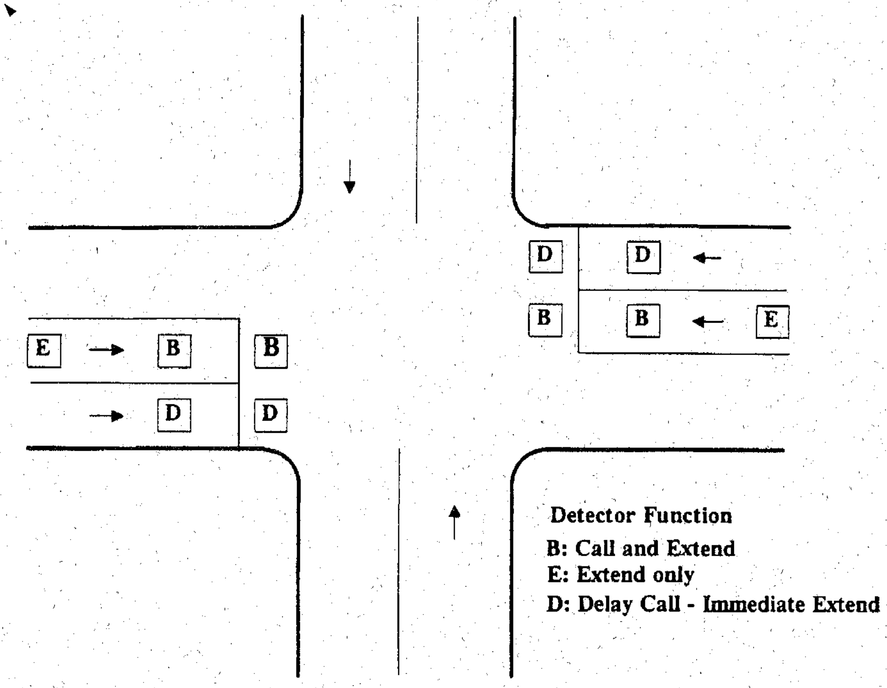
Report Number 95-05

Research



Development and Application of On-Line Strategies for Optimal Intersection Control Phase II

UNIVERSITY OF MINNESOTA
CENTER FOR TRANSPORTATION STUDIES

Funding for this project was provided through the University of Minnesota Center for Transportation Studies and the Minnesota Department of Transportation Office of Traffic Engineering.

Report Documentation Page

1. Report No. MN/RC-95/05	2.	3. Recipient's Accession No.
4. Title and Subtitle DEVELOPMENT AND APPLICATION OF ON-LINE STRATEGIES FOR OPTIMAL INTERSECTION CONTROL		5. Report Date October 1994 6.
7. Author(s) Yorgos J. Stephanedes, Eil Kwon and Xiao Liu		8. Performing Organization Report No.
9. Performing Organization Name and Address Department of Civil Engineering University of Minnesota 110 CME Building, 500 Pillsbury Drive S.E. Minneapolis, Minnesota 55455		10. Project/Task/Work Unit No. 11. Contract(C) or Grant(G) No. (C)69570 TOC #87 (G)
12. Sponsoring Organization Name and Address Minnesota Department of Transportation Office of Research Administration 117 University Avenue Mail Stop 330 St.Paul Minnesota, 55155		13. Type of Report and Period Covered Final Report 14. Sponsoring Agency Code

15. Supplementary Notes

16. Abstract (Limit: 200 words)

This project evaluates various intersection control strategies in a simulated environment and also helped establish a live laboratory for use in future testing of new control strategies. The report reviews major intersection control strategies, including the state-of-the-art strategies with adaptive and on-line timing generation features. In addition, it details simulation results for the OPAC control strategy. The NETSIM simulator created the simulation environment for a test network that included part of downtown Minneapolis. Comparison results indicate that OPAC performs best with low-traffic demands, and pretimed control was the most effective during peak periods when traffic demand reached capacity.

In conjunction with this project, Minneapolis city traffic engineers installed a machine-vision video detection system at a live intersection laboratory. Located at Franklin and Lyndale Avenues, the test site will help researchers evaluate new control strategies before full-scale implementation in later phases of this research.

17. Document Analysis a. Descriptors SCOOT NETSIM SCATS PRODYN OPAC		18. Availability Statement No restrictions. Document available from: National Technical Information Services, Springfield, Virginia 22161.	
19. Security Class (this report) Unclassified	20. Security Class (this page) Unclassified	21. No. of Pages 149	22. Price

DEVELOPMENT AND APPLICATION OF ON-LINE STRATEGIES FOR OPTIMAL INTERSECTION CONTROL

PHASE II

OFF-LINE EVALUATION OF CONTROL STRATEGIES AND DEVELOPMENT OF A LIVE LABORATORY

Final Report

Prepared by

Yorgos J. Stephanedes, Eil Kwon and Xiao Liu

Department of Civil Engineering
University of Minnesota

October 1994

Published by

Minnesota Department of Transportation
Office of Research Administration
200 Ford Building Mail Stop 330
117 University Avenue
St Paul Minnesota 55155

ACKNOWLEDGEMENT

This research was supported by the Center for Transportation Studies, University of Minnesota, and the Minnesota Department of Transportation. Metropolitan Council of the Twin Cities, City of Minneapolis, Image Sensing Systems Inc. and Farradyne Inc. are also acknowledged for their support.

TABLE OF CONTENTS

LIST OF FIGURES

LIST OF TABLES

EXECUTIVE SUMMARY

The most advanced concept for signalized network management employs demand-responsive control using on-line timing generators with adaptive features. Software developed for this type of control include SCOOT, SCATS, PRODYN and OPAC. While individual tests of each software have been conducted by various agencies, no comprehensive effort has been made to evaluate and quantify the performance of the state-of-the-art control software, especially in terms of their applicability to detection both with loops and machine-vision image processing. The previous phase of this research, Phase 1, has reviewed the algorithms of existing intersection control strategies. This report documented the final results of the second phase of this research, which seeks to evaluate various intersection control strategies in a simulated environment, and to develop a live laboratory that can be used in the subsequent phase of the research for the development and testing of new control strategies.

First, major intersection control strategies developed to date were briefly reviewed including the state-of-the-art strategies with adaptive and on-line timing generation features. SCOOT and SCATS seek to adjust the cycle time, phase split, and offset so that the optimization criteria (i.e., stops, delays and queue lengths) are minimized. By contrast, PRODYN and OPAC attempt to find optimal acyclic settings. SCOOT is based on centralized methods in performing optimization, whereas SCATS performs much of the optimization procedure in its vehicle-actuated controllers. PRODYN and OPAC perform the optimization at each intersection using dynamic programming techniques. OPAC tries to minimize vehicle delays and percentage of stopped vehicles and PRODYN attempts to minimize total delay. In OPAC, detectors are located far upstream of the stopline, while PRODYN requires two detectors, upstream and near the stopline. In addition to the above algorithms, the current intersection control strategies in three major cities in the U.S. and Canada, i.e., Toronto, Minneapolis and Los Angeles, were also reviewed in this research. The Toronto system operates on a preset timing plan with the main controller retaining three primary cycle settings. In Minneapolis, the master controller monitors the operation of all intersections and overrides the local controller if necessary. The Los Angeles system selects a timing plan for each intersection from a group of 30 timing plans depending on traffic volume in real time. Owing to the availability of the control software, the OPAC control strategy was selected as the initial control algorithm to be evaluated in this research. The evaluation of other control strategies, such as CARS, will also be considered in a future phase depending on their availability.

Second, a simulation environment was developed using the NETSIM simulator, and a test network located in downtown Minneapolis. This network, located north of the Minneapolis central downtown area, contains 15 signalized intersections. Currently, all signals are being operated in the pretimed mode, and the timing plans of most signals were updated in the 1960's. Further, the network links serve as the feeder links to the nearby I-394 freeway, and thus, their traffic volume can be substantially influenced by the traffic conditions in the freeway. As a first step towards a comprehensive evaluation of intersection control strategies, a hypothetical actuated control operation was simulated in the test network and its performance was compared with that of the current pretimed operation, which was also simulated with NETSIM. The evaluation results indicate that the conversion of three intersections on the central arterial of the test network, i.e, First Ave. from pretimed to fully-actuated control mode could improve the traffic performance in terms of delay, queue and stop time. However, it should be noted that, owing to limitations in the NETSIM software, only the intersections in the internal links, not boundary links, can be operated in actuated control mode. Further, the performance of actuated control was compared with only that of the current pretimed operation which was last updated in the 1960's on First Avenue. A comprehensive evaluation of additional pretimed signal operations should be conducted before drawing conclusions regarding the effectiveness of actuated control over pretimed operation in the test network. The OPAC control strategy was next evaluated in the simulated environment using an intersection located in the Minneapolis downtown as the test intersection. The performance of OPAC was compared with that of pretimed and actuated control simulated with the same demand pattern at the same intersection with NETSIM. The comparison results indicate that OPAC performs best with low traffic demand, and pretimed control was most effective during peak periods when the traffic demand was near capacity.

Another important accomplishment of the current project is the selection of the site for the live intersection laboratory and the installation of a machine-vision video detection system at the laboratory intersection, located at Franklin and Lyndale Avenues in downtown Minneapolis, Minnesota. The location of the live laboratory was determined in consultation with the traffic engineers from the City of Minneapolis and the Minnesota Department of Transportation. The selected intersection currently exhibits frequent congestion and delay during peak hours. Further, the location and distance of the intersection from the adjacent intersections make it possible to operate it as an isolated intersection, but it can be easily incorporated into coordinated network control. The installation of the video system was conducted by the City traffic engineers. Using the data collected from the newly installed machine-vision detection system, the traffic performance of the intersection was quantified and analyzed. A performance index quantifying the traffic delay at the intersection was developed and delay was estimated using the data from the machine-vision detection. The Minneapolis laboratory will be used as a test site for new control strategies prior to full scale implementation in subsequent phases of this research.

Future work includes the development of a comprehensive operational plan for the live intersection laboratory, installation of additional cameras at the laboratory to fully cover the intersection for incident detection research, and development of new control strategies that take advantage of machine-vision detection features, such as type of data that can be collected and detector location flexibility. The new control strategies will be tested and refined at the live laboratory after performing off-line evaluation using simulation. The effort to obtain additional advanced control strategies, such as CARS, will continue; once such strategies are available, their performance will be analyzed and compared with that of OPAC and other available control strategies.

I. INTRODUCTION

I. 1 Background

The most common type of intersection control strategies determines the best timing plan off-line by applying arterial or network simulation/optimization software with an expected traffic demand pattern. The resulting timing plan is stored in the computer for implementation by various on-line criteria. The computer models used for this type of control include TRANSYT7F, NETSIM, SIGOP and AAP. However, owing to the daily variations of traffic demand, the timing plan optimized with an expected demand pattern may become suboptimal to the actual traffic flow conditions. Further, the timing plans stored in the traffic controller are not updated frequently enough to reflect current traffic conditions. More recently, traffic demand-responsive control strategies with on-line timing generators and adaptive features have been introduced. The latter type of control, represented by SCOOT, SCATS, PRODYN and OPAC, continuously updates its control parameters in response to the changing traffic demand on a cycle-by-cycle basis.

While the concept of control strategies with adaptive features looks promising and there have been individual tests of each control strategy by various agencies, no comprehensive effort has been made to quantify and evaluate the performance of intersection control algorithms, especially in terms of their applicability to detection with both loops and machine-vision image processing. The previous phase of this research, Phase 1, has reviewed the algorithms of existing intersection control strategies. The current phase, Phase 2, extends the previous research efforts by testing the state-of-the-art intersection control strategies in a simulated environment and by starting the development of a live intersection laboratory with installation of a machine-vision detection system at a selected intersection. Further, the traffic performance of the selected intersection is analyzed with the data collected using the machine-vision detection system. The comprehensive operational plan for the live laboratory will be developed in the next phase.

I.2 Research objectives

The ultimate objective of this research is the development and application of on-line control strategies for intersections and arterials using available data collection systems including loops and machine-vision. The resulting strategies will provide a comprehensive, real-time control scheme that includes optimal signal timing and can be extended to include incident detection methods. The major accomplishments of the current project, Phase 2 of this research, are:

- Testing existing on-line intersection control algorithms in a simulated environment.
- Development of a live laboratory for testing intersection control strategies with machine-vision and loop detection systems (to be completed in Phase 3).

- Evaluation of the traffic performance of the intersection laboratory using the data collected with the machine-vision detection system.

I.3 Report organization

This report summarizes the final results of the current project. The second chapter presents an overview of the major available on-line control strategies and identifies control strategies to be evaluated in this research. Chapter 3 develops a simulation environment for off-line evaluation of control strategies using the NETSIM simulator and the test network located in downtown Minneapolis. The description of the data collected for off-line testing is also included in this chapter. Chapter 4 summarizes the off-line evaluation results of the selected strategies for network control. The off-line evaluation results for single intersection control strategies including pre-timed, actuated and OPAC, are described in chapter 5. Chapter 6 describes the installation of a machine-vision based video detection system to develop a live intersection laboratory. Chapter 7 analyzes the traffic performance of the intersection selected as the live laboratory site using the data collected with the video detection system. Finally, Chapter 8 contains conclusions and future research directions.

II. SELECTION OF CONTROL STRATEGIES FOR OFF-LINE EVALUATION

II.1 Introduction

Intersection control strategies have evolved from simple time-of-day control with predetermined timing plans to sophisticated traffic control with on-line, adaptive timing generation features. While variations of intersection control schemes are numerous, operating control concepts may be grouped into the following fundamental categories:

- Pretimed isolated control,
- Pretimed coordinated control,
- Traffic responsive isolated control,
- Traffic responsive coordinated control.

Among the above control strategies, traffic responsive coordinated control represents the most advanced concept in managing urban traffic networks. However, because of the relative complexity of traffic behavior and the variety of prevailing traffic conditions, no universal "best" method exists for determining the optimal type of control for a given intersection or urban network. This chapter briefly reviews the major intersection control strategies currently in operation and selects the strategies to be evaluated.

II.2 Overview of intersection control strategies

II.2.1 *Pretimed control*

The simplest form of intersection control consists of the pretimed isolated intersection control, where the traffic timing parameters, such as, cycle length, phase and split, are fixed or conform to a typical traffic flow pattern and do not change in response to the variation of traffic flows. In pretimed coordinated control, applicable when more than one intersections in a network are controlled, the offsets of each intersection controller are preset with respect to a standard time reference, so that to the extent possible traffic can flow through the coordinated signals without stopping. The timing plans in pretimed control are usually prepared using off-line optimization techniques on the expected values of traffic demand derived from historical traffic patterns. The computer models used for this type of control include TRANSYT7F, NETSIM, SIGOP and AAP [1-4].

