecutive 30-minute periods during the evening peak. The counts were aggregated into 4-second steps. An initial inspection of the data showed that the critical approaches were those on George Mason Avenue while there was very little demand on 16th Street.

In the short run, traffic volumes tend to be very erratic. In the longer run, however, flow rates tend to be somewhat constant. OPAC calculates new averages for its estimates of the arrivals in the tail every minute. This is a very short period of time, and flows tend to be very 'noisy'. On the other hand, 10-minute averages provide a better basis on which to choose the smoothing factor, k. Hence, while the FTAIL routine calculates its averages every minute, for comparison purposes, 10-minute averages were analyzed.

Corresponding to each step (of which there were a total of 1796) were an actual volume count and a predicted average calculated by FTAIL. For each approach, an initial, educated guess was provided to FTAIL. FTAIL was executed in a mock real-time test using the 1796 steps of data; the resulting approximations to volume were monitored by step. Using statistical packages the resulting data was then averaged over 10-minute periods. Plotted, the data might look like the graph in figure 20, depending on the initial guess and the value of K.

Two criteria were used to evaluate the performance of FTAIL. First, the overall mean or average flow rate (measured in vehicles per step) of the FTAIL averages should compare with the actual mean flow rate. Two statistical analyses exist which test

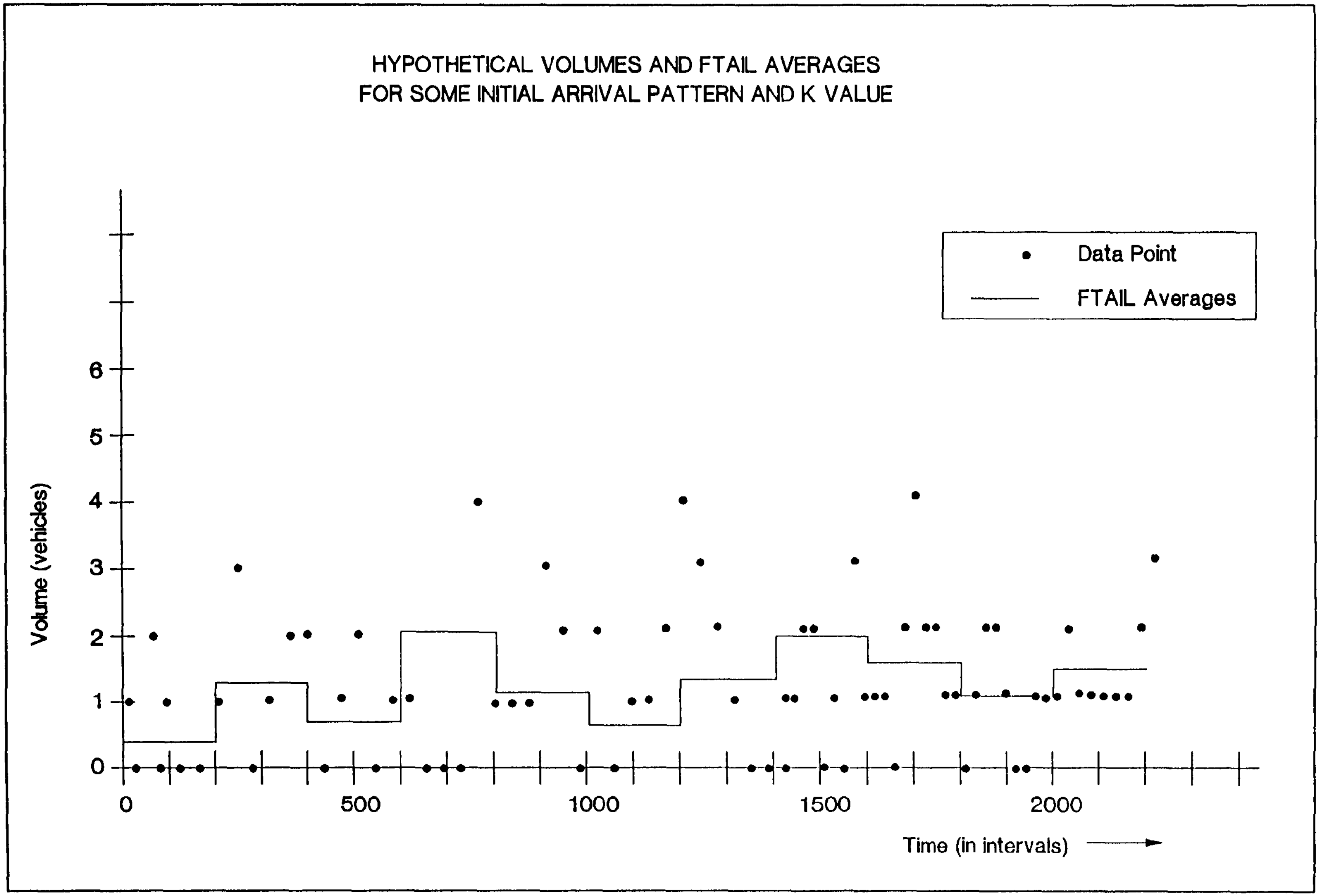


Figure 20. Hypothetical traffic patterns and corresponding FTAIL averages.

the hypotheses that two processes produce the same mean value for some measure by separating the variation in the observations into that which is due to the process and random variation and that which is due to random variation only. If the former is not much larger than the latter, then it can be concluded that the variation is due mostly to chance and the means are equal. In this case, the two processes are the actual volumes and the FTAIL average approximations. The analyses are the Paired T-test, which assumes that the observations have been drawn from normal populations, and the Wilcoxon Paired Comparisons Test, which does not require the assumption of normal populations. Both analyses were performed, with emphasis placed on the Wilcoxon tests since it is not known whether the population of volume per step is normal.

The analyses were conducted using levels of significance of 0.05 and 0.01. This means that the hypothesis that the means are equal was tested with the probability of rejecting the hypothesis when it is actually true being 0.05 and 0.01, respectively. The Paired T-test and the Wilcoxon Test calculate values of a T distribution and an F distribution, respectively, and a probability of getting the calculated value. If the probability is greater than 0.05, it can be concluded that the hypothesis is reasonable, and the means are indeed equal. If the probability is less than 0.05 or 0.01, it can be concluded that the means are significantly different and the hypothesis is rejected.

The second criterion is a measure of how well the FTAIL averages fit the actual data. For a given step, the difference in the FTAIL average and the measured volume is squared. These squares are then summed over the total number of steps. The smaller the sum, the better the FTAIL model fits the actual data. Since a measure of how well FTAIL follows the actual data over extended periods was also required, 10-minute sums of squares were also calculated.

d. Results

In all cases, for all values of K and for all input approximations of volume for FTAIL, both the T-test and the Wilcoxon test yielded the result that there was no significant difference in mean volume between the populations of actual volume and FTAIL average approximations. In other words, the FTAIL equation is a good representation of flow, regardless of the value of K or the initial approximation of volume supplied to the FTAIL algorithm.

While useful, this result does little to facilitate the selection of the optimum value for K. Hence, the second criterion, the sums of squares of differences, must be closely evaluated. Figure 21 is a plot of the sums of squares of differences in the actual volume observed on approach A and the FTAIL approximations for all values of K and all initial approximations of volume. This is a representation of the raw data, not the longer term 10-minute averages which are also important. As indicated by the graph, the optimum value for K is 0.3 or 0.4.

Figure 22 is a plot of the 10-minute averages of the sums of squares of differences for approach A. This plot indicates that a small value of K yields high sums of squares in the long run, while at values of K higher than 0.5 there is little difference in the sums of squares.

e. Conclusions

The plots of the sums of squares for the other three approaches are similar and yield the same observations. Thus, in the short run, the data for the Arlington, Virginia site indicates that a small value of K yields the best results. In the long run,