II.2.2 *Traffic responsive isolated control*

A typical example of traffic responsive, isolated intersection control is the operation of a fully actuated control, where all signal phases are controlled by detector actuations. Figure 2.1 illustrates a typical detector layout for a two-phase semi-actuated intersection in Minneapolis. The duration of each phase is determined by the traffic controller based on the detected traffic demand on the associated approaches and is limited by preset

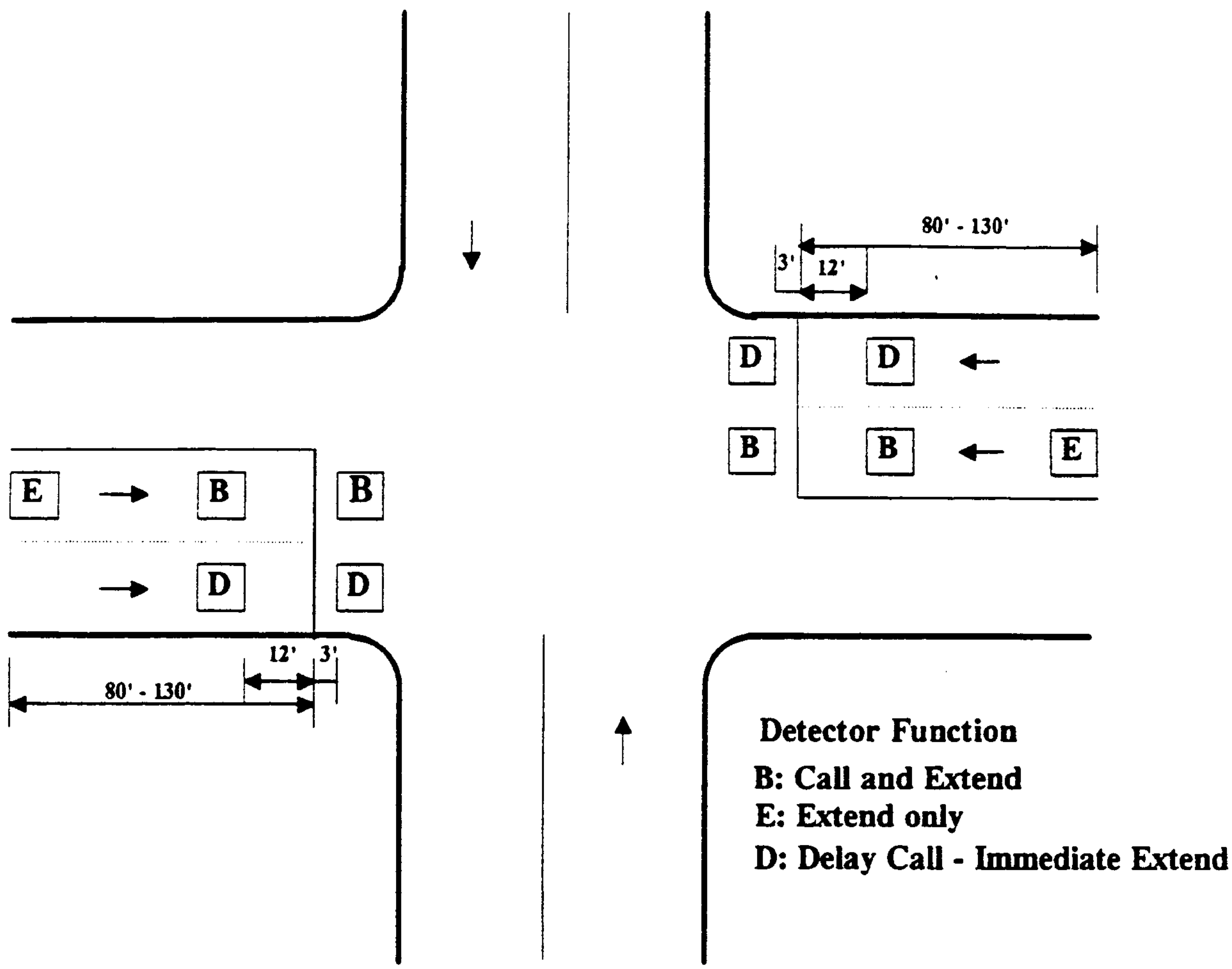


Figure 2.1 Typical Detector Layout for 2-phase Semi-actuated Intersection in Minneapolis
(Source: City of Minneapolis)

minimum/maximum green intervals. The maximum green interval determines the maximum length of time that a phase can hold the green in the presence of a conflicting call, and minimum green interval is usually set to provide sufficient green time for aiding the standing vehicles to clear the intersection. The underlying concept of the fully actuated operation is that the competing demands are equally important, and no structural arrival patterns exist.

II.2.3 *Traffic responsive, coordinated control*

Traffic responsive coordinated control for multiple intersections in a network represents the most advanced concept in urban network management. This type of control is characterized by on-line signal timing generators with adaptive features and is represented by SCOOT, SCATS, PRODYN and OPAC. The principles upon which the four algorithms depend vary from cyclical to acyclical, and centralized to decentralized. In particular, SCOOT and SCATS seek to adjust the cycle time, phase split, and offset so that the optimization criteria (i.e., stops, delays, and queue lengths) are minimized. By contrast, PRODYN and OPAC attempt to find optimal acyclic settings.

SCOOT is based on centralized methods and does not include microprocessor vehicle- actuated control tactics at local intersections, whereas SCATS performs much of the optimization procedure (e.g., phase optimization) in its vehicle-actuated controllers. PRODYN and OPAC, following a decentralized philosophy, perform the optimization at each intersection through dynamic programming techniques and a rolling horizon. More specifically, OPAC minimizes vehicle delays and percentage of stopped vehicles and PRODYN attempts an explicit minimization of total delay. SCOOT, SCATS, and OPAC require one detector for each link, whereas PRODYN uses two detectors per link. In SCOOT and OPAC, detectors are normally placed well upstream from the intersection, preferably just downstream from the previous one (SCOOT) or 120 to 180 m from the stopline (OPAC). Since the two systems measure the flow entering the link a considerable distance upstream from the intersection, platoon dispersion between entrance and exit detectors becomes a significant phenomenon. By contrast, SCATS detectors are placed at the stopline of the intersection. Since the method focuses on measuring saturation flow, it encounters difficulty in detecting the queue length of each approach.

Section II.3 summarizes the principles of each control strategy. Detailed description of each strategy can be found elsewhere [37].

II.3 Traffic responsive control strategies

II.3.1 SCOOT [5-9]

SCOOT (Split, Cycle, and Offset Optimization Technique) is a vehicle responsive traffic control signal system, developed by the British Government's Transport and Road

Research Laboratory (TRRL). The three key principles of SCOOT are:

- Measurement of cyclic flow profiles in real time
- Updating an on-line model of queues continuously
- Incremental optimization of signal settings.

The equipment required for the implementation of SCOOT consists of vehicle detectors connected to the controlling computers via appropriate communications lines. One detector is required for each link and the sample time interval is 4 seconds. Although inductive loops have been used to date, other types of detector can be used, providing similar information on vehicle presence. The detectors are normally placed well upstream from the intersection, preferably just downstream from the previous one to detect queue length at high demand. For very long links, which may contain more than one platoon at a time, the detectors must be placed 80-100 m before the stopline.

SCOOT is relatively insensitive to sensor failures, mainly because of the incremental nature of the optimiser. The optimiser evolves new signal timings by accumulating a large number of small, frequent alterations of timings. Therefore, a few poor decisions by the optimiser are of no great importance. Default procedures ensure that the performance degrades gradually to a fixed time plan if successive failures occur and are not rectified. Simulation studies suggest that benefits from SCOOT are lost if 15% or more of sensors are faulty. Experience to date indicates that, with appropriate maintenance procedures, fault rates of well below 5% could be attained [3,4]. Nevertheless, it is accepted that in urban areas, such as Minneapolis, 30 to 50 percent of detectors do not operate accurately at any given time.

SCOOT software is written in a high-level language and implemented on a variety of computer systems. For example, in Wirral System a DECPDP11/83 computer is sufficient for a 60 node network. In Aberdeen a VAX based system is used. In Madrid a DEC VAX computer is employed. If the traffic information provided by SCOOT is directed to a database, an IBM compatible PC is additionally required. In this case, use of dBASE and dGE graphics software packages is necessary. In Southampton, the ASTRID database receives, processes and stores the traffic information produced by SCOOT and provides graphical displays of data profiles and trends. The database is integrated to an incident detection system and an active bus priority system that are also based on data from SCOOT detectors.

In the implementation of SCOOT in Beijing, China, the communications system operates at a speed of 200 baud, leading to a transmission in each direction every second. The lines are provided by normal telephone service. Occasional noise causes loss of 1 sec or 2 transmissions per hour on approximately 10% of the lines. SCOOT has been also installed at 75 signalized intersections in Toronto, Canada, where fine-tuning of SCOOT system operations has recently begun. A detailed report on the effectiveness of SCOOT in Toronto was expected to be completed in summer 1993 [32].

II.3.2 SCATS [19-28]

SCATS (Sydney Coordinated Adaptive Traffic System) is a vehicle actuated control method developed by the Department of Main Roads, New South Wales, Australia. SCATS divides an area into smaller sub-areas of about 1 to 10 intersections sharing a common cycle time. Each sub-area contains one critical intersection, for which the sub-area green split plans, internal and external offset plans, and cycle lengths are selected. Green splits are altered every three cycles; offsets are altered every five cycles; cycle time is altered in steps of up to 6 seconds, according to the degree of saturation of the critical intersection of the sub-area, on a cycle by cycle basis. The degree of saturation is measured using detectors placed at the stopline. SCATS first determines the cycle time required for each sub-area. This cycle time is shared among various phases at each intersection according to a selected phase split plan. The offset plan within a sub-area may be, by default, one selected by an algorithm which may also be used to select an external offset for sub-system "marriage", or, optionally, one which is tied to the phase split plans.

The advantages of traffic responsive control can potentially be achieved by the provision of detectors in representative lanes of each movement requiring accurate phase split adjustment at each critical or major intersection, and (optionally) detectors at adjacent intersections in representative lanes of approaches upstream of the primary strategic detectors at the critical intersections. In a typical system, 50 to 70% of approaches require detection in certain lanes for maximum traffic responsiveness, but this can vary according to system complexity. The advantage of detector redundancy, reducing the urgency with which critical faulty detectors have to be repaired, must be weighed against the disadvantage of greater maintenance costs of a larger number of detectors when such detectors are loops placed in the pavement. For authorities not equipped for the repair of detectors, the system can be installed initially with fixed time operation and, subsequently, gradually upgraded by the addition of detection at the most needy locations. To be sure, the number of detectors may not be an issue when virtual detectors are placed in a wide-area video environment.

SCATS presents certain limitations regarding the hardware system, loop detectors, adjustment of offsets and compatibility of controllers. First, algorithm and SCATS hardware system are inseparable. The control method can only be implemented on a Digital PDP11 computer. All software has been developed in Assembler language specific to Digital. With detectors located at stoplines, monitoring platoon progression is hard and no feedback information exists regarding the performance of the offset adopted. Additionally, the software cannot indicate whether a queue fills up

Therefore, special action to prevent the blocking of the upstream intersection cannot be taken.

SCATS has been operational at 28 signalized intersections in Troy, Michigan, since June 1992. Further, because SCATS requires extensive detection and the authority in Michigan was experiencing difficulty in maintaining inductive loop detectors, a machine vision system was chosen as the detection system for SCATS. A detailed report on the effectiveness of SCATS in Troy is not available yet [39].

II.3.3 OPAC [21-24]

OPAC (Optimized Policies for Adaptive Control) is a vehicle responsive traffic control signal system, developed in the United States. It features a dynamic optimization algorithm that provides the computation of signal timing without requiring a fixed cycle time, i.e., unlike SCOOT, it tries to find acyclic settings. The signal timing is constrained only by minimum and maximum green times. The optimization criteria to be minimized are vehicle delays and percentage of stopped vehicles. For each isolated intersection, the optimization procedure is performed through a dynamic programming technique using a rolling horizon approach. A projection horizon consists of an integer number of basic time steps (usually one step is 5 seconds). The optimization procedure calculates the optimal signal timing plan for the entire horizon using projected demand. Actual arrival data measured from upstream detectors are used as the projected demand for the first **r** (usually 3-4) steps in a projection period. For the rest of time steps, the smoothed average volume data are used. The optimal signal timing plan calculated for the entire projection horizon is implemented only for the first **r** steps and the projection horizon is then shifted **r** units ahead.

The detectors are located well upstream (120 to 180 m) of the stop bar on all approaches to an intersection. Additional detectors (call-only detectors to register demand for service) are placed at the confluences of driveways with the links. It is important that call-only detectors be present, since the OPAC detectors are located far upstream. Without call-only detectors, vehicles entering the traffic stream from driveways and shopping centers downstream of the OPAC detectors would not be detected. Similarly, even if no vehicles were waiting at the confluence of a driveway with a link, the system would assume vehicles are waiting to enter the link and service them unnecessarily.

OPAC provides an optimization algorithm that may be overridden by special signal plans in the presence of congestion, as defined by a user-specified occupancy threshold. A special "congestion override" facility is provided, since the optimization is intended for operation under undersaturated conditions. During periods of congestion, measures of effectiveness such as queue length might be preferable to stops and delay, used as optimization criteria under undersaturated conditions. Moreover, 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. If the occupancy of 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. Since the OPAC detectors are 120 to 180 m upstream of the intersection, left turning volumes are modeled by the software. To accomplish this, a smoothed, expected duration for each minor phase is maintained. Based on the current expected phase duration 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.

OPAC presents certain limitations regarding intersection coordination, estimating saturation flow rates, estimating queue length, and compatibility. For example, the system cannot coordinate sets of intersections; it is only applicable in controlling an isolated intersection. However, a research project currently being conducted by Farradyne Systems Inc. under contract with FHWA is expanding the OPAC algorithm to handle congestion and coordinated network control. This project, to be completed by the first quarter in 1994, is also expected to produce a revised OPAC/NETSIM software that can evaluate the expanded OPAC control algorithm in a simulated environment.

II.3.4 PRODYN [10-17]

PRODYN is an urban traffic control method, developed over the last decade by Centre d' Etudes et des Recherches de Toulouse (C.E.R.T.), France. The algorithm computes, in real time, the best signal settings with respect to a delay criterion for varying demand in traffic networks.

PRODYN attempts to find acyclic settings, unlike SCOOT, which is based upon cyclic settings. The main characteristics of the method are explicit minimization of total delay and use of automatic control, Bayesian estimation, dynamic programming, and decentralized methods. More specifically, the optimization procedure is performed, for each intersection, through an adapted forward dynamic programming algorithm, which is based on a 5-second sample time; the control policy is the decision to switch over from one stage to another.

The objective function to be minimized is the accumulated expected queue at the intersections of interest. To estimate the queue length, arrivals are considered binomially distributed. The queue length evolution forms a Markov chain, leading to objective function calculations that require manipulation of large probability arrays. Such manipulation is inefficient in terms of computer time and storage. Several approximate methods for the calculation of the objective function are in good agreement with the Markov approach.

The equipment required for implementation consists of detectors providing the controlling computer with traffic information via appropriate communications lines. Two magnetic loop sensors are used by lane. One sensor is at the entrance of the link (or at about 200 m upstream if the upstream intersection is farther) and the other, at 50m upstream of the stopline.

In part hindered by sensor placement, the software does not provide the traffic engineer with facilities estimating on-line saturation flow rates (SFR) and turning movement ratios (TMR). Methods for estimating on-line SFR and TMR have been proposed, but cannot cope with detector failures. PRODYN has been shown to perform slightly less efficiently than fixed time plans when congestion originates at downstream intersections under oversaturated conditions.

II.3.5 MOVA [26-30]

The Microprocessor Optimized Vehicle Activation (MOVA) methodology was originally developed to provide traffic control strategies for isolated intersections. The MOVA methodology developed and tested in Berkshire, England, by the Transportation and Road Research Laboratory, has led to control strategies that are substantially improved over the conventional vehicle actuation signal systems throughout England.

All detectors used with MOVA have been limited to buried inductive loops. Such detectors provide lane-by-lane counts and information on the presence of vehicles. These data lead to estimates of flows, delays, stops and queue length. To accomplish this, two diamond shaped detectors are installed in each approach lane at 40 and 100 meters from the stop bar. MOVA calculates the vehicle travel time between the loops and the stop bar; based on average vehicle speed in urban areas this travel time is typically 3.5 and 8.0 seconds for each respective loop location. However, these values are not critical and location of the detectors is flexible provided that the algorithms reflect the actual length between detectors and the stop bar.

The 40/100 m detection system has certain disadvantages. Without detectors closer than 40 meters, vehicles that fail to clear the green after their arrival have a greater probability of remaining undetected and having to wait until another vehicle arrives to activate the detector. As a solution, a third detector can be included at the stop bar. The stop bar detector is also added when an exclusive right turn lane is needed for the right-turn only phase. (This is similar to the lagging left turn phase in the U.S.)

During the green period, MOVA makes a number of decisions based upon traffic flow and queue information derived from the vehicle detectors placed within each approach.

The decision to change phases is based upon minimum green calculations, determination of the end of saturation flow, optimization of delay and stops and oversaturated conditions. For example, to facilitate the calculation of green time, MOVA assigns a stop penalty value to each approach that indicates the relative importance of stops to that approach. When the green phase at an approach is nearing the end, MOVA assesses the merits of extending it against the stop penalties accumulating from vehicles arriving and stopping at the other approaches. The assessment is based on a performance index that is similar to the TRANSYT performance index and is a function of delays and stops. Using the stop-penalty technique to determine the length of green time offers certain advantages over the classical vehicle actuation systems that use the gap-seeking control technique, which extends green times based on the time intervals between vehicle detections. In particular, the stop-penalty technique considers the delay time of waiting vehicles and does not extend green time unnecessarily during undersaturated conditions. This optimization technique is superior to the existing vehicle actuation system requirement of presetting maximum green times which are inefficient during undersaturated conditions.

II.3.6 CARS [40]

CARS (Control Autoadaptativo para Redes Semaforizadas) is a demand responsive traffic control system, developed by Universidad Politecnica de Cataluna in Spain. The system implements an adaptive centralized control based on small variations using an underlying simulation model and a real time prediction model.

II.4 Major intersection control systems in U.S. and Canada

In order to meet the needs for efficient traffic management, certain municipalities have developed their own control systems for interconnected signalized networks. Leaders in this area include the cities of Minneapolis, Minnesota; Los Angeles, California; and Toronto, Canada. This section summarizes detection and control methods of each system.

II.4.1 Minneapolis [35-36]

The City of Minneapolis presently has 760 signalized intersections, of which one-third are actuated and two-thirds are pretimed. Within the citywide network, 710 or 93% of the signals are centrally controlled via a centrally-supervised, digital computer based traffic control system. The central control is monitored by a modified T-200 Traffic Control Program software, developed by Traffic Control System, Inc., now Fortron Traffic Systems, and installed in the mid 1970's.

The system has three states of operation for the signal controller; offline, local and computer control. Under the OFFLINE state the master computer equipment may be operational but field equipment is locked into a condition uncontrolled by the master controller. Under the LOCAL state master computer equipment is operational and field equipment is designated as ready for pick-up. Under COMPUTER CONTROL field equipment is operating under control of the master computer. Each of these operating states is scheduled at an individual intersection or group of intersections.

Two basic methods of system operation provide effective control of the full range of traffic signal controller equipment used in the system. The methods used include a system master controller supervision technique on motor driven intersection controllers together with coordination units for pretimed and actuated intersections; and system master computer control on those intersections without coordination at the intersection controller.

Two special control techniques provide phase split adjustment under control of the master controller. The techniques are identified as Multiple Split Intersection Control (MSIC) and Bus Priority Operation (BPS).

MSIC operation is a special form of traffic responsive control which provides for split adjustment on a cycle by cycle basis, i.e., special control operation of certain critical intersections in the system. MSIC operation is automatically selected at an intersection based upon congestion levels at that location. This form of operation can be applied to any intersection with appropriate detector layout which includes detectors at all approaches and at the stop bar.

The Minneapolis BPS operation is a special form of semi-actuated control and can be applied to any intersection with suitable detectorization 30 feet upstream of the intersection within the bus lane approach. When a bus is detected the green time of non-bus movement is reduced providing an early green to the bus movement. The amount of split variation is under full control of the master controller and may, therefore, be as much or as little as deemed appropriate by the traffic engineer for any particular time of day. The net result of this technique is to maintain offset control for beginning the green phase for the non-bus movement.

The scheduling mechanism for the Minneapolis traffic control system consists of individual entries for each intersection containing both time-of-day related direct control information and indirect traffic control information related to each intersection operation. The primary technique for arranging groups of intersections is the lead intersection arrangement. This entry permits one intersection to duplicate (or copy) the schedule entries of other intersections within the group.

Provisions within the system enable extensive monitoring of system performance and hardware operation. Data are returned from each of the detectors and controllers in the system to the system master controller where all data are tested for validity with errors noted and logged. Valid data are used to provide system records, measures of effectiveness and inputs to the traffic responsive portion of system software. Performance data are made available to the traffic engineer upon request and depending upon data type, are displayed on the system map, system CRT or are printed as hard copy records.

The operation of all hardware including controllers, detectors, and communications equipment is monitored to ensure that each component is performing properly in relation to issued commands and expected responses. If a device is operating improperly the unit is declared automatically by system software to be either controlled through another mechanism or unusable within the system. This information is logged, recorded and corrected as soon as possible.

II.4.2 Los Angeles [33-34]

The City of Los Angeles includes 3900 signalized intersections within the city street network. Of these, 747 are pretimed and centrally controlled through a network system called Automated Traffic Surveillance And Control (ATSAC). With this system, various timing plans automatically respond to fluctuating traffic demands on a real time basis. Key subnetworks within the ATSAC system include 8 major parts of the Metro Area.

The ATSAC system includes a control console and supervisory (main) computer at the control center, subarea computers and front end processors at the central subarea centers, and traffic signal controllers and loop detectors at the intersections. The main computer monitors traffic development and chooses the optimum timing plan for each level of traffic. The plan is selected from a group of 30 timing plans for each intersection or group of intersections. The timing plans include a.m. peak, p.m. peak, off peak and modifications of each of these depending on the day of the week or a special event.

Computers and software

The main central control computer is a Concurrent Computer System 3280 with 16 megabytes of main memory. This computer provides the interface between the system computers in each network subarea and the rest of the central system equipment. Each ATSAC subarea includes a Concurrent Computer System 3280 mini-computer with 10 megabytes of main memory. This computer is capable of handling up to 400 intersections with 1600 detectors within the subarea. The central computer communicates with the subarea computer over an Ethernet network which has an effective data transfer rate of 50 Kbytes per second. Each subarea computer has a front end peripheral processing unit (PPU) that assists the processing of data accumulated from the large number of intersections and detectors within the subarea.

The application software used with the ATSAC system is the UTCS developed by the Federal Highway Administration [41]. The UTCS Software is enhanced under the

ATSAC system to include color graphics, display monitors, a supervisor/subarea computer network, network for communicating signal plans to local signal controllers, and automation of signal plan updates.

Communication of data between the ATSAC control center and the subarea computer near the center of each ATSAC subarea is performed with fiber optics cable which is suitable for both video and traffic control surveillance data. Data from the subarea computer hub to each intersection controller within the subarea are transmitted over a 1200-Bd twisted pair telephone cable network. This network is also used for the communication of the traffic data and equipment status from the intersection controller back to the subarea computer.

The Type 170 controller is used at all ATSAC intersections, equipped according to Caltrans standard requirements. For on-line signal controllers, the subarea computer monitors the intersection controller through each signal phase. Volume counts and occupancy data are initially processed by the signal controller and transmitted to the control center via the subarea computer once per second. The intersection controller uses backup plans stored in its local memory when it operates off-line or when it is at a standby status. Each intersection signal can store up to 9 off-line timing plans for that intersection.

Loop detectors

ATSAC loop detectors are located on the major legs of signalized intersections, 250 feet in advance of the intersection. The data acquired by the detector include volume, saturation, occupancy, speed and queue length.

At intersections of arterial streets and local streets, the signal is semi-actuated, controlled with detectors on the local street only. Traffic data from the local street are sent to the control center for monitoring. At intersections of major arterial streets, the detectors are placed upstream of each approach lane. Detectors can be laid out in two possible configurations. Following one configuration, detectors are placed within each marked approach lane at least 250 feet upstream of the signalized intersection; alternatively, detectors are placed 100 feet downstream from the nearest signalized upstream intersection. The second method is more economical since it places the detector closer to a signal controller box and, therefore, requires less detector wire and conduit. However, this method is used only where no significant additions or losses of traffic occur between the detector and the downstream intersection, and where distances between intersections are not long.

Video observation

The City of Los Angeles is installing video observation cameras at 38 intersections; these include junctions for regional shopping centers, sports arenas, major crossroads, airport area and critical interchanges with the interstate system. The ATSAC operator can visually detect accidents, disabled vehicles, spilled loads, construction activity and police and fire operations, and implement an override timing plan if necessary. This is accomplished by installing a video camera 45 feet above the intersection on a pole or nearby building providing a 1/2 mile wide overhead view of the two intersecting streets.

Control modes

Four modes of control are available in the ATSAC system, depending on the time of day, volume of intersection traffic, location and type of intersection. The four modes include Time of Day Control, Critical Intersection Control, Traffic Responsive Control and Manual Override. Time of Day Control mode includes timing plans developed off-line using the TRANSYT VII model and manually acquired traffic data and turning counts. Three to nine timing plans are available per intersection including a.m. peak, p.m. peak, off-peak and modifications of each, depending upon the day of the week or a special event. Once on-line, signal offsets and splits are finetuned by the ATSAC operators.

The Critical Intersection Control mode operates on a real time algorithm that modifies the cycle green time split at signalized intersections. Detectors are required at all approaches for this mode. Traffic demand equations are updated at each cycle, and green time is prorated to each approach based upon relative demand, i.e., volume and occupancy. The range of green time modifications is limited by the minimum pedestrian clearance time. Signal offset is maintained on the major street causing performance degradation on the secondary street. This mode automates the process of modifying the allocation of green time in response to changing traffic conditions along the main street and eliminates the manual override procedure for fine tuning signal splits on a regular basis.

The Traffic Responsive Control mode uses the automated functions of the UTCS Enhanced software. Timing plans available to an intersection controller are computed using historical traffic data. A specific timing plan is selected by comparing and closely matching the real time surveillance data with the historical traffic data. This method is a major improvement over Time of Day mode in which day to day variations are significant. Extreme errors from implementing erroneous timing plans are prevented by limiting the number of available timing plans for a particular time period or day.

The Manual Override mode provides greater responsiveness to non-recurring traffic conditions. This mode can be implemented at a single intersection or group of intersections along an arterial route or within a particular area. This mode is operator controlled and activated during special, non-regular events such as special events at the Coliseum, holiday season traffic, major construction projects, temporary lane/street closures, diversion of traffic from a freeway, or to assist the traffic flow past an accident at a critical location.

II.4.3 Toronto [31-32]

The City of Toronto has a total of 1641 signalized intersections with 1585 signals operating within a centrally controlled coordinated system developed approximately 30 years ago. Of these, 686 signals operate in a fixed time mode and 899 are semiactuated.

Traffic data (vehicle presence) are collected with inductive loops located at the stop bar and left turn lanes. Each traffic signal system can support a 12 phase cycle, a specification more powerful than the typical 8 phase cycle in other U.S. systems. Of the semiactuated signals, approximately 100 are truly actuated; they allow both pedestrians and vehicles to communicate with a particular phase and extend the minimum green time. The remaining signals are activated by the presence of vehicles but do not allow extension of green time. This centrally controlled system has a capacity for 64 cells within the network and 32 intersections per cell. The signal controllers for each intersection are inter-connected into cell groups. Each controlling intersection within the cell group is connected to the central controller. The central controller monitors the progress and status of each signal to ensure proper timing, phasing and cycle offsets for that signal.

The timing of the cell groups is based upon historic traffic data, i.e. manual traffic counts including turning movements. Based on this information, signal timing, cycle length and cycle offsets are determined and adjusted. The main controller retains three primary cycle settings, a.m. peak (6:30 -9:30), p.m. peak (3:30 - 6:30) and off-peak. Thus, the Toronto system operates on preset timing, not real timing.

Capacity problems are the basis for modifying a preset timing plan. When a saturation problem occurs on a fairly regular basis, city staff acquire traffic volume counts and recompute the timing plan. If the saturation effect spills over into adjacent signalized intersections, the cycle length of these intersections is reviewed as well. The result is a delayed-traffic responsive system. Although the system can change timing plans every minute, it lacks the real time detector data, and therefore, relies mainly on the three preset timing plans described above.

Toronto has recently installed SCOOT at 75 signalized intersections and a detailed report on its effectiveness was expected in 1993 [32].

II.5 Summary

This chapter briefly reviewed the major intersection control strategies developed to date including the state-of-the-art techniques with traffic responsive, adaptive features, SCOOT, SCATS, PRODYN, OPAC and MOVA. SCOOT and SCATS seek to adjust the cycle time, phase split, and offset so that the optimization criteria (i.e., stops, delays and queue lengths) are minimized. By contrast, PRODYN and OPAC attempt to find optimal acyclic settings. SCOOT is based on centralized methods in performing optimization, whereas SCATS performs much of the optimization procedure in its vehicle-actuated controllers. PRODYN and OPAC perform the optimization at each intersection using dynamic programming techniques. OPAC tries to minimize vehicle delays and percentage of stopped vehicles and PRODYN attempts to minimize total delay. In OPAC, detectors are located far upstream of the stopline, while PRODYN requires two detectors, upstream and near the stopline. SCOOT and SCATS have been implemented in the urban traffic control systems of many cities worldwide and have demonstrated their ability to coordinate large arterial and grid networks. By contrast, PRODYN and OPAC have been implemented only for evaluation purposes in small networks. Finally, MOVA, an on-line signal optimization package, tries to improve efficiency and capacities at signalized intersections while reducing stops and delays. Its application has been limited to isolated intersections since the control algorithm can handle only phase split and cycle length adjustment, and does not allow offset evaluation.

While the above control strategies look promising, because of the variety of prevailing traffic conditions and the complexity of traffic flow behavior, no universal "best" method can determine the optimal type of control for a given intersection or network. Further, the only control strategy available to this research team is OPAC, and other strategies are either too expensive or unavailable for off-line evaluation. Therefore, OPAC will be the primary control strategy which will be initially tested in this research, and its performance will be compared with that of conventional strategies, i.e., pretimed and vehicle actuated control, in the simulated environment. Table 2.1 compares the major features of each control system reviewed in this chapter.

This chapter also reviewed the current intersection control strategies and data collection methods in three major cities in the U.S. and Canada. The Toronto system operates on a preset timing plan with the main controller retaining three primary cycle settings. In Minneapolis, the master controller monitors the operation of all intersections and overrides the local controller if necessary. The Los Angeles system selects a timing plan for each intersection from a group of 30 timing plans depending on traffic volume in real time.

Table 2.1 Comparison of traffic responsive control systems

	SCOOT	SCATS	OPAC	PRODYN	MOVA
Cyclic vs Acyclic	Cyclic	Cyclic	Acyclic	Acyclic	Acyclic
Central. vs Decentral.	Central.	Decentral.	Decentral.	Decentral.	Decentral.
Number of Detectors Detector Location	1 per link Upstream	1 per link Stopline	1 per link Upstream	2 per link Upstream Near Stoplin	2 per link 40 & 100m from Stopline
Optimization Index	Delay & Stops	Delay & Stops	Delay & Stops	Delay	Delay & Stops

III. DEVELOPMENT OF SIMULATION ENVIRONMENT FOR OFF-LINE EVALUATION OF INTERSECTION CONTROL STRATEGIES

III.1 Introduction

Developing a simulation environment where various intersection control strategies can be evaluated under a variety of traffic and geometric conditions is a major objective of this project. A portion of the Minneapolis downtown network, located north of the central area, was selected as a test network in consultation with the traffic engineers in the City of Minneapolis and the Minnesota Department of Transportation. Figure 3.1 shows the location of the test network. The NETSIM software, a microscopic model for urban networks developed by FHWA, was selected as a traffic-network simulator since it has many features that are not available in other traffic software for intersections, such as TRANSYT-7F, PASSERII and SOAP. In particular, it updates detailed controller, detector and vehicle information once per second. It includes two types of detectors, actuated and surveillance detectors. The surveillance detectors are ideal for the implementation of external control strategies, such as OPAC.

For these reasons, the OPAC algorithm has been integrated into NETSIM, so that the OPAC control strategies can be simulated and evaluated under various traffic conditions. The combined OPAC/NETSIM package has been provided by its developers and is currently being installed by this research team. Major features offered by NETSIM and other traffic software developed for intersection analysis are summarized in Table 3.1 [38]. An overview of the software, the test network and the data collected from the test network for the simulation are presented in the following sections.

III.2 Overview of NETSIM software

NETSIM (NETwork SIMulation) is a stochastic, microscopic computer software that simulates individual vehicular behavior in urban networks using the Monte Carlo technique [2,38]. The software keeps track of the time and position of each vehicle in the network. Vehicles enter the network at a uniform rate proportional to the input volume specified by the user. Upon entering, each vehicle is assigned to either through or left/right-turn lane depending on its travel direction. Vehicles entering a lane accelerate to the free flow speed while maintaining a safe stopping distance between one another. When a vehicle approaches a stop line, a deceleration rate (user specified or default) is applied until it completely stops. NETSIM can reflect operational characteristics of different vehicle classes, such as truck, bus and car-pool vehicles by applying different acceleration/deceleration rates, speed, vehicle length and headway.