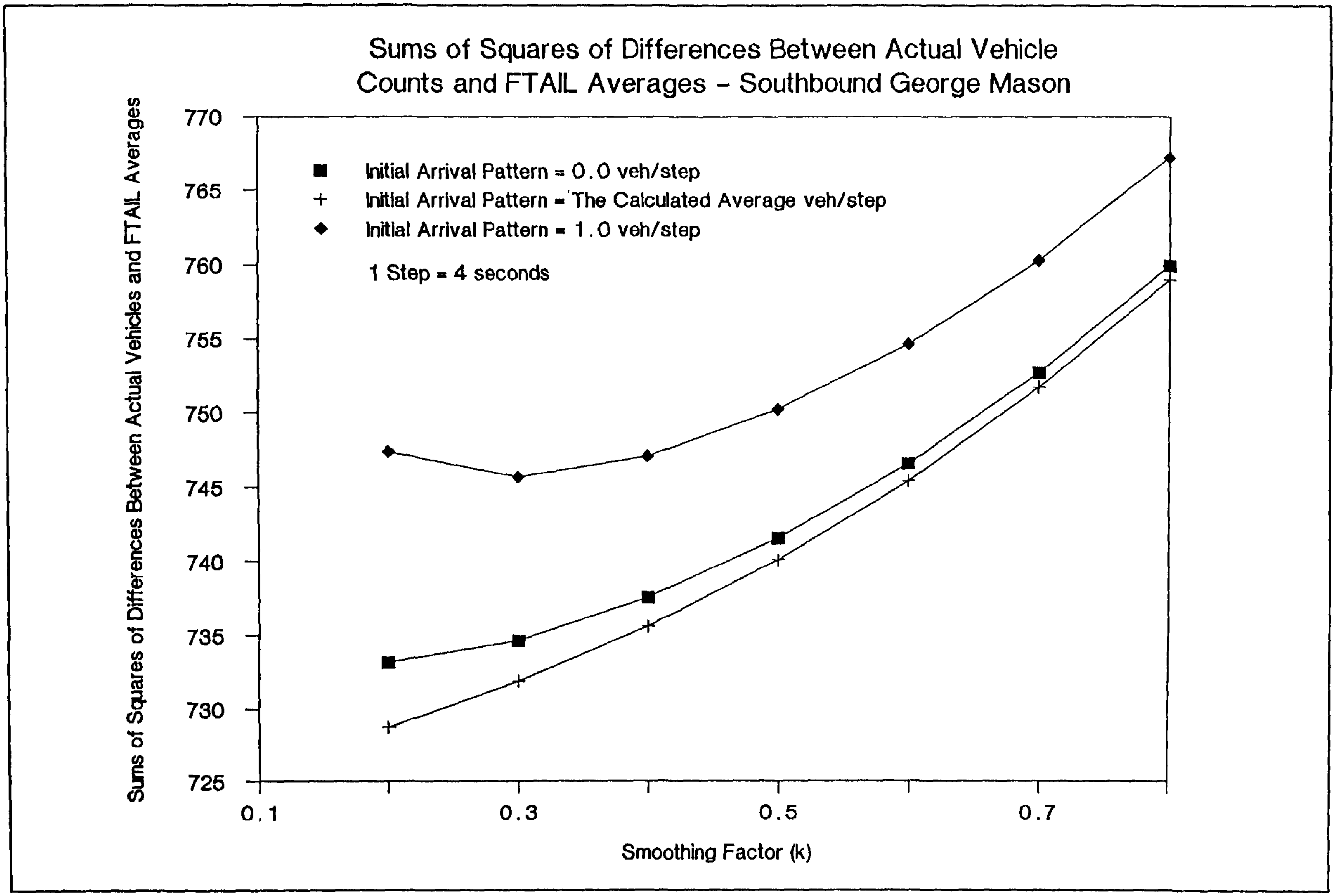


Figure 21. Sums of squares of differences between actual volumes and FTAIL approximations - southbound George Mason Drive.

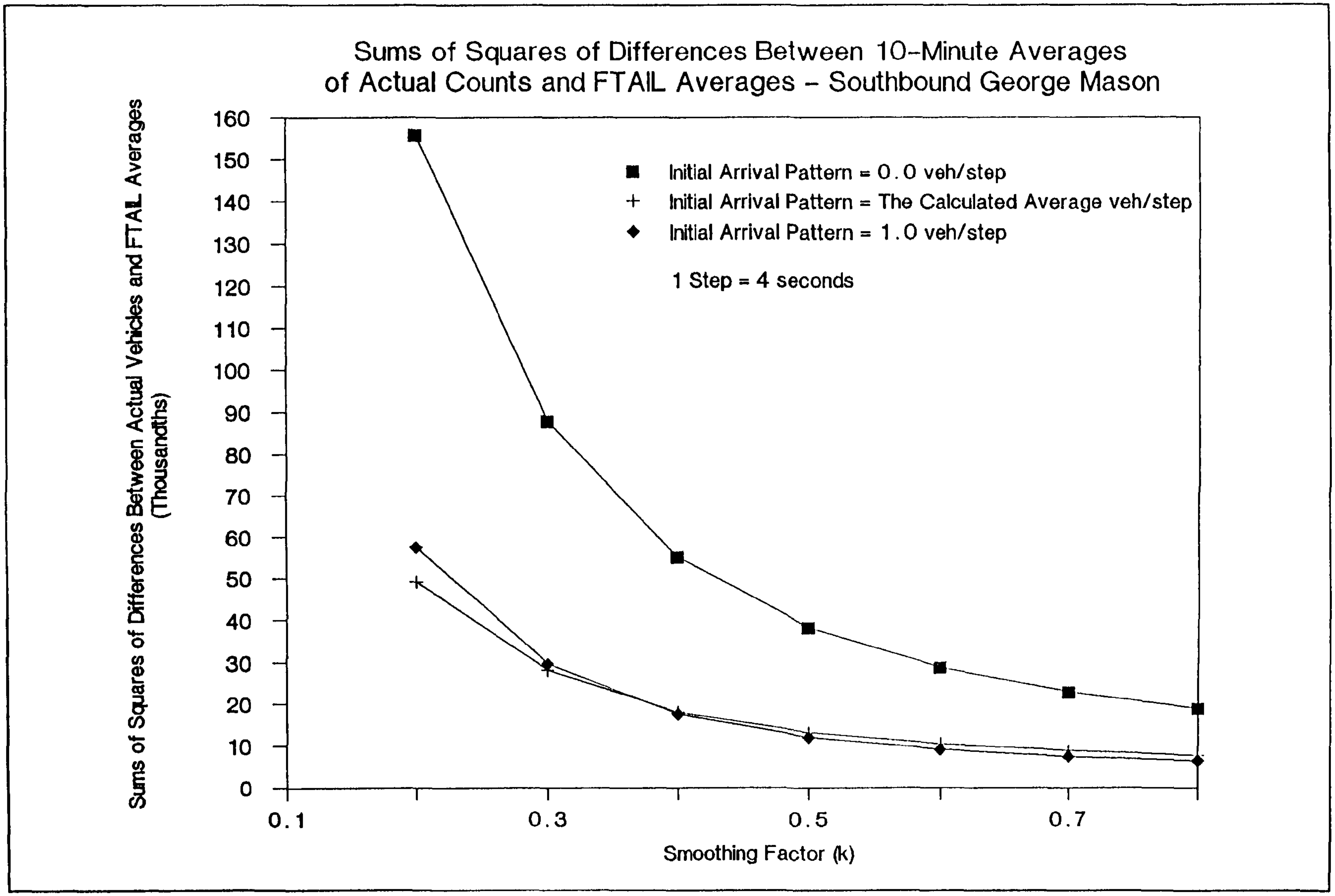


Figure 22. Sums of squares of differences between actual volumes and FTAIL approximations - 10-minute averages - southbound George Mason Drive.

however, the data indicates that a larger value of K yields the best results. Functionally, a small value of K will result in a function which tracks the actual volume very closely and is therefore erratic. A large value of K will result in a function which follows the actual volume less closely but which is much more smooth.

Since the long-term performance of the algorithm is of more importance than the short-term, it is reasonable to choose a larger value for K. Considering figure 22 again, the benefit of choosing larger values of K, measured by the reduction in the sums of squares, becomes smaller as K increases. Hence, choosing a value of 0.7 does not produce much better results than choosing a value of 0.6 in the long run, however it is much worse in the short run. From considering both plots, it appears that a value of 0.5 results in the optimum performance in both the short and long run. In the short run, the sums of squares is not much worse than the optimum 0.3 or 0.4 and is much better than higher values. In the long run, very little is gained by selecting a larger value of K. The result is a function which is a good approximation to the actual volume but which is not as erratic.

2. Horizon Length, Travel Times, and Saturation Flows

a. Introduction

The plan for testing the OPAC-RT optimization algorithm required the calibration of three parameters. As described in the text, these parameters were:

- Saturation flow per approach (Version 1.0) or phase (Version 2.0).
- Travel time from the detectors to the stop bar.
- Horizon length.

The horizon is the time period over which the optimization algorithm calculates its switching decisions. It consists of a head and a tail portion. In the head portion of the horizon, the algorithm has available real-time vehicle arrival patterns. In the tail portion, the arrival patterns are estimated from historical data.

The performance of the OPAC algorithm is affected by the values of these parameters. Below is a description of the procedure used to determine the values which optimized the performance of the algorithm at the Arlington, Virginia test site.

b. Methodology

Saturation flows for the intersection were needed before any calibration could be carried out. Because the queues at the intersection were not long enough to determine saturation flow by conventional methods, a hybrid procedure was defined.

The field study conducted to measure saturation flows required a stop watch to be started at the onset of green for the approach. The cars were counted as they entered the intersection and the watch was stopped when the last vehicle in the queue entered the intersection. The time and number of vehicles was recorded. The time was then adjusted according to table 10, Saturation Flow Timing Adjustments. These adjustments are estimates of the startup lost time, most of which is normally experienced during the first 6 seconds of green. From the adjusted times and queue lengths saturation flow was determined. These flows were averaged to obtain observed saturation flows for each approach.

For conducting the calibration studies of saturation flow, travel time, and horizon length standard, low, and high values for each parameter were defined. For saturation flow on each approach, a

Table 10. Saturation flow timing adjustments.(4)

Number of vehicles	Adjustment (sec)
1	-1.7
2	-2.7
3	-3.3
4	-3.6
5	-3.7
6+	-3.7

standard value equal to the measured saturation flow was used. For travel time, a standard of 12 seconds was used. OPAC requires that the same value be used for each approach. For horizon length, a standard of 15 steps, where a step is 4 seconds, was defined. For each variable low and high values were also defined, as indicated in tables 11, 12, and 13 below.

Table 11. Calibration study saturation flow rates (vehicles/step).

Data Category	George Mason		16th Street	
	Northbound	Southbound	Eastbound	Westbound
Low	4.0	4.0	2.0	2.0
Standard	7.2	5.8	3.5	2.5
High	8.0	8.0	4.0	4.0

Table 12. Calibration study travel times (seconds).

Data Category	All Approaches
Low	8
Standard	12
High	16

Table 13. Calibration study horizon lengths (steps).

Data Category	Horizon Length
Low	12
Standard	15
High	18

Several datasets of various combinations of values of these parameters were created. They were supplied as input to the OPAC algorithm and then operation of the intersection was observed. Table 14 lists the various combinations used in the calibration.

In addition, a dataset was created with the standard values for travel time and horizon length and standard values for saturation flow on George Mason but high values for saturation flow on 16th. This was thought to better reflect the flow on 16th because of the high number of vehicles making right turns on red from 16th onto George Mason.

Table 14. Combinations of parameter values for the calibration study.

Test Number	Saturation Flow	Travel Time	Horizon Length
1	Standard	Standard	Standard
2	Standard	Low	Standard
3	Standard	High	Standard
4	High	Standard	Standard
5	Low	Standard	Standard
6	Standard	Standard	High
7	Standard	Standard	Low

c. Results

Each test number indicated above represents a 25-minute study. Test number 1 was repeated three times to serve as control group for variations in saturation flow, travel time, and horizon length. For each study an average measure of delay per vehicle was obtained. This measure of effectiveness was used to evaluate the performance of the OPAC algorithm. Table 15 is a summary of the results.

d. Conclusion

Based on this comparison, the standard values for saturation flow and travel time and a horizon length of 12 steps or 48 seconds were chosen as the best parameter values for testing the OPAC algorithm.

Table 15. Summary of calibration study test results.

Test Num	Sat Flow (v/m)	Travel Time (sec)	Horizon (steps)	Cycle (sec)	Demand (veh/min)	Delay (v-m/min)	Delay (sec/veh)
1	Std	Std	15	42	25	2.4	5.8
2	Std	Low	15	46	22	1.9	5.1
3	Std	High	15	48	25	3.1	7.3
4	High	Std	15	49	22	3.0	8.1
5	Std	Std	15	52	26	2.7	6.4
6	Low	Std	15	50	28	2.9	6.1
7	Std	Std	18	59	32	5.0	9.3
8	Std	Std	15	54	41	5.5	8.1
9	Std	Std	12	36	*	3.6	*
10	Std	Std	12	49	34	2.8	4.9

APPENDIX C - TEST PLAN FOR THE EVALUATION OF THE OPAC-RT SYSTEM

Overview of the Test Plan

This appendix describes the data collection work plan as required by Task H, Field Test Work Plan, under the contract, 'Evaluation of the Optimized Policies for Adaptive Control (OPAC) Strategy'. This plan describes the data to be collected, the field data collection procedures, and the methods to be used in analyzing the data.