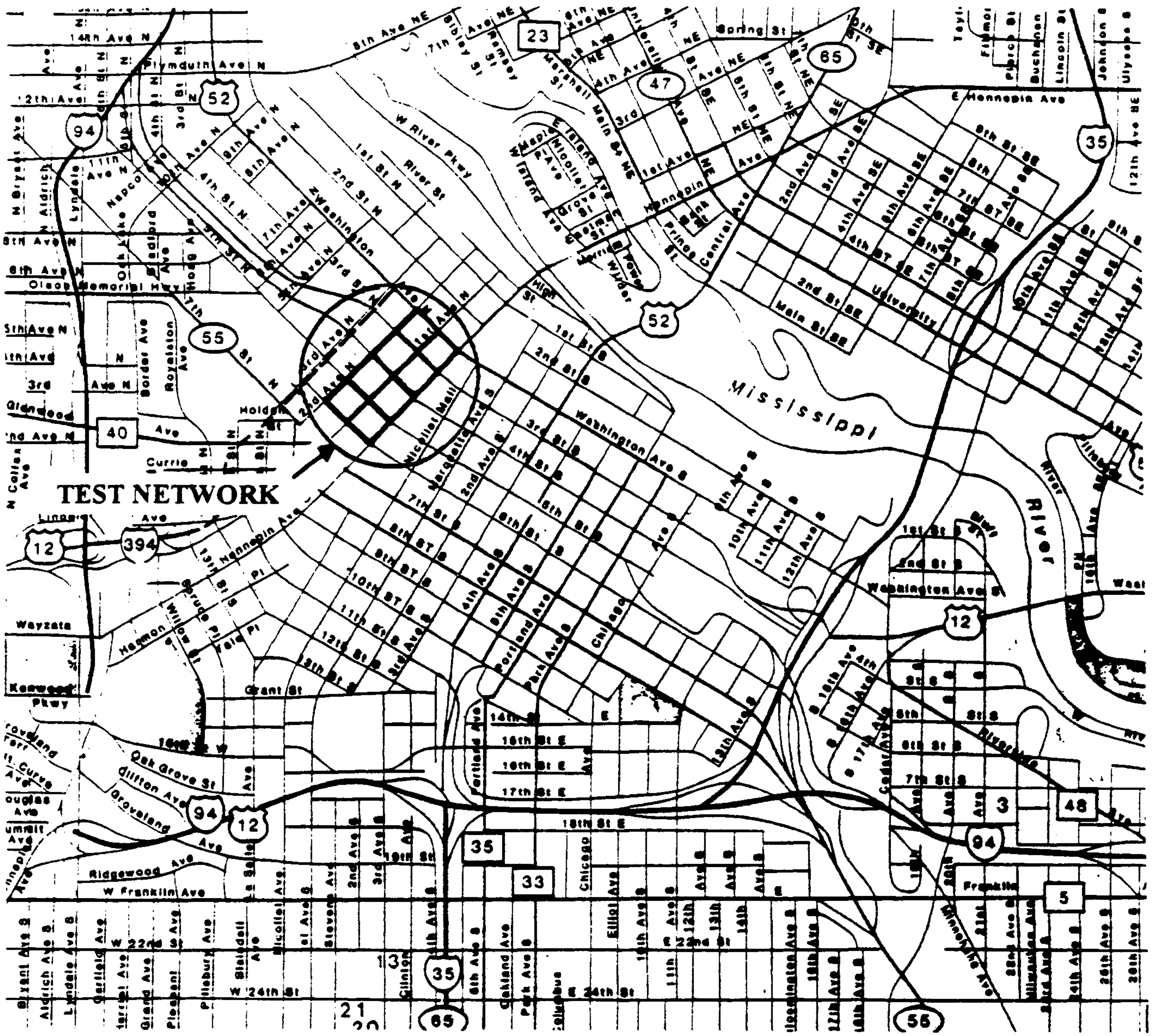


Figure 3.1 Location of test network

Table 3.1 Comparison of NETSIM with other intersection analysis software [38]

Program features	NETSIM	TRANSYT-7F	PASSERII	SOAP
Simulates				
- Isolated intersections	Yes	Yes	Yes	Yes
- Fixed time signals	Yes	Yes	Yes	Yes
- Actuated signals	Yes	No	No	No
- Stop and Yield signs	Yes	Yes	No	No
- Network	Yes	Yes	No	No
- Signals with different cycle lengths	Yes	No	No	No
- Saturated conditions	Yes	No	No	No
- Pedestrians	Yes	No		No
- Buses	Yes	Yes	No	No
- Lane closures	Yes	No	No	No
- Parking	Yes	No	No	No
- any combination of the above features	Yes	No	No	No
Optimizes timing plans	No	Yes	Yes	Yes
Program features	NETSIM	TRANSYT-7F	PASSERII	SOAP

III.2.1 Simulation Capabilities

The latest NETSIM version, V3.0, can simulate a network of intersections with various types of control including yield/stop signs, fixed-time signals, actuated signals and signals with different cycle lengths. Further, it can simulate the operation of bus routes, lane closures and parking operations. The following list summarizes the major possible applications of the software:

Evaluation of signal timing plans including design of new timing plans.
Evaluation of network geometrics including left-turn pocket.
Evaluation of bus stop location.
Evaluation of lane closure policy in response to short/long term events.
Evaluation of parking policies including double parking.

III.2.2 Input/Output

The minimum required inputs for each intersection are, approach length, number of lanes, allowable movements, and vehicle turning volumes or turning percentages. In addition, cycle length, phase length, phase sequence, and offset are required if the intersection is under fixed signal control. For actuated signal control, phase sequence, minimum/maximum green intervals, and vehicle extension interval are required. With the given input data, NETSIM produces traffic performance by link and by network. The major outputs of NETSIM are, vehicle travel miles, delay, travel, queue and stop times, percent of stopped vehicles, average speed, number of phase failures, number of queued vehicles by lane, number of vehicles discharged, number of vehicle stops, number of vehicles by turning movement and fuel consumption and emission by vehicle type.

III.2.3 Hardware requirements and installation

NETSIM requires an IBM-compatible personal computer with 640 KB of memory, a hard disk and a math coprocessor with an EGA or VGA color monitor to view graphic outputs. In this research, the latest version, V3.0, was installed in the Gateway 2000, 486-33 Mhz computer purchased for this project. Further, an independent software, GTRAF, was installed to capture the inputs/outputs from NETSIM. The software can also display a link-node diagram, input data and output measures of effectiveness (MOEs).

III.3 Test network and data collection

III.3.1 Test network

Figure 3.2 shows the schematic representation of the test network for the NETSIM simulation. This network, located north of the Minneapolis central downtown area, contains

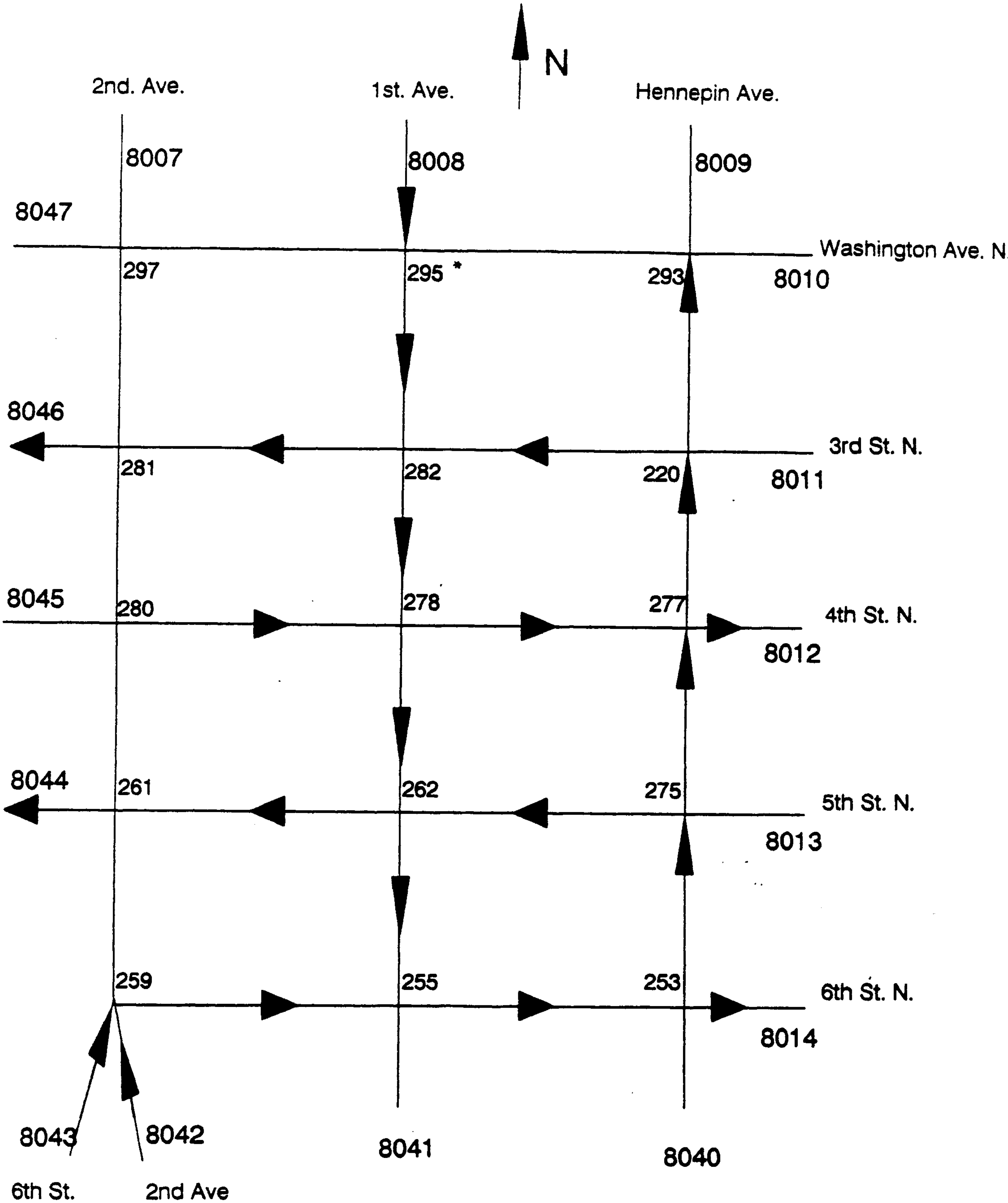


Figure 3.2 Network geometry (* Node Number)

15 signalized intersections. Currently, all signals are being operated in the pretimed mode, and the timing plans of most signals were updated in the 1960's. Further, the network links serve as the feeder links to the nearby I-394 freeway, and thus, their traffic volume can be substantially influenced by the traffic conditions in the freeway. As a preliminary evaluation, the performance of pretimed and fully-actuated control strategies will be compared. The next section describes the data collected for this preliminary evaluation effort.

III.3.2 Data collection

The data for this test network were obtained from the City of Minneapolis and Metro Council. More specifically, the geometry of the network and current signal timing plans of all 15 intersections were provided by the City of Minneapolis. The traffic volumes of all links including turning vehicles, were calculated by Metro Council using the TRANPLAN software. All signals have a common 90 second cycle length and each signal has three timing plans, i.e., plans for off-peak, morning peak (6:00 - 8:45 a.m.) and afternoon peak (3:30 - 6:30 p.m.) periods. Further, 3.5-second yellow and 1.5-second clearance intervals are used at each intersection. The detailed traffic demand data and current signal timing plans for this test network are included in the Appendix.

III.4 Summary

A simulation environment was developed with the NETSIM simulator and a test network located in the Minneapolis downtown area. The latest version of NETSIM, V3.0, was installed in a 486-33 Mhz personal computer and the current geometry and signal timing plans of all intersections in the test network were coded into the NETSIM simulator. Using this test network represented in the NETSIM simulator, various types of control strategies, e.g., pretimed and fully-actuated, can be simulated and evaluated under a variety of traffic conditions.

IV. EVALUATION OF NETWORK CONTROL STRATEGIES IN SIMULATED ENVIRONMENT

IV.1 Introduction

As an initial step towards a comprehensive evaluation of intersection control strategies, the effectiveness of actuated over pretimed signal control was analyzed using the simulation environment introduced in chapter III. First, as a benchmark simulation, the current pretimed signal operations of the test network were simulated using NETSIM with the external boundary traffic demand calculated by TRANPLAN. The internal link volumes that resulted were compared with those calculated by TRANPLAN to identify any substantial differences between the two network traffic patterns. Table 4.1 summarizes the results of the internal link volumes over a typical weekday hour obtained from NETSIM and TRANPLAN. As the table indicates, the link volumes obtained with the two methods are very close and the link-to-link volume variations show similar trends.

IV.2 Preparation of actuated control simulation in test network

Actuated control intersections and data

The test network contains 15 signalized intersections, 12 of which are located on the external boundary links. Owing to limitations in the NETSIM software, the intersections on the external boundary links cannot be operated in fully-actuated control mode. Therefore, the three intersections located inside the test network, i.e., those on First Ave., are assumed to be controlled in fully-actuated mode, and the remaining intersections are operated following the current pretimed timing plans. Table A.5 in Appendix contains the values of the parameters used in the NETSIM simulation for the actuated intersections. These values were determined after considering the crossing time by pedestrians and the traffic volume on each link.

Performance indices selected for analysis

The following indices were selected for comparing the performance of pretimed and actuated control strategies in the test network:

Delay time (seconds per vehicle): Delay experienced by the average vehicle in completing one vehicle trip on a link, i.e., the difference between actual travel time and the idealized moving time that would exist if vehicles always moved at the mean free-

Table 4.1. Link Volume Hourly Comparison under Pretimed Control

	VEH/ONE HOUR	
	NETSIM	TRANPLAN
HENNEPIN AVENUE		
(253, 275)	801	832
(275, 277)	765	794
(277, 220)	740	845
(220, 293)	630	751
1ST AVENUE		
(295, 282)	747	850
(282, 278)	519	570
(278, 262)	452	525
(262, 255)	278	311
2ND AVENUE NB		
(259, 261)	70	72
(261, 280)	560	600
(280, 281)	388	450
(281, 297)	358	236
2ND AVENUE SB		
(297, 281)	676	939
(281, 280)	276	280
(280, 261)	408	505
(261, 259)	452	563

flow speed without slowing for other vehicles or stopping in response to intersection control.

Queue time (seconds per vehicle): Average time spent by a vehicle waiting in a queue before it is discharged.

Stop time (seconds per vehicle): Average time over which one vehicle is forced to travel at the speed of 3 feet per second (or 1.9 miles per hour) or less on a given link.

Efficiency ratio (%): The ratio of total moving time to total travel time.

Average speed (miles/hr): Space mean speed defined as

Total vehicle miles of travel / Total vehicle hours of travel

IV.3 Comparison of pretimed and actuated control performance in test network

Figures 4.1 - 4.16 show the comparison results of the link-specific delay, queue and stop time obtained from a typical weekday hour simulation, using NETSIM, of the current pretimed operation and the hypothetical actuated-control operation in the test network described in the previous section. Because of the stochastic nature of the NETSIM simulation, each case was simulated seven times with different random number seeds. The values of the performance indices in the above figures are the average values resulting from seven simulations. As indicated in these figures, the average delay reduction with actuated control ranges from 2.1% (Second Ave.) to 3.7% (First Ave.). The average queue time was also reduced by 4.3% on First Ave. and by 1.9% on Second Ave. with actuated control. Further, the increase of efficiency ratio with actuated control is between 1.7% and 3.7%. The average stop time is also reduced with actuated control by 3.4% on First Ave., where three intersections are assumed to be controlled in fully-actuated mode. To quantify the link-wide improvement in average speed, a new index is defined over N links:

$$100/N \sum_{i=1}^{N} (V_{ai} - V_{pi}) / V_{pi}$$

where, V_{ai} = average speed of link i with actuated control,

V_{pi} = average speed of link i with pretimed control.

Using the above index, the average speed with actuated control was increased by 4.1% on First Ave. and 1.6% on Second Ave. over the pretimed control operation.

The above results indicate that the traffic performance on First Ave., where three intersections are converted into fully-actuated control mode, could be improved over the pretimed operation; however, improvements in other links are likely to be marginal. Further, it should be noted that pretimed plans were last determined in the 60's. If the above

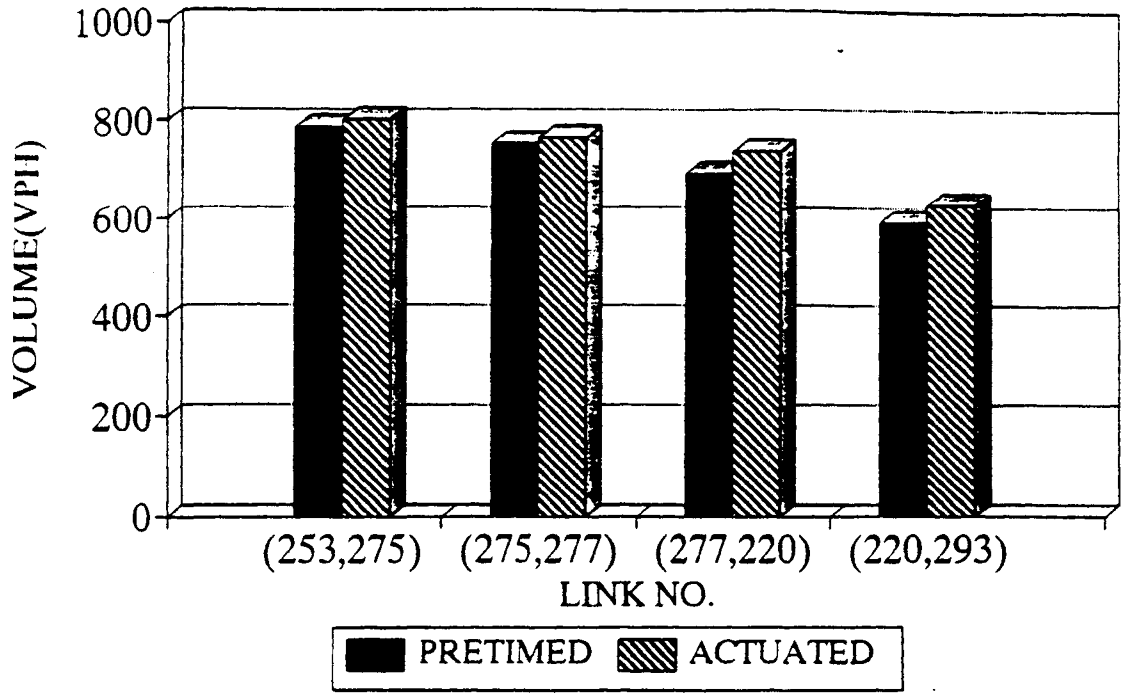


FIGURE 4.1. LINK VOLUME COMPARISON
(HENNEPIN AVE.)