There are two phases in the plan. First, data are collected to determine optimum settings for three of the algorithm calibration parameters: travel times from the OPAC-RT vehicle detectors to the stop line, horizon time, and saturation flow rates. Second, the algorithm itself is evaluated by comparing the intersection operating under OPAC control with the same intersection operating under full-actuated control. Field measures of intersection stopped-time delay and demand volumes are used for the comparisons. An overview of the test plan activities is shown on figure 23.

The test plan itself is a conventional 'Before' and 'After' comparison. The 'Before' condition is the intersection operating with the Econolite D2000 used as a full-actuated controller. The 'After' condition is the intersection operating with the OPAC algorithm supervising the same controller.

The primary figure-of-merit is intersection stopped-delay per cycle. Each observation of delay is coupled with the demand volumes and duration of the green for each approach during the same cycle. Thus, one observation consists of the intersection delay, the number of vehicles counted on each of the four approaches, and duration of the phase green times.

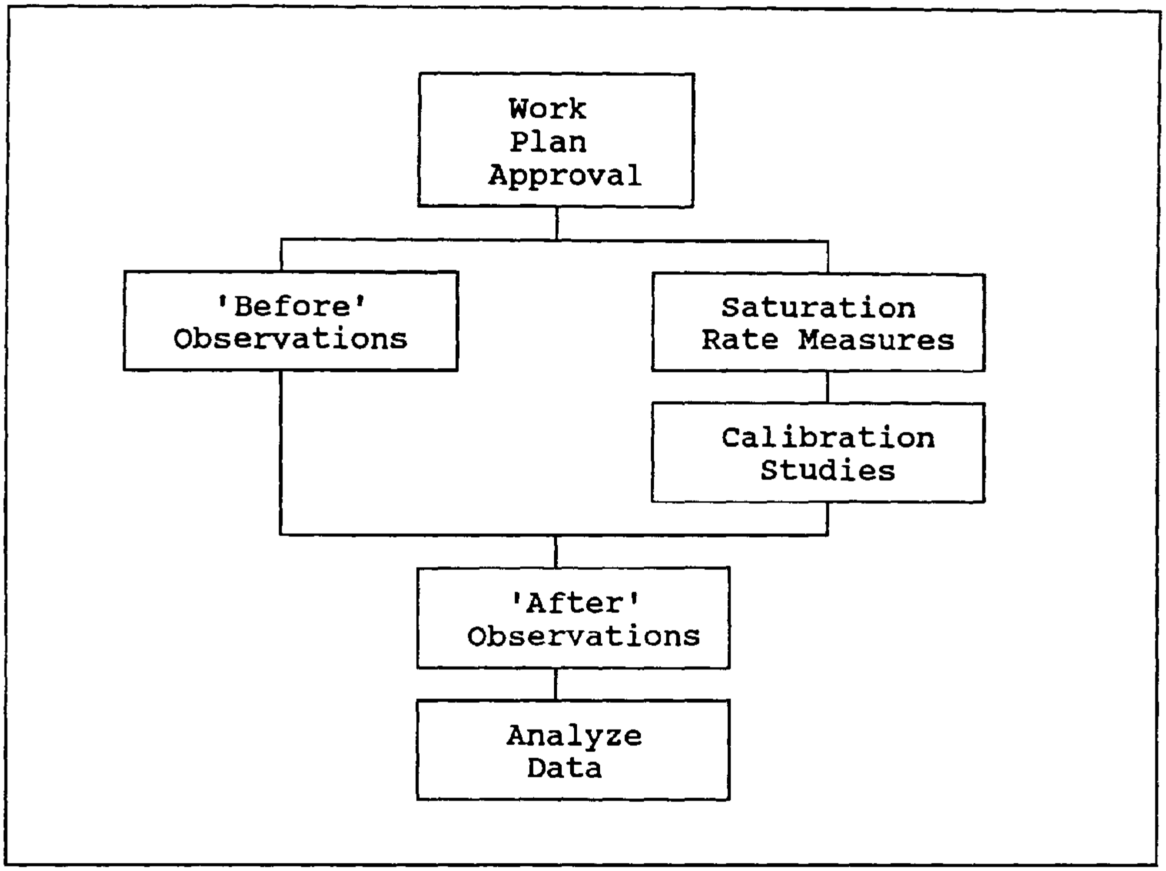


Figure 23. Evaluation plan.

Available traffic count data were obtained from Arlington County. Of the data available, the directional road-tube counts were useful in developing the test plan. These data were available for George Mason Drive based on counts made on June 2, 1986. These data show directional flow rates ranging from 400 vehicles per hour (VPH) to more than 800 VPH during daylight hours. Since the higher flows in both directions occurred during the evening peak period, the period from 3:00 pm to 6:00 pm was selected. This period provides a reasonable range of demand as well as encompassing the peak demand for the intersection. Directional traffic volumes are shown in figure 24.

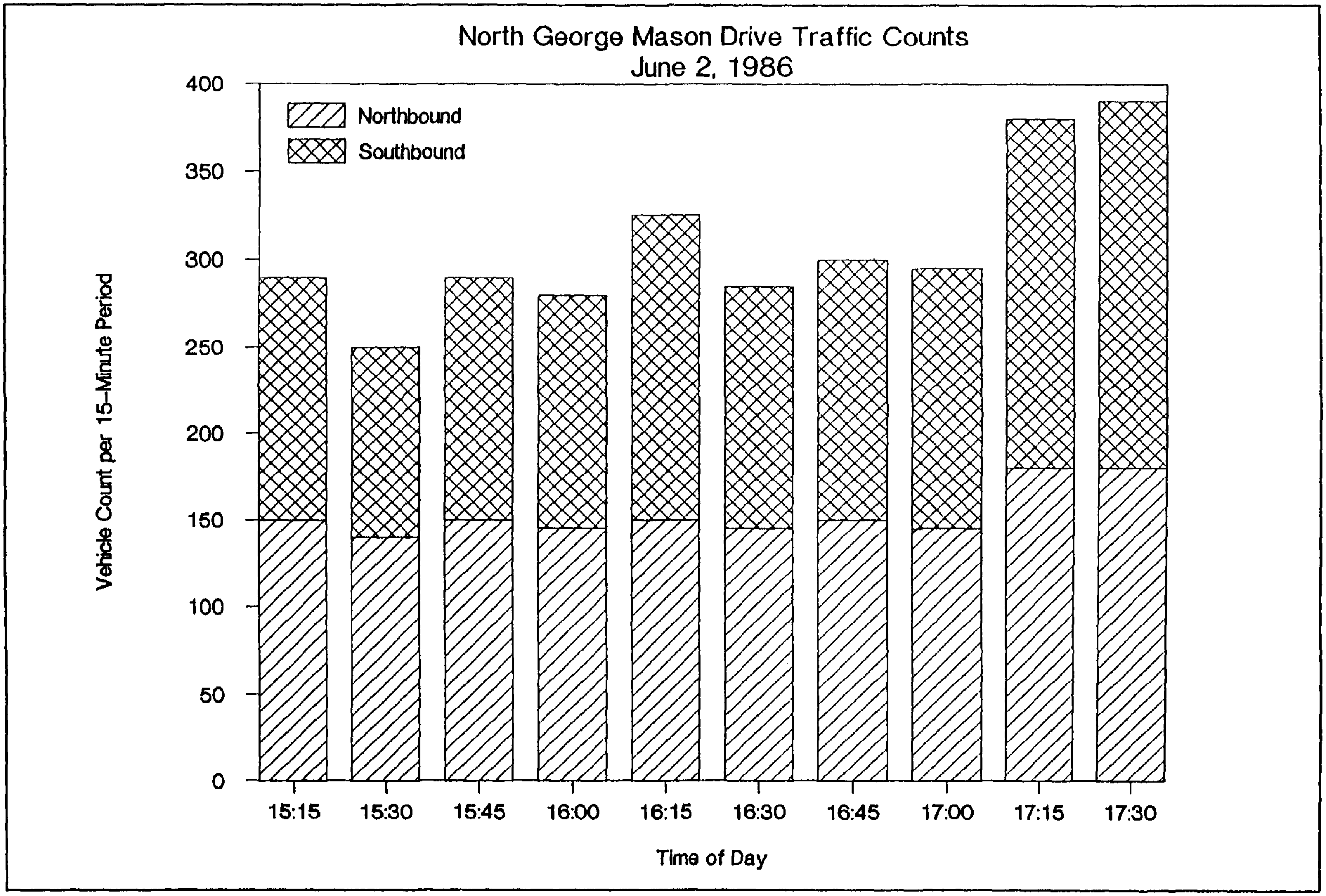


Figure 24. Directional demand on George Mason Drive.

The Field Crew will spend at least 2 hours at the test site 1 week prior to the scheduled 'Before' study. The purpose of this trip is threefold: to locate unobtrusive positions from which the intersection approaches can be observed; to finalize the coordination procedures between the Delay Observer and the two Demand Observers; and to collect saturation flow rate data for all four approaches to the intersection.

The test plan as presented herein exceeds the requirements of the contract (Task I-2) in that a total of approximately 7.5 hours of 'Before' data and 7.5 hours of 'After' data is scheduled. The requirement of at least 1/2 hour of peak period data be collected is exceeded as the plan calls for data to be collected during the peak hour (5 pm to 6 pm) on 3 days.

Saturation Flow Measures

The procedures that are described in 'Road Note 34, A Method Of Measuring Saturation Flow at Traffic Signals', Road Research Laboratory, 1963, were initially intended to be followed to measure saturation flow rates. This procedure calls for the number of vehicles entering the intersection during each 6-second interval after the beginning of green to be recorded on a form while there is constant demand.

A review of existing traffic counts on both 16th Street and George Mason Drive indicated volumes so low that it is rare that there would be two consecutive 6-second intervals of saturation flow.

Because of these low rates, a different procedure will be followed. This procedure requires a stop watch to be started at the onset of green for the approach. The cars are counted as they enter the intersection and the watch is stopped when the last vehicle in queue enters the intersection. The time and number of vehicles is recorded. The time is then adjusted according to table 10 in appendix B, Saturation Flow Timing Adjustments.

These adjustments are estimates of the startup lost time most of which is normally experienced during the first six seconds of green. The data are recorded on the Saturation Flow Study Form; a sample form is included as figure 26 at the end of this appendix.

Calibration Studies

There are two algorithm parameters that require calibration studies before the OPAC test can be conducted. These are the saturation flow rates for each approach and the duration of the horizon.

The saturation flow rate for a given approach-demand condition is a measurable quantity. The question, therefore, is how well will the algorithm operate if a nonoptimum value is selected. To address this issue, the optimum value will be determined by conducting field measurements. The sensitivity of this parameter will be examined by operating the algorithm with higher values for 25 minutes, the optimum values for 25 minutes, and then with lower values for 25 minutes. This test will be conducted during a period that the traffic demand is expected to be relatively stable.

The 'higher' values will be 20 percent greater than the 'optimum' as measured. The 'lower' values will 20 percent less than the optimum. Delay data will be collected during these three periods using the procedures described in the following section of this Test Plan.