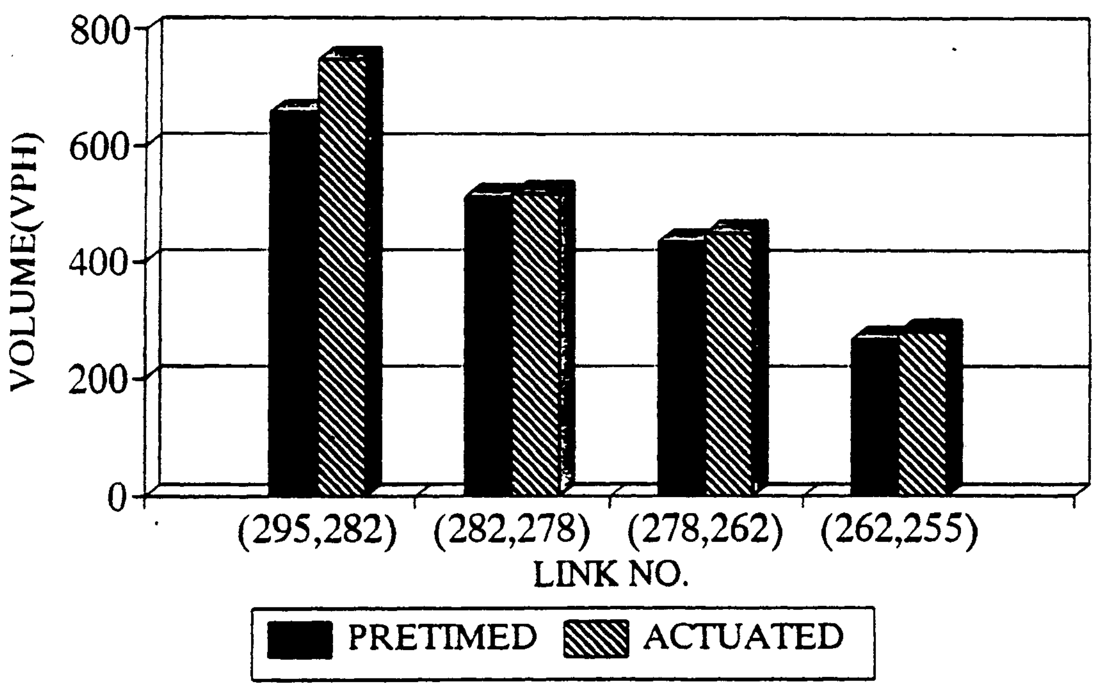


FIGURE 4.2. LINK VOLUME COMPARISON
(1ST AVE.)

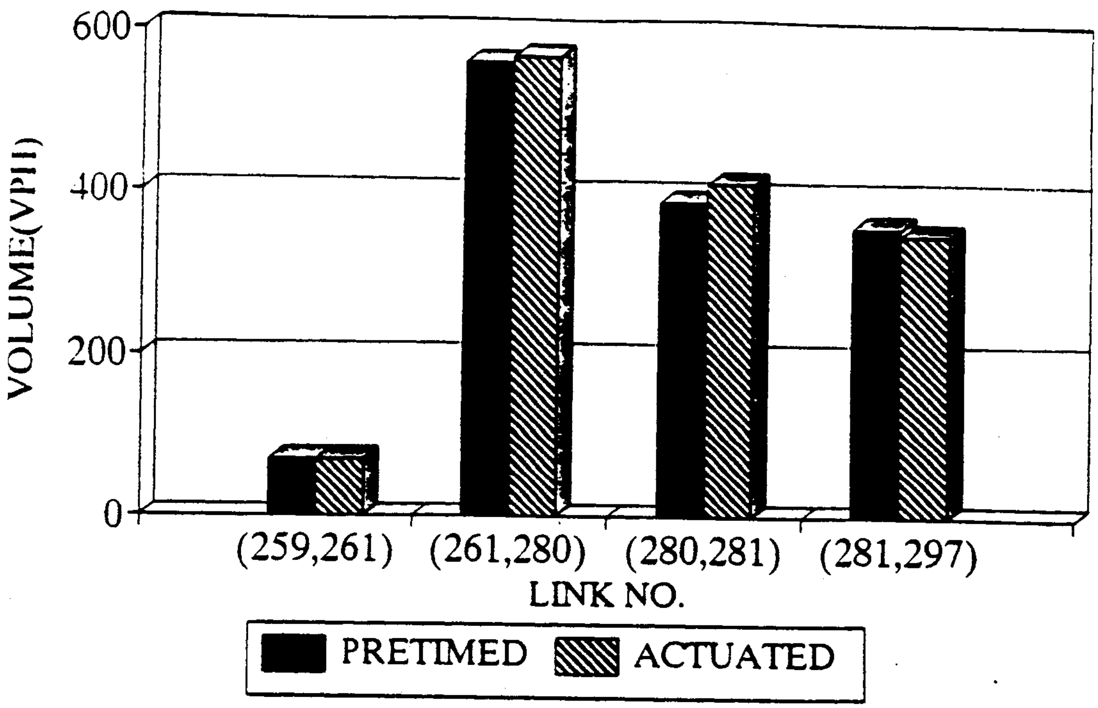


FIGURE 4.3. LINK VOLUME COMPARISON
(2ND AVE. NORTHBOUND)

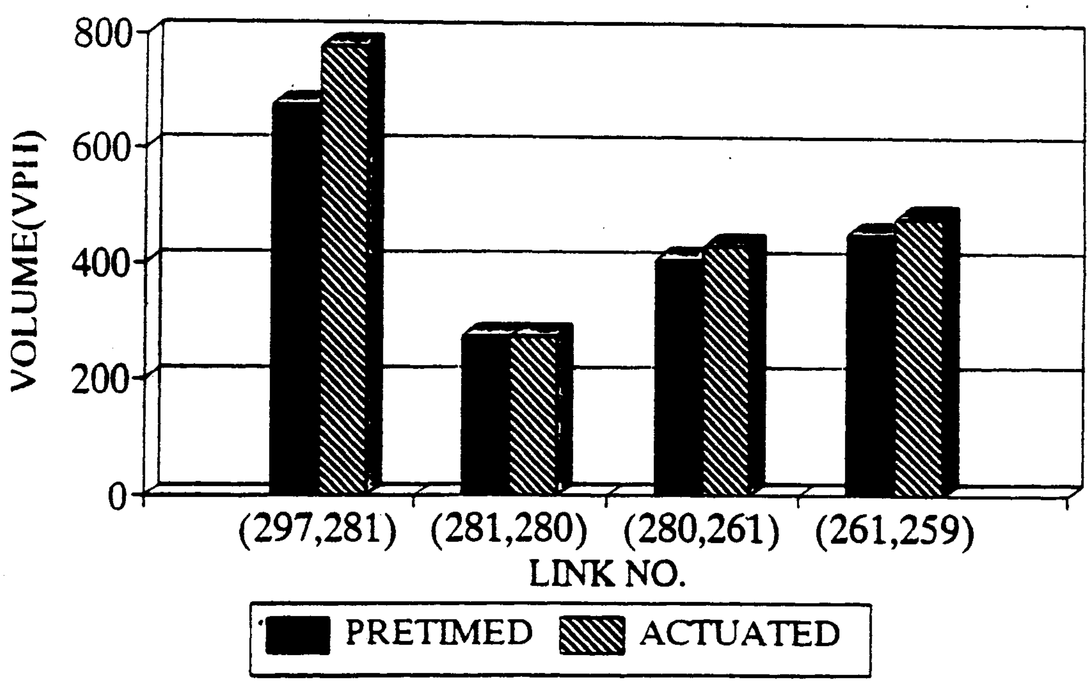


FIGURE 4.4. LINK VOLUME COMPARISON
(2ND AVE. SOUTHBOUND)

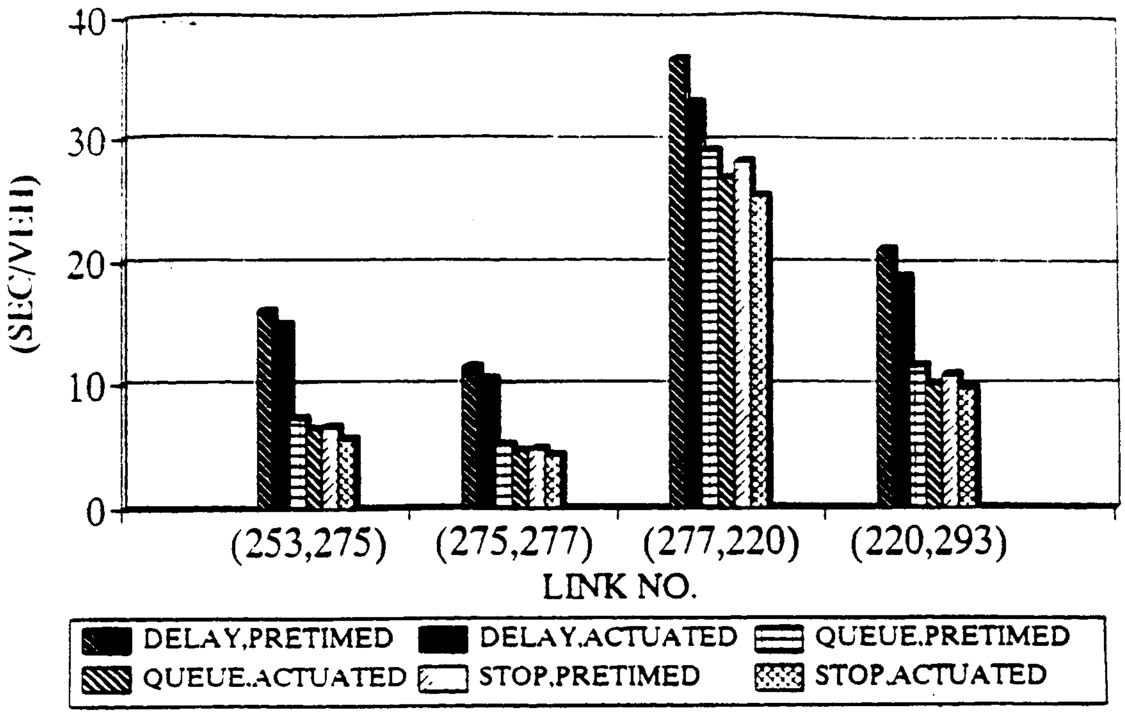


FIGURE 4.5. DELAY, QUEUE, STOP TIME COMPARISON (HENNEPIN AVE.)

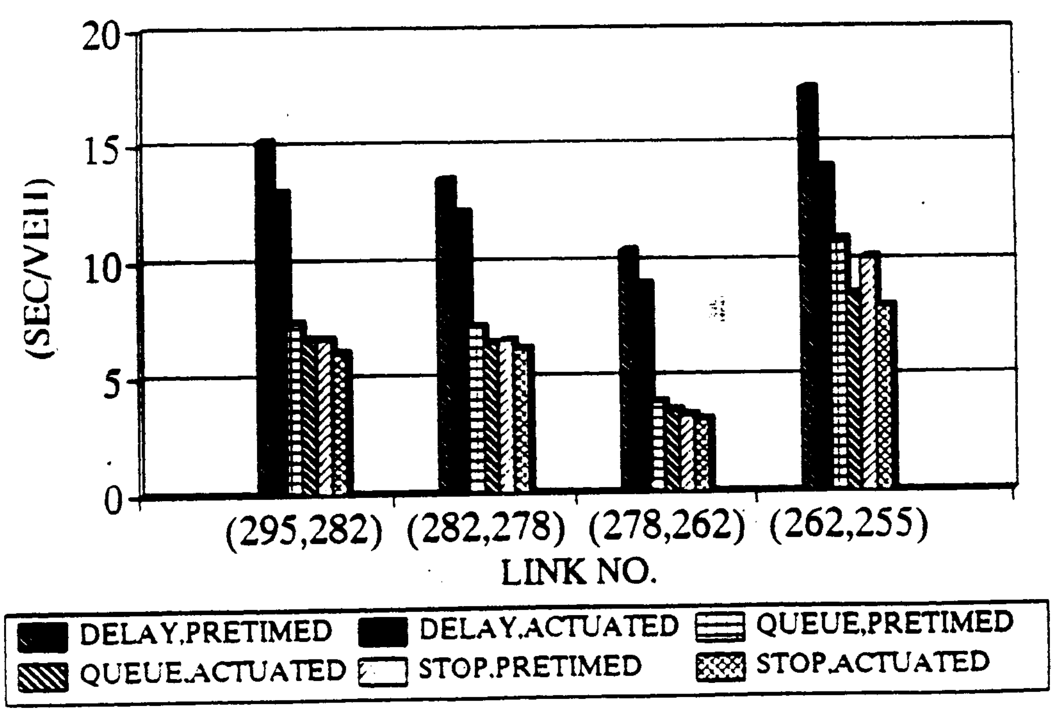


FIGURE 4.6. DELAY, QUEUE, STOP TIME COMPARISON (1ST AVE.)

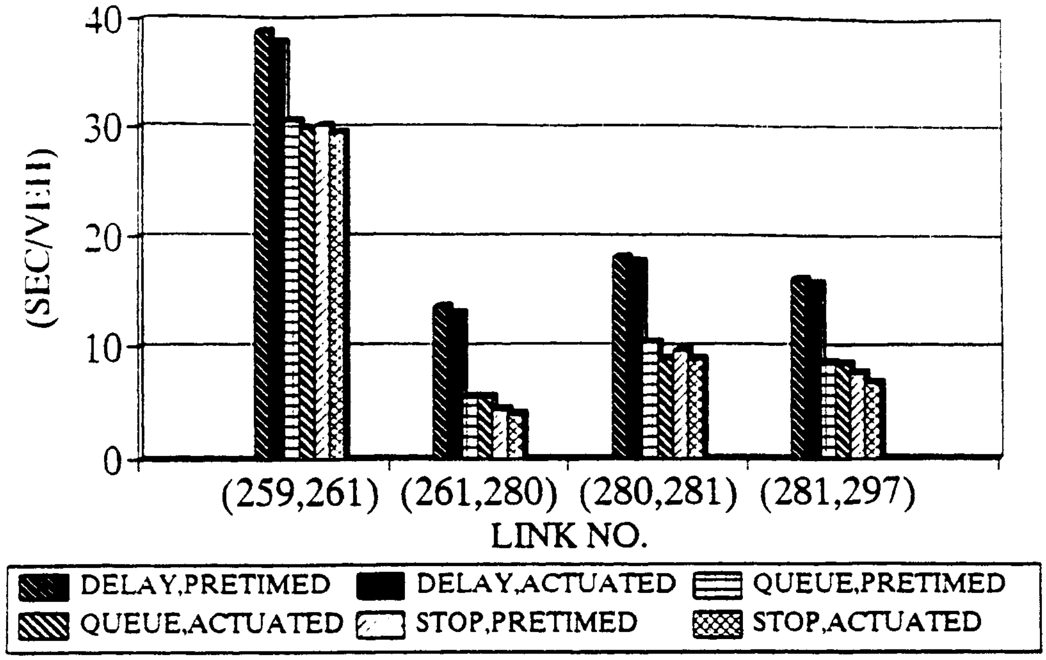


FIGURE 4.7. DELAY, QUEUE, STOP TIME COMPARISON (2ND AVE. NORTHBOUND)

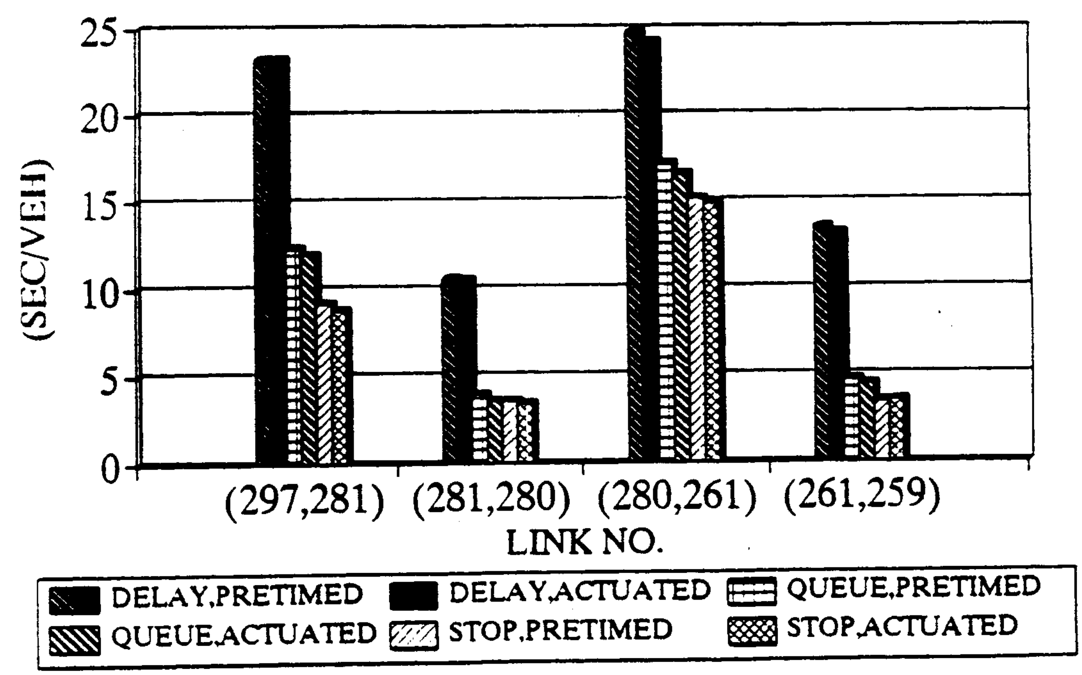


FIGURE 4.8. DELAY, QUEUED, STOP TIME COMPARISON (2ND AVE. SOUTHBOUND)

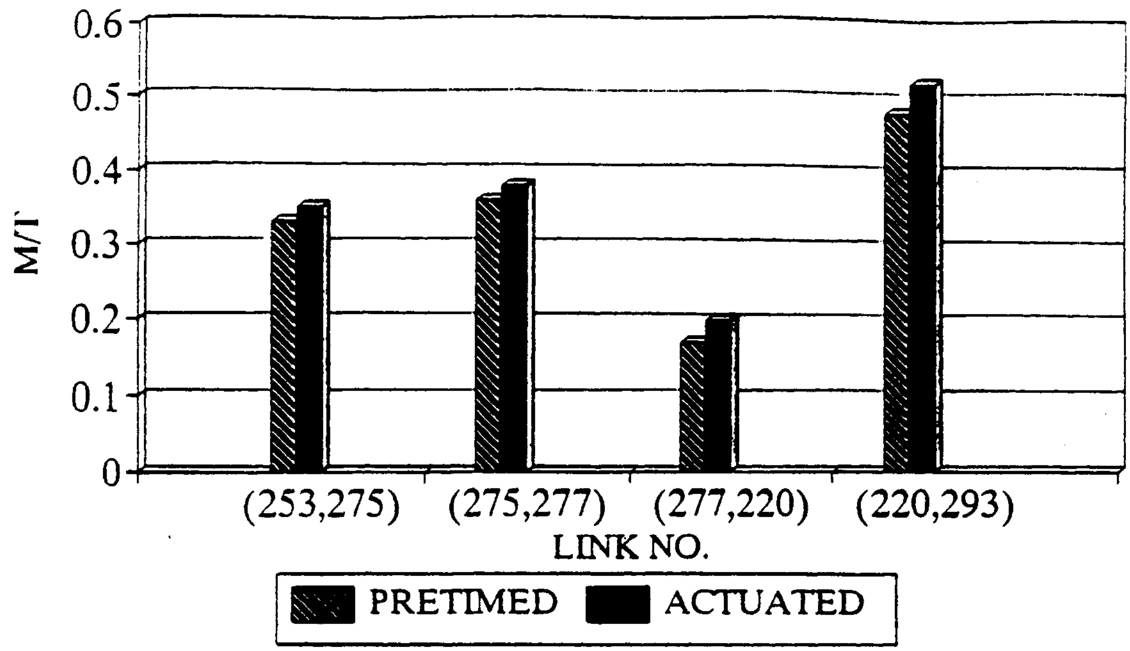


FIGURE 4.9. MOVING/TOTAL TRAVEL TIME COMPARISON (HENNEPIN AVE.)

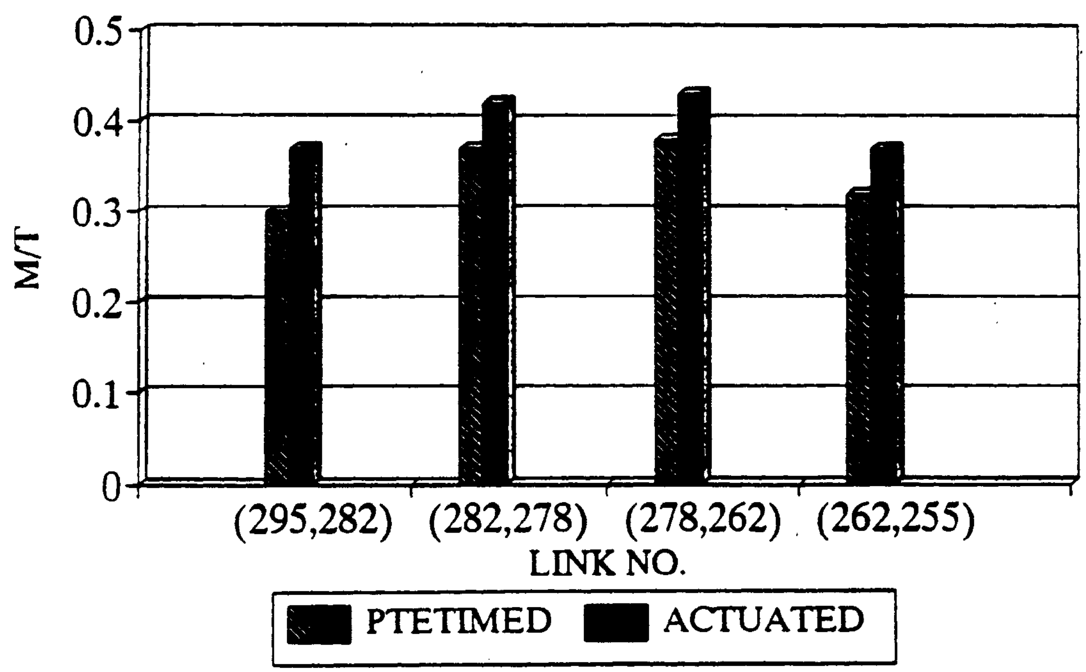


FIGURE 4.10. MOVING/TOTAL TRAVEL TIME COMPARISON (1ST AVE.)

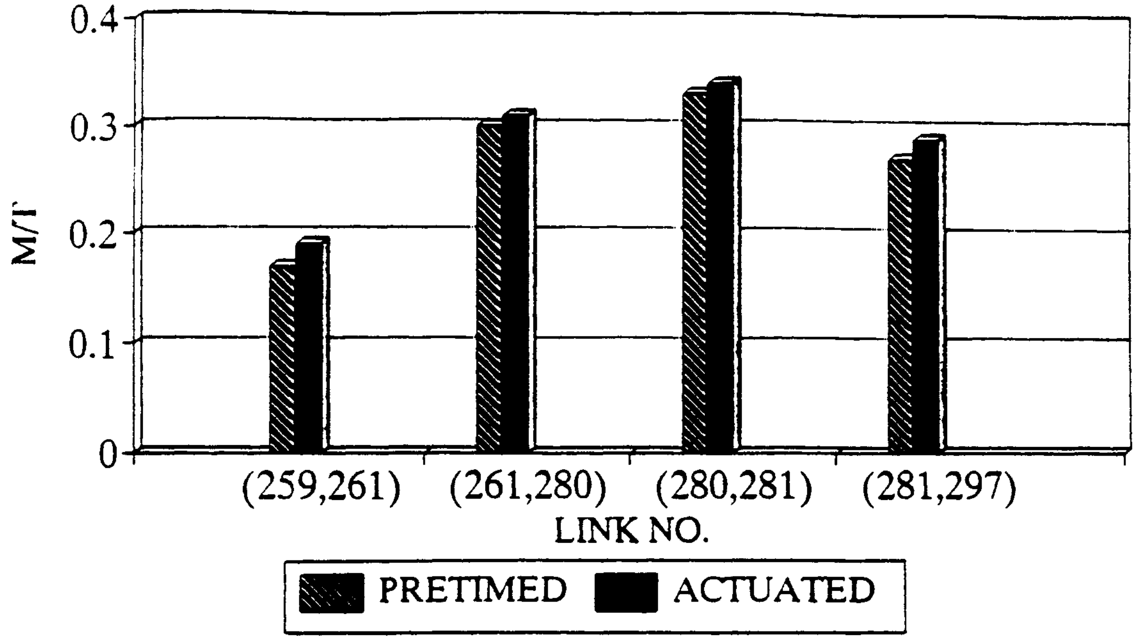


FIGURE 4.11. MOVING/TOTAL TRAVEL TIME COMPARISON (2ND AVE. NORTHBOUND)

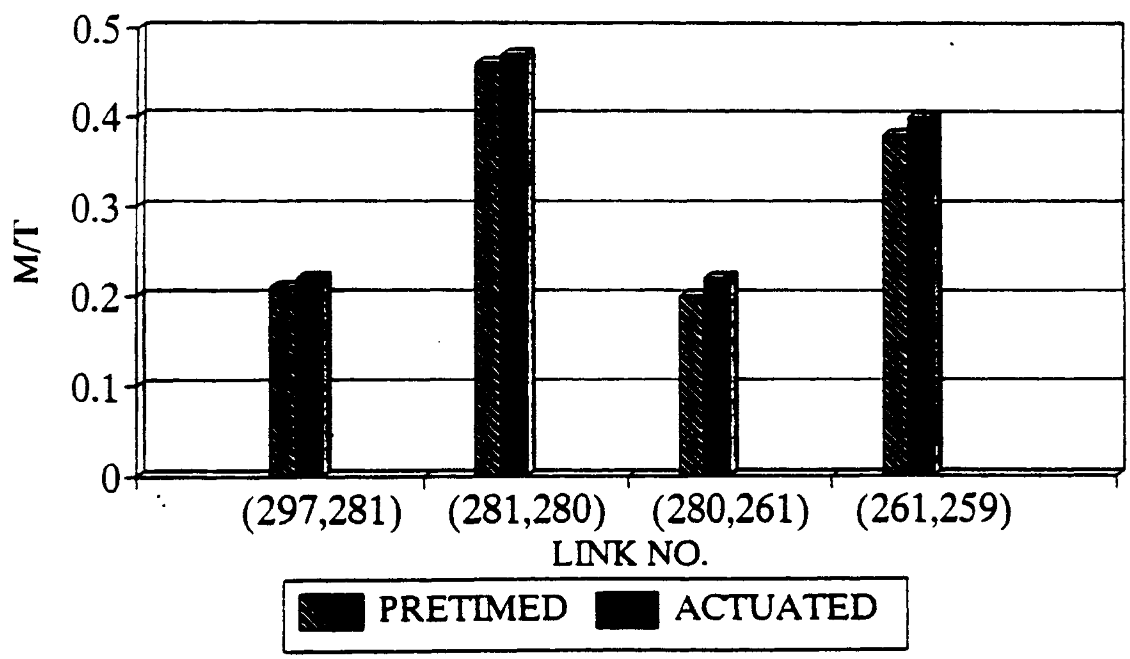


FIGURE 4.12. MOVING/TOTAL TRAVEL TIME COMPARISON (2ND AVE. SOUTHBOUND)

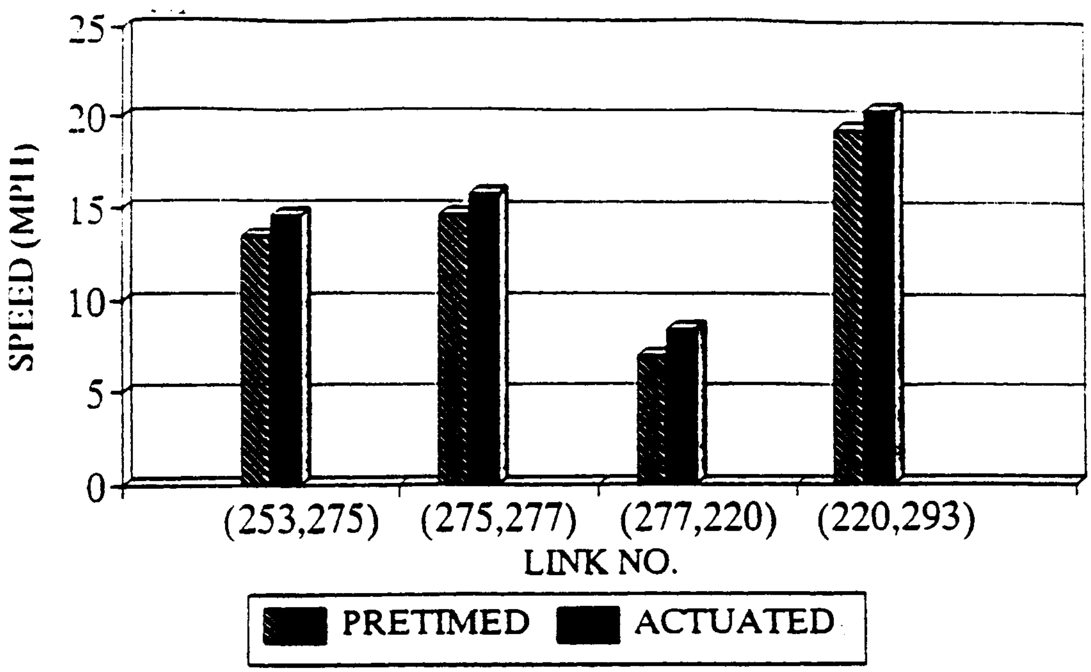


FIGURE 4.13. AVERAGE SPEED COMPARISON
(HENNEPIN AVE.)

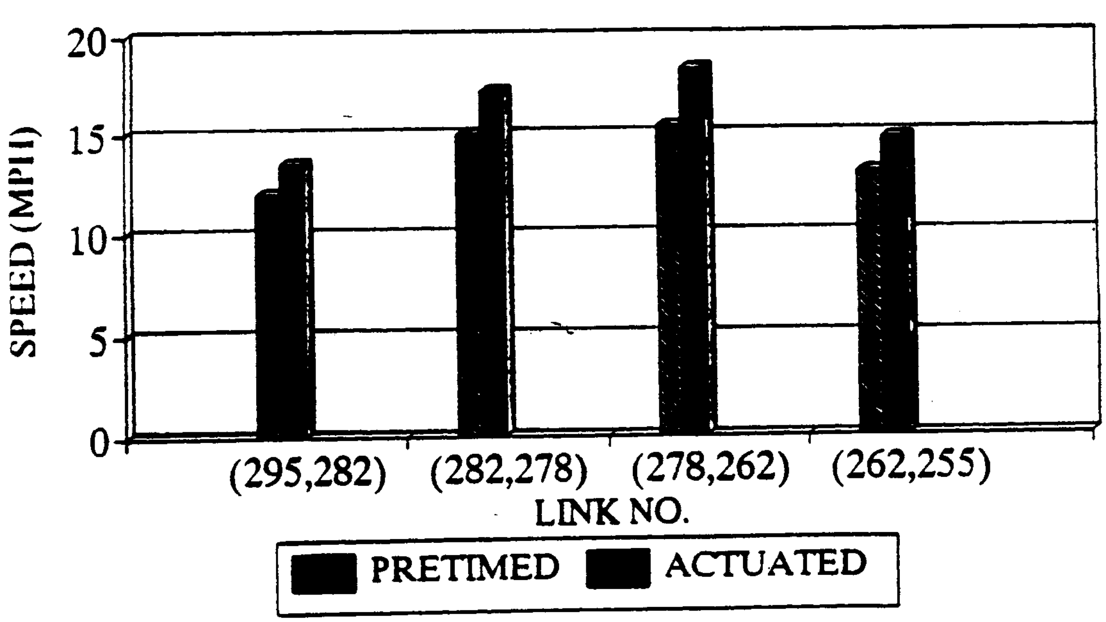


FIGURE 4.14. AVERAGE SPEED COMPARISON
(1ST AVE.)