The effect of different values of the timing horizon will be subjected to a similar test. Experiments to date with the OPAC algorithm have been limited to simulation with a horizon (optimization period) of 60 seconds. The primary field testing will be conducted with the same value to enable the potential of comparisons of the field results with simulation results. The sensitivity analysis will test both a longer and a shorter project horizon. The longer period will be 72 seconds, the shorter period will be 48 seconds.

As with the saturation flow studies, field observations of delay will be conducted for the three 25-minute periods. The total delay at the intersection will be determined for each of the three conditions by summing the delay observed during each cycle. This total delay is divided by the total number of vehicles entering the intersection during the same period to calculate delay per vehicle. The condition that results in the lowest delay per vehicle will be used for the 'After' tests.

Delay Study Field Procedures

A total of three persons will be involved in the delay studies. One person, the Delay Observer, will be responsible for operating the laptop computer and entering the delay observations. The other two will be responsible for vehicle counting. To maintain the alertness of the field crew, jobs will be rotated each data collection period (25 minutes).

A description of the Data Collection (DATCOL) program that will run on the laptop and a listing of the program is included in appendix D.

Prior to starting each data collection period, The Delay Observer initializes the DATCOL program and verifies the date and time, Selection-1 from the Main Menu. Next, the number of the study data file (1-99) is entered (Selection-2 from the main menu) and an 'A' is pressed at the beginning of A-phase green to begin the data collection period.

The Delay Observer records the number of vehicles stopped on each of the four legs of the intersection as prompted by the program. As each approach-specific observation is entered, the time of day (in seconds) is stored and used to calculate the delay on each approach. Each observation entry is preceded by an 'A' or a 'B' signifying the signal phase. With practice, by being cognizant of the demand and clearance intervals, the delay observer is able to time the observations to be within one second of the start of each phase.

Simultaneously, the two demand observers record vehicles as stopping or not stopping for each approach using the Traffic Count Form; a sample form is included as figure 27 at the end of this appendix. The cycle number is checked with the Demand Observer at least once each cycle. The Demand Observer reads the cycle number from the laptop computer display.

At the end of the 25-minute period, the data file in RAM memory is transferred to cassette tape and listed on a printer for initial review. If desired, the data from the listing could be transferred to the Approach Delay Form; a sample of this form is included as figure 28 at the end of this appendix. The listing and the forms used to record the counts are stapled together for data reduction in the office.

'Before' Observations

The test plan requires 3 days during 1 week for the 'Before' case and 3 days the following week for the 'After' case. The data will be collected each day from 3 pm to 6 pm in six 25-minute periods with a 5 minute break between each set. With good weather, data will be collected Monday through Wednesday. In the event of inclement weather, the data collection will be postponed 1 day.

The plan is expected to yield between 400 and 600 observations of delay where each observation is the delay experienced during one cycle. The actual number of observations obtained will be a function of the traffic demand and the signal timing.

'After' Observations

The 'After' data will be collected during the same day of week as the 'Before' data if at all possible. For example, if the 'Before' data are observed on a Monday, Wednesday, and Thursday. Then the 'After' data will be observed on the same day of the week. In the event of inclement weather, the field observations will be delayed 1 week. Thus it may be possible to have the Monday and Wednesday comparisons during 1 week and the Thursday comparison during the following week. If weather is a problem during the second week, data will be collected during the first possible weekday.

Analysis

Although both the delay and the count data are recorded as approach-specific observations, the primary analysis of the data is predicated on the total intersection delay and volume. For each observation, therefore, the total observed delay on all four approaches is divided by the total volume on the four approaches to derive the delay per vehicle. The volume is converted to an hourly rate by dividing the observed cycle length into 3600. Thus the data are reduced to delay per vehicle and a demand rate.

It is anticipated that a plot of these observations may be estimated by a curve similar to that in figure 25.