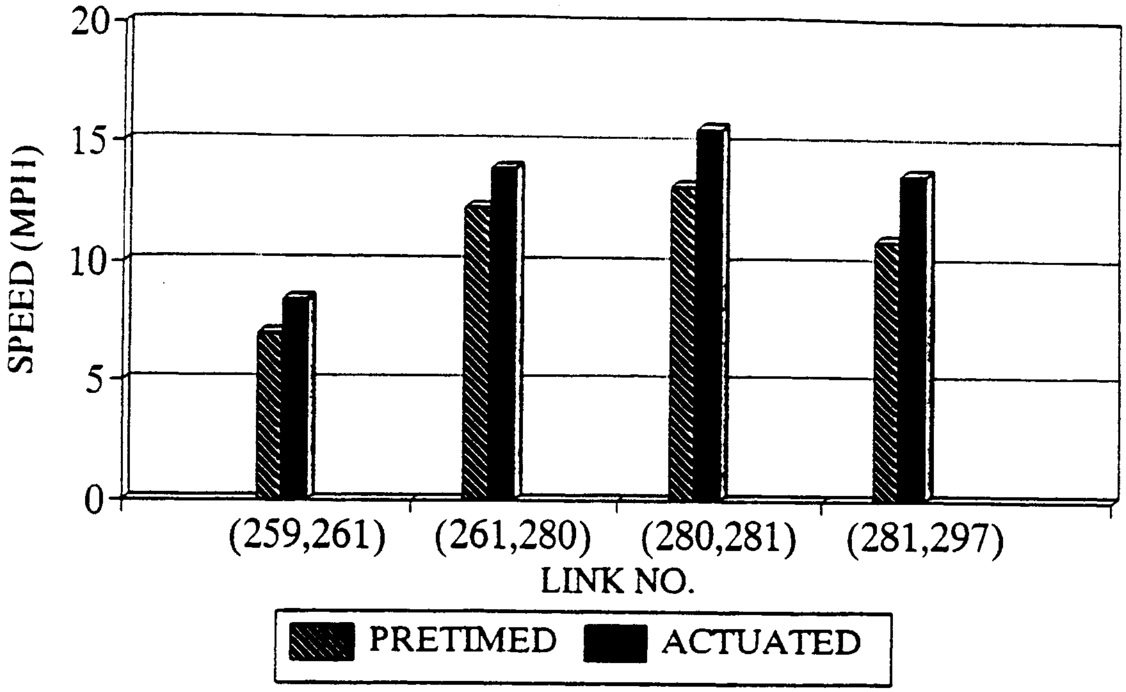


FIGURE 4.15. AVERAGE SPEED COMPARISON
(2ND AVE. NORTHBOUND)

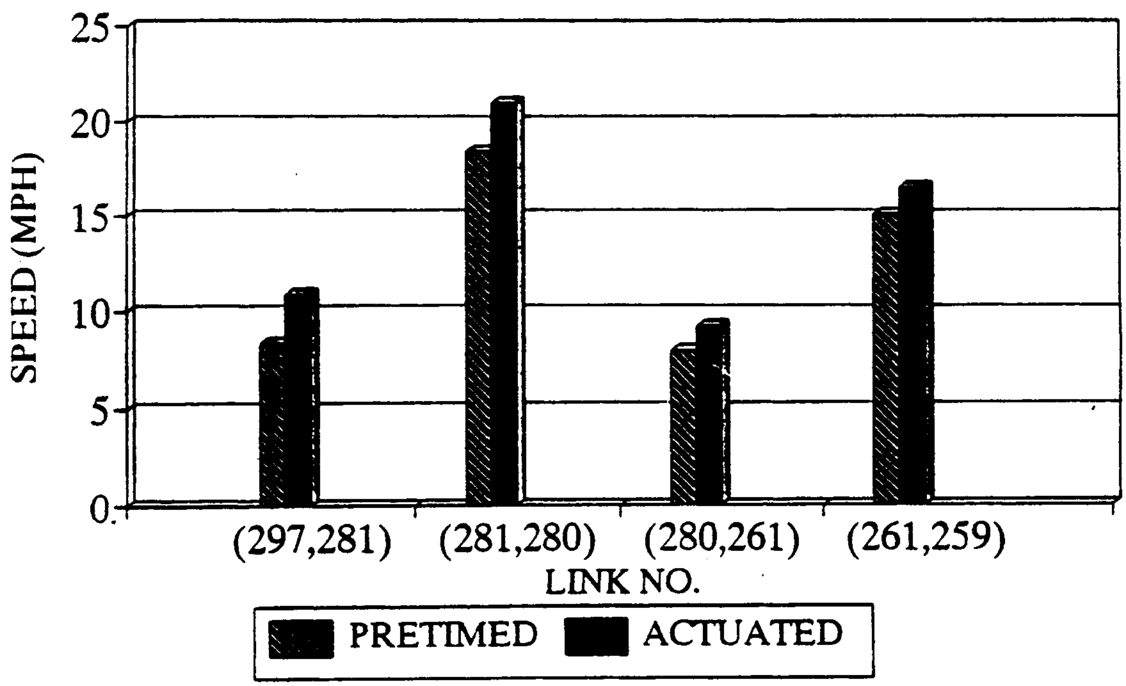


FIGURE 4.16. AVERAGE SPEED COMPARISON
(2ND AVE. SOUTHBOUND)

comparison were made over better prepared pretimed plans, the improvement might be reduced.

IV.4 Summary

This chapter described the preliminary evaluation results of the pretimed and actuated control operations in the test network. The evaluation results indicate that the conversion of three intersections on First Ave. from pretimed to fully-actuated control mode could improve the traffic performance in terms of delay, queue and stop time. However, it should be noted that, owing to limitations in the NETSIM software, only the intersections in the internal links, not boundary links, can be operated in actuated control mode. Further, the performance of actuated control was compared with only that of the current pretimed operation which was last updated in the 1960's on First Avenue. A comprehensive evaluation of additional pretimed signal operations should be conducted before drawing conclusions regarding the effectiveness of actuated control over pretimed operation in the test network.

V. OFF-LINE EVALUATION OF CONTROL STRATEGIES IN A SINGLE INTERSECTION

V.1 Introduction

In chapter III we briefly reviewed the features of NETSIM, a widely used simulator, regarding its main principles, simulation capabilities, input/output, and various performance indices (Measures of effectiveness). In this chapter we present the results from using NETSIM to evaluate three control strategies, i.e., pre-timed, actuated, and OPAC in an isolated intersection. Performance comparisons and preliminary analysis are also given.

V.2 Test site and traffic demand

V.2.1 Test site

The selected test site is the isolated intersection of Franklin and Lyndale Avenues in Minneapolis, Minnesota. This intersection is currently under pre-timed control. The demand level at the intersection is close to saturation flow during peak hours, and this results in congestion and substantial delays.

Fig. 5.1 illustrates the geometric configuration of the intersection. As the figure indicates, the intersection includes two full-lanes on each approach, and left turn pockets on Southbound and Northbound Lyndale Avenue. Detectors are embedded approximately 300 feet upstream of the intersection on the left full-lane in each approach, to measure the demand.

V.2.2 Demand

Five-minute demand data at the test site were collected by the City of Minneapolis on a typical weekday in February. The data span the AM-peak (7:15 AM to 8:45 AM), PM-peak (3:45 PM to 5:15 PM) and off-peak (7:30 PM to 9:00 PM) periods. They have been normalized to hourly demand and are summarized in Tables 5.1, 5.2 and 5.3, and in Figures 5.2, 5.3, and 5.4. The turning movement data at the intersection were collected by the University of Minnesota in the same time periods and are shown in Figures 5.5, 5.6, and 5.7.

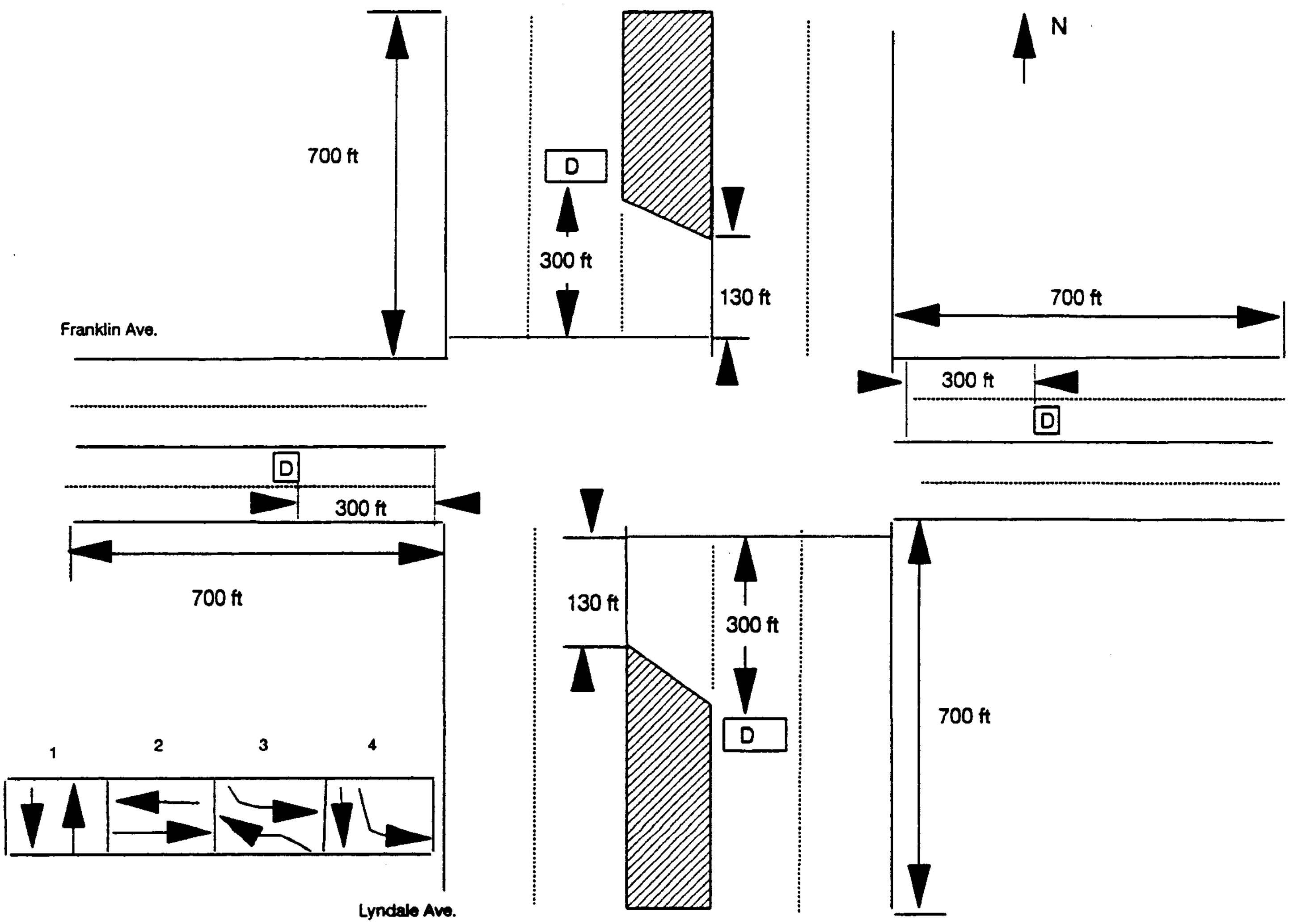


Fig. 5.1 Geometry of Intersection at Franklin Ave. and Lyndale Ave. (not to scale)