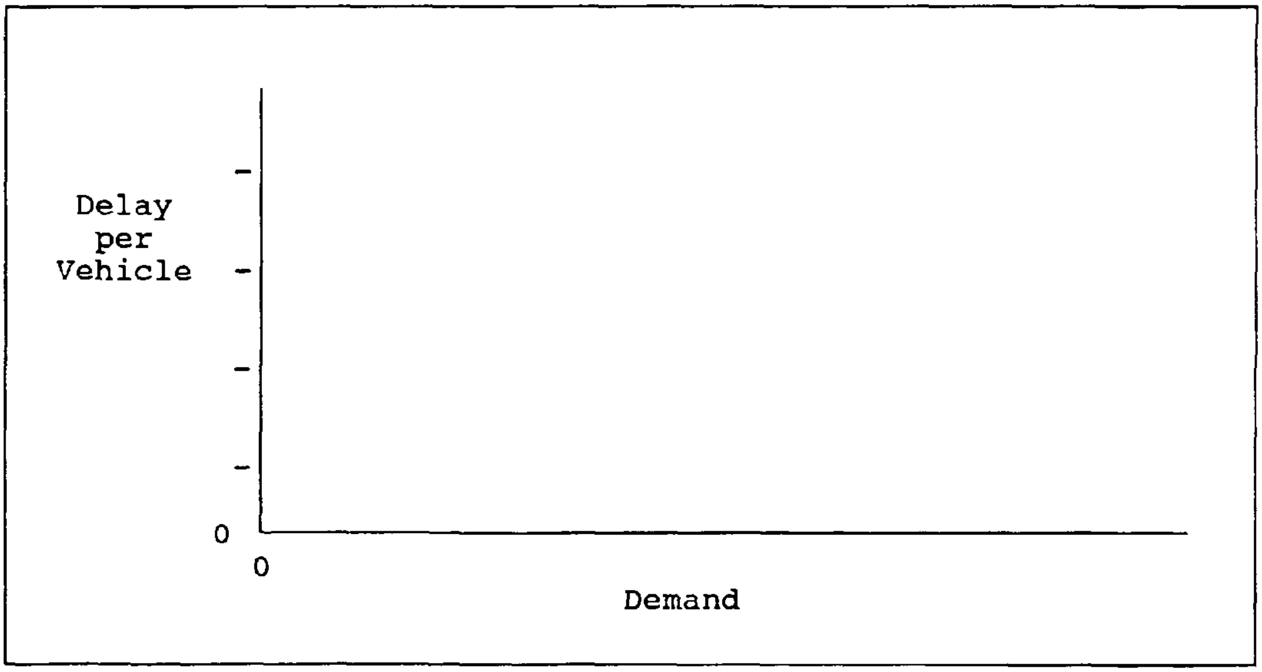


Figure 25. Hypothetical relationship between volume and delay.

It is entirely possible that OPAC will perform better than the full-actuated alternative under some demand conditions and worse under others. To more clearly examine the demand conditions under which each alternative may excel, the observed demand values will be converted to demand by phase expressed as an hourly flow rate. The higher demand on the two approaches for each phase will be used in this analysis. For each phase (George Mason green and 16th Street green) the demand will be divided into thirds. Each observation will be classified into one of the nine cells defined by the demand stratification as noted in table 16.

This stratification will be generated for the 'Before' and 'After' data sets using both average delay and percent stops. Analysis of these paired comparisons will be based on the use of

Table 16. Demand stratification.

16th STREET	GEORGE MASON DRIVE		
	low 1/3	med 1/3	high 1/3
low 1/3	D1	D4	D7
med 1/3	D2	D5	D8
high 1/3	D3	D6	D9

the Chi-squared test for each of the individual cells. The null hypothesis used will be the full actuated controller case.

Form for Saturation Flow Study

Location:______________________________ Date:___________

Start Time:______________________________ Study #:___________

Cycle	Count	Time (sec)	Adjust (sec)	Sat. Flow
1				
2				
3				
4				
5				
6				
7				
8				
9				
10				
11				
12				
13				
14				
15				
16				
17				
18				
19				
20				
21				

Figure 26. Form for Saturation Flow Study.

DELAY STUDY - Traffic Count Form

Location : ____________________ Date : __________

Start Time : ____________________ Project Num : __________

CYCLE				
	STOP	NO STOP	STOP	NO STOP
1				
2				
3				
4				
5				
6				
7				
8				
9				
10				
11				
12				
13				
14				
15				
16				
17				
18				
19				
20				

Figure 27. Traffic Count Form for Delay Study.

DELAY STUDY - Approach Delay Form

Location : ______________________ Date : __________

Start Time : ______________________ Project Num : __________

CYCLE	Cycle Begin Time	Phase Times		Approach Delay (veh-sec)			
		A	B	NB	SB	EB	WB
1	:						
2	:						
3	:						
4	:						
5	:						
6	:						
7	:						
8	:						
9	:						
10	:						
11	:						
12	:						
13	:						
14	:						
15	:						
16	:						
17	:						
18	:						
19	:						
20	:						

Figure 28. Approach Delay Form for Delay Study.

APPENDIX D - DATA COLLECTION PROGRAM (DATCOL)

DATCOL is a straightforward BASIC program that runs on a Radio Shack Model-100 laptop computer. The program is short, approximately 110 lines of executable code. It functions as an efficient recording device. There are eight blocks of code in the program. Each block performs one primary function as follows:

1. Main menu selection provides the User the opportunity to check the date and time, to commence data collecting, or to exit to the operating system.

2. The date and time block allows the user to check both parameters and to reset them if necessary.

3. The initialization block defines the approach names and allows the User to input a 'Study Number'. This number, with a range of 1 to 99, is incorporated into the data file name. For example, study 23 will produce an output file named 'DATA23.DO'.

4. The next block is the beginning of the data collection phase. Initial observations and times of each observation are recorded.

5. The primary data collection loop is coded in this block. The primary function is to determine whether the phase has ended or not. If the display is the same as the previous observation, then the queue length subroutine is called. If the display has changed from A-phase green to red, then the duration of the green time is computed and the queue length subroutine is called. If the display has changed from red to green indicating the beginning of a new cycle, then the routine that computes the end of cycle functions is called and the results are written to the data file.

6. The queue observation block prompts the user for the queue length on each approach in succession. As the observation is keyed in, the time that the observation was entered is recorded in memory. When the User verifies

that the observations are correct, the delay (vehicle-seconds) for each approach is computed by multiplying the average queue length by the time between observations. This value is added to the cumulative delay for each approach since the beginning of the cycle.

7. The A-phase to B-phase change block simply computes the duration of the A-phase green and then calls the queue observation routine.

8. The last block does three things. It computes the duration of B-phase and the cycle length. It calls the queue routine for the final observation for that cycle. And it writes the following to the file:

   - Cycle Number.
   - Time of day that the cycle began.
   - Duration of A-phase.
   - Duration of B-phase.
   - Delay on each approach (1-4).

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(4) B. D. Greenshields, et. al. "Traffic Performance at Urban Street Intersections."