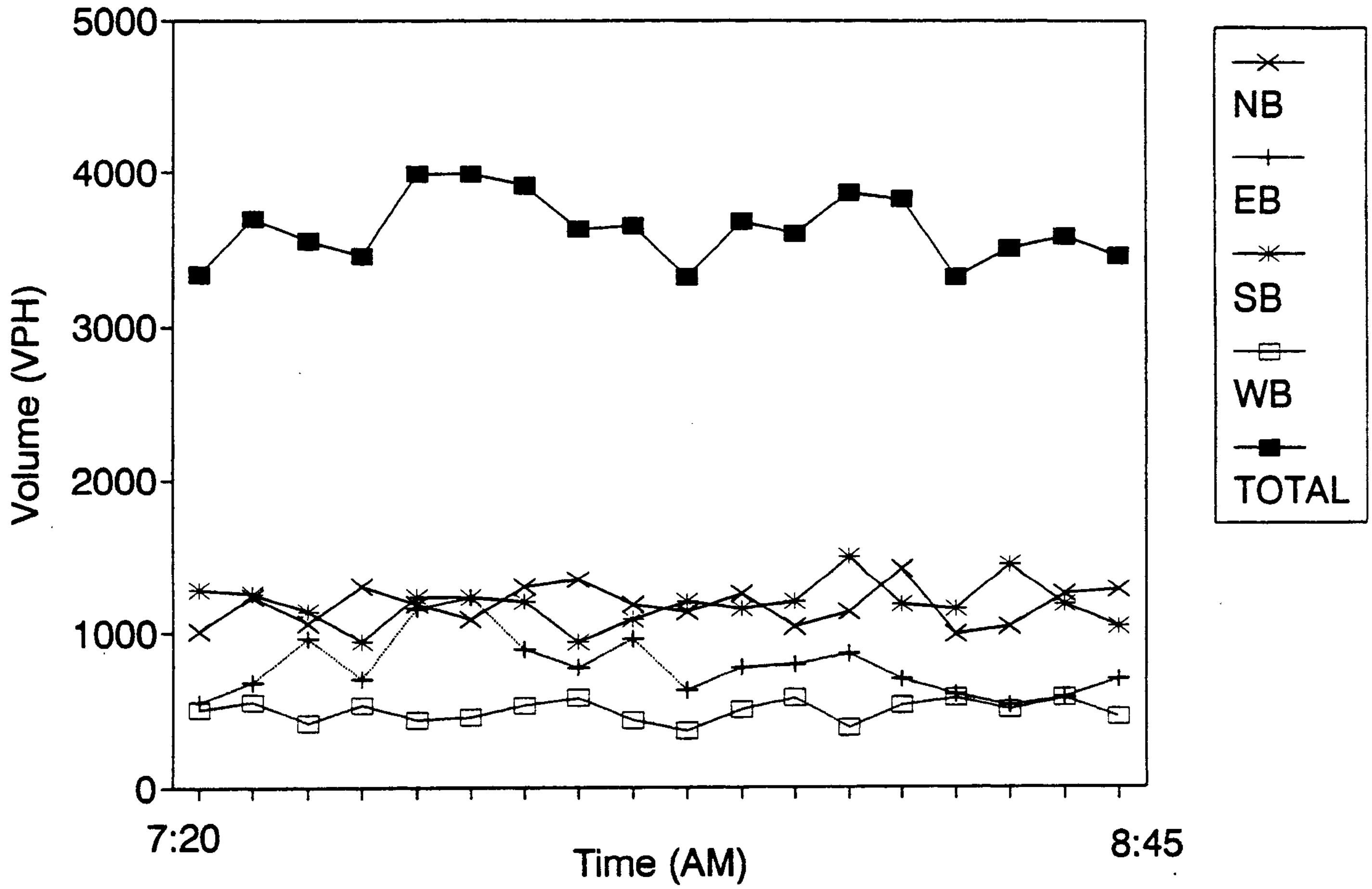


Fig.5.2. AM-peak demand

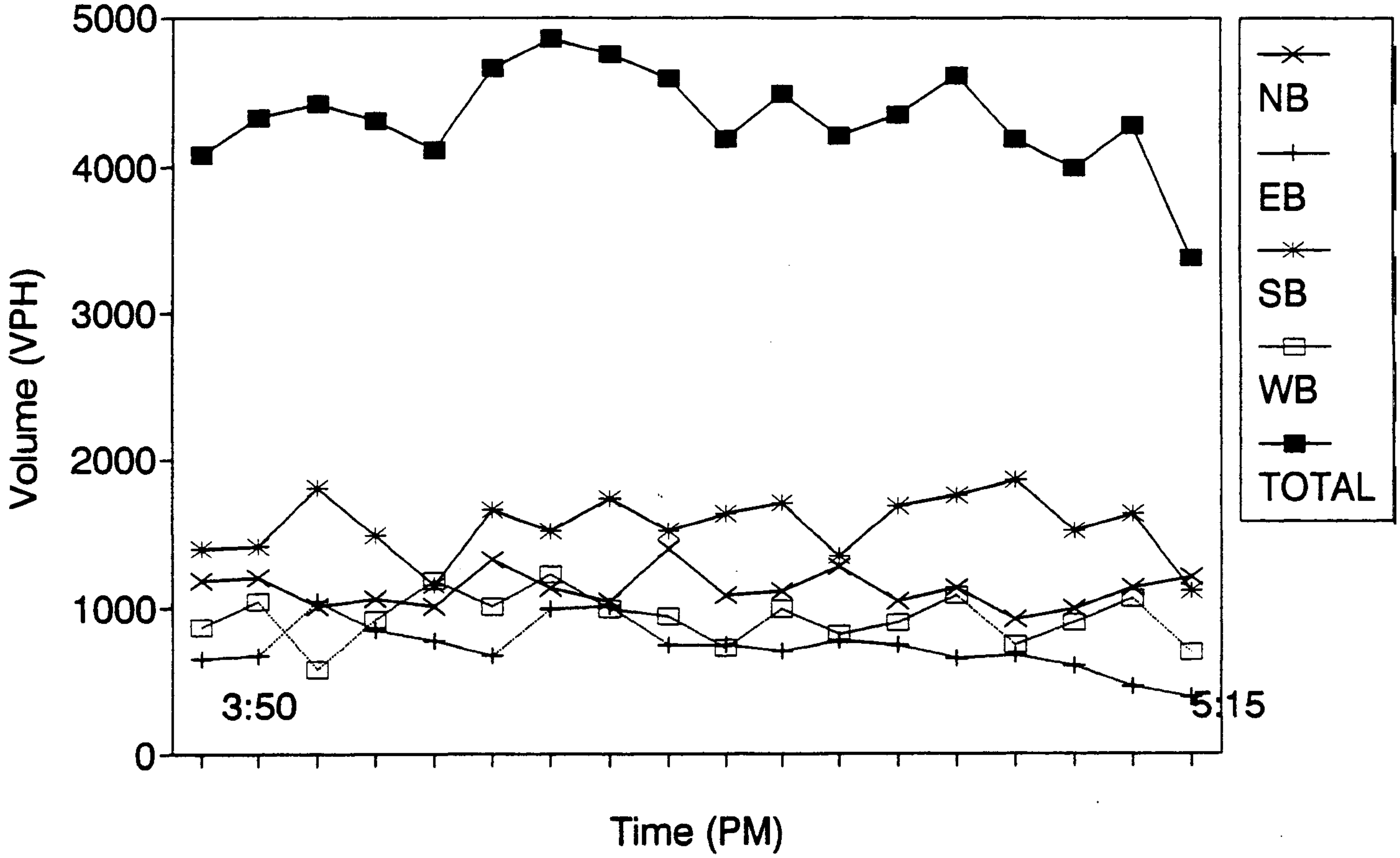


Fig. 5.3 PM-peak demand

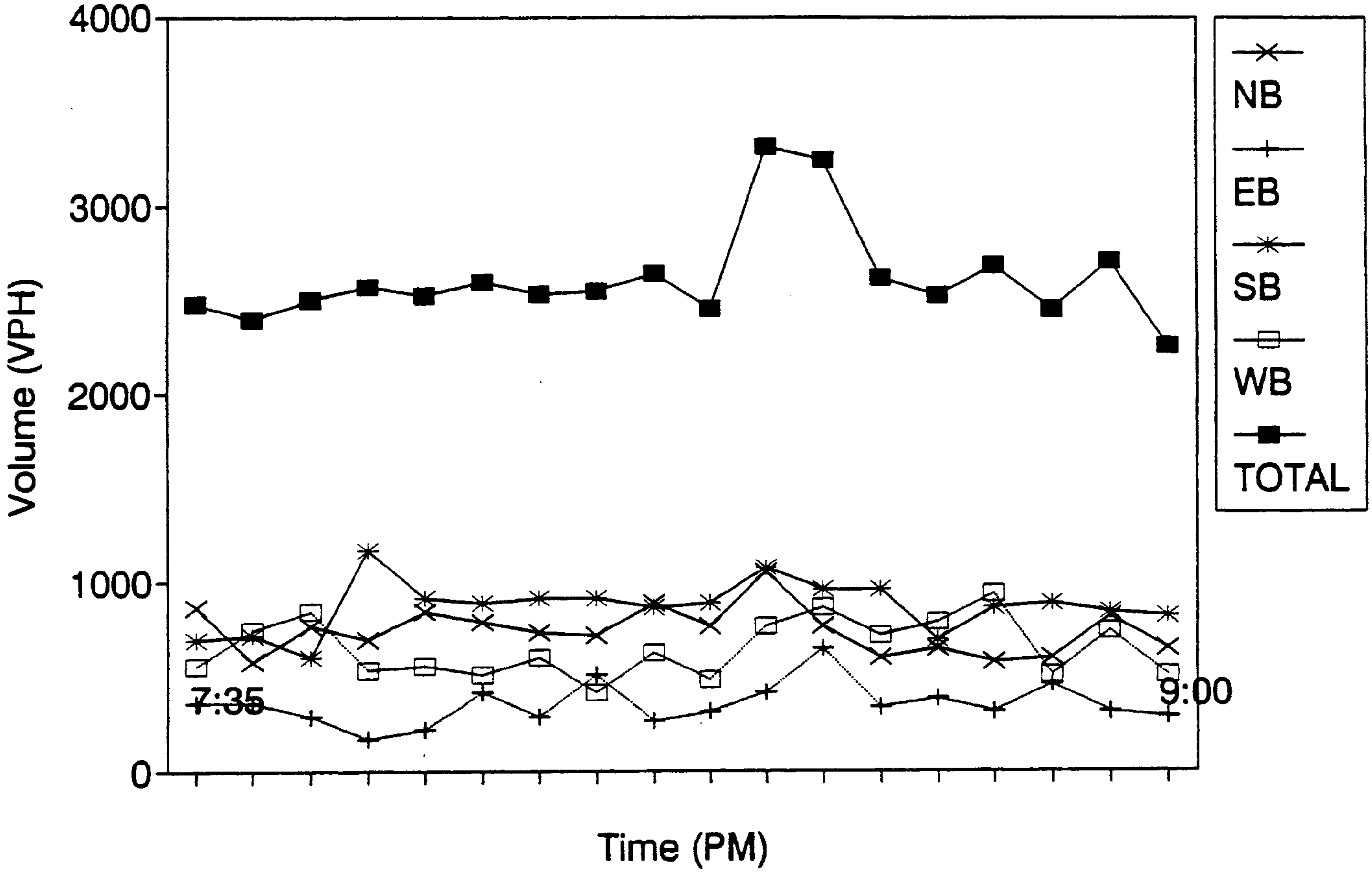


Fig. 5.4 Off-peak demand

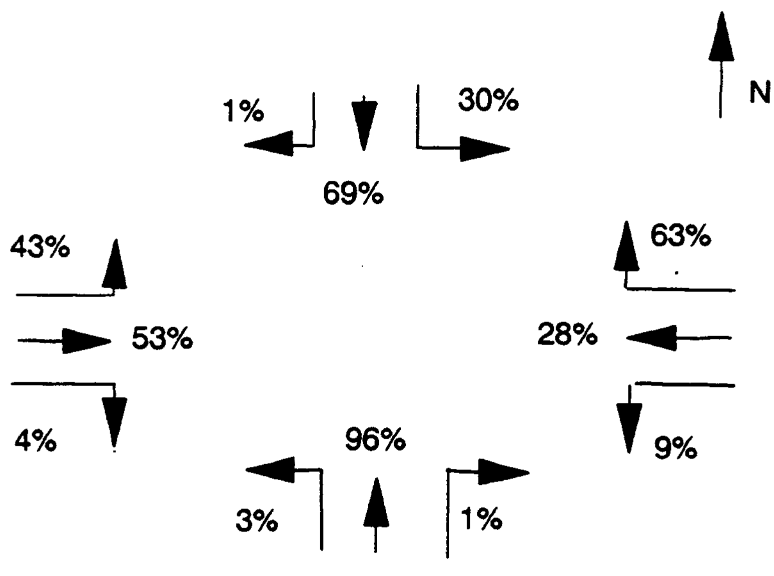


Fig. 5.5 Turning movements during AM-peak

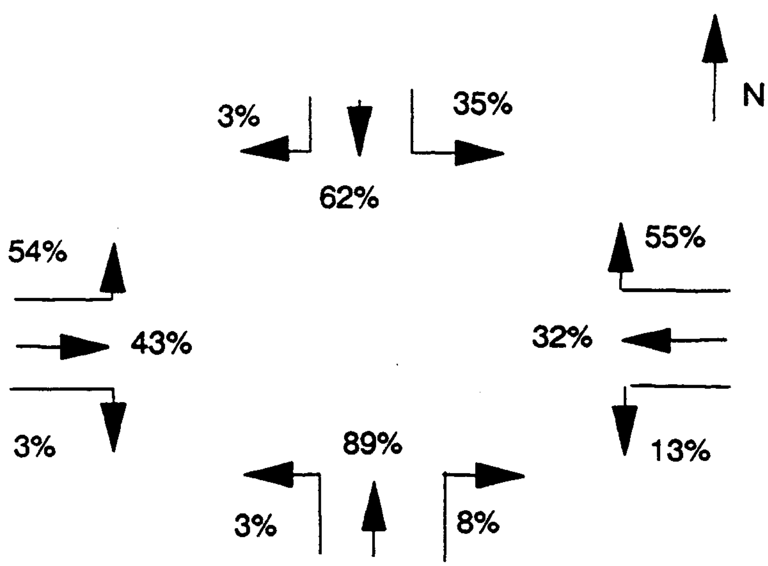


Fig. 5.6 Turning movements during PM-peak

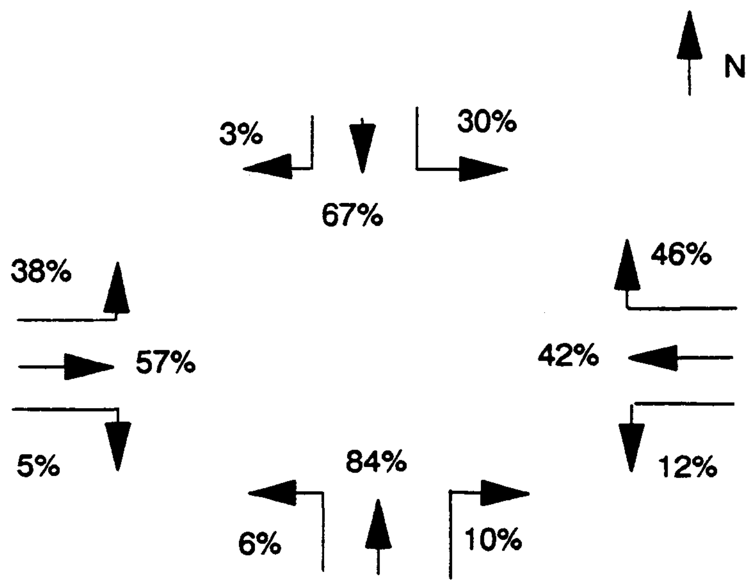


Fig. 5.7 Turning movements during Off-peak

Table 5.1 AM-peak demand (VPH)

TIME (AM)	NB	EB	SB	WB
7:20	1008	552	1272	504
7:25	1224	672	1248	552
7:30	1056	960	1128	408
7:35	1296	696	936	528
7:40	1176	1152	1224	432
7:45	1080	1224	1224	456
7:50	1296	888	1200	528
7:55	1344	768	936	576
8:00	1176	960	1080	432
8:05	1128	624	1200	360
8:10	1248	768	1152	504
8:15	1032	792	1200	576
8:20	1128	864	1488	384
8:25	1416	696	1176	528
8:30	984	600	1152	576
8:35	1032	528	1440	504
8:40	1248	576	1176	576
8:45	1272	696	1032	456

Table 5.2 PM-peak demand (VPH)

TIME (PM)	NB	EB	SB	WB
3:50	1176	648	1392	864
3:55	1200	672	1416	1032
4:00	1008	1032	1800	576
4:05	1056	840	1488	912
4:10	1008	768	1152	1176
4:15	1320	672	1656	1008
4:20	1128	984	1512	1224
4:25	1032	1008	1728	984
4:30	1392	744	1512	936
4:35	1080	744	1632	720
4:40	1104	696	1704	984
4:45	1272	768	1344	816
4:50	1032	744	1680	888
4:55	1128	648	1752	1080
5:00	912	672	1848	744
5:05	984	600	1512	888
5:10	1128	456	1632	1056
5:15	1200	384	1104	864

Table 5.3 Off-peak demand (VPH)

Time (PM)	NB	EB	SB	WB
7:35	864	360	696	552
7:40	576	360	720	744
7:45	768	288	600	840
7:50	696	168	1176	528
7:55	840	216	912	552
8:00	792	408	888	504
8:05	792	288	912	600
8:10	720	504	912	408
8:15	888	264	864	624
8:20	768	312	888	480
8:25	1056	408	1080	768
8:30	768	648	960	864
8:35	600	336	960	720
8:40	648	384	960	792
8:45	576	312	864	936
8:50	600	456	888	504
8:55	816	312	840	744
9:00	648	288	816	504

V.3 Simulation Results and Comparison

The test intersection is under pre-timed control with four phases as shown in Figure 5.1. In this simulation study we keep the same phases in the same order. Three different demand patterns, AM-peak, PM-peak, and off-peak, are each simulated in an one-and-a-half (1.5) hour period each, under pre-timed, actuated, and OPAC control. Measures of effectiveness (MOEs) selected for comparison are: **accumulated-total-delay** (vehicle-hours), **period-delay-per-vehicle-per-trip** (min), and **period-stop-percentage** (%). These MOEs are defined in Appendix.

The three demand patterns are substantially different in terms of volume and turn percentage. Therefore, for each demand pattern we should determine a different set of control parameter values that minimize accumulated total delay. So for each demand pattern, control parameters related to each control strategy, such as the distribution of time to each phase for pre-timed, minimum and maximum green time for actuated or OPAC, etc., were determined by several trial-and-error runs. All the trial-and-error NETSIM runs use the same random seed, noted as No. 0 (See section III.2 for more details).

In addition, because NETSIM uses random distribution of demand as input, different random seeds in the demand pattern input yield different MOE values, for the same demand pattern. Our study has shown that such differences can be substantial. For increasing the reliability with which the MOE values describe the performace of the control strategies, an experimental process was followed. In particular, following the determination of the control parameters, for each control strategy and demand pattern, ten simulation runs were performed. Each simulation run is based on a different random seed (noted as Nos. 0 to 9 in Tables 5.5, 5.6 and 5.7).

The accumulated total delays with random seed No. 0 are given in Table 5.4. All accumulated total intersection delays are given in Tables 5.5 to 5.7 and shown in Figures 5.8 to 5.10. The average accumulated total delay and standard deviations over each set of ten runs are also given in Tables 5.5 to 5.7 and shown in Figures 5.11 and 5.12, respectively. Here standard deviation is defined as

$$\sqrt{\frac{\sum_{i=1}^{n} (x_i - \bar{x})^2}{n - 1}} \tag{5.1}$$

where x_i is the value of MOE_i and $\bar{x}$ is its mean; n=10. Average accumulated delays are summarized in Table 5.8.

Table 5.4. Accumulated total delay (Vehicle-hours) with random seed No. 0

Demand Pattern	Pre-timed	Actuated	OPAC
AM-peak	95.98	112.17	106.65
PM-peak	163.06	167.43	185.99
Off-peak	38.62	38.36	35.88

Table 5.5. Accumulated total delay (Vehicle-hours) comparison (AM-peak)

Random Seed No.	Pre-timed	Actuated	OPAC
0	95.98	112.17	106.65
1	103.97	115.54	101.75
2	103.04	117.37	97.25
3	91.40	103.19	108.78
4	81.22	99.43	100.26
5	91.48	110.85	117.60
6	102.75	123.30	110.11
7	101.62	110.97	105.85
8	93.49	106.64	100.49
9	113.79	124.05	115.09
Average (Mean)	97.87	112.35	106.38
Comparison	100	114.8	108.7
%	- +14.8%	+8.7%	
Standard Deviation	9.06	8.03	6.66

Table 5.6. Accumulated total delay (Vehicle-hours) comparison (PM-peak)

Random Seed No.	Pre-timed	Actuated	OPAC
0	163.06	167.43	185.99
1	176.85	165.97	181.55
2	175.05	169.14	187.46
3	177.95	166.97	194.57
4	182.26	167.17	189.95
5	170.08	165.71	184.45
6	160.37	178.01	193.49
7	168.58	167.53	181.85
8	141.98	162.01	182.16
9	159.57	172.41	189.31
Average (Mean)	167.58	168.24	187.08
Comparison	100	100.4	111.6
%	-	+0.4%	+11.6%
Standard Deviation	11.85	4.32	4.72

Table 5.7. Accumulated total delay (Vehicle-hours) comparison (Off-peak)

Random Seed No.	Pre-timed	Actuated	OPAC
0	38.62	38.36	35.88
1	37.73	40.45	37.04
2	38.20	40.13	37.69
3	37.69	38.11	34.97
4	39.58	38.36	35.76
5	38.87	39.47	36.97
6	39.22	41.43	35.40
7	38.30	38.63	35.27
8	38.84	39.19	36.45
9	38.19	40.65	35.88
Average (Mean)	38.52	39.48	36.13
Comparison	100	102.5	93.8
%	-	+2.5%	-6.2%
Standard Deviation	0.62	1.14	0.88

Table 5.8. Average accumulated total delay (Vehicle-hours) of ten runs

	Pre-timed	Actuated	OPAC
AM-peak	97.87	112.35	106.38
Comparison	-	+14.8%	+8.7%
PM-peak	167.58	168.24	187.08
Comparison	-	+0.4%	+11.6%
Off-peak	38.52	39.48	36.13
Comparison	-	+2.5%	-6.2%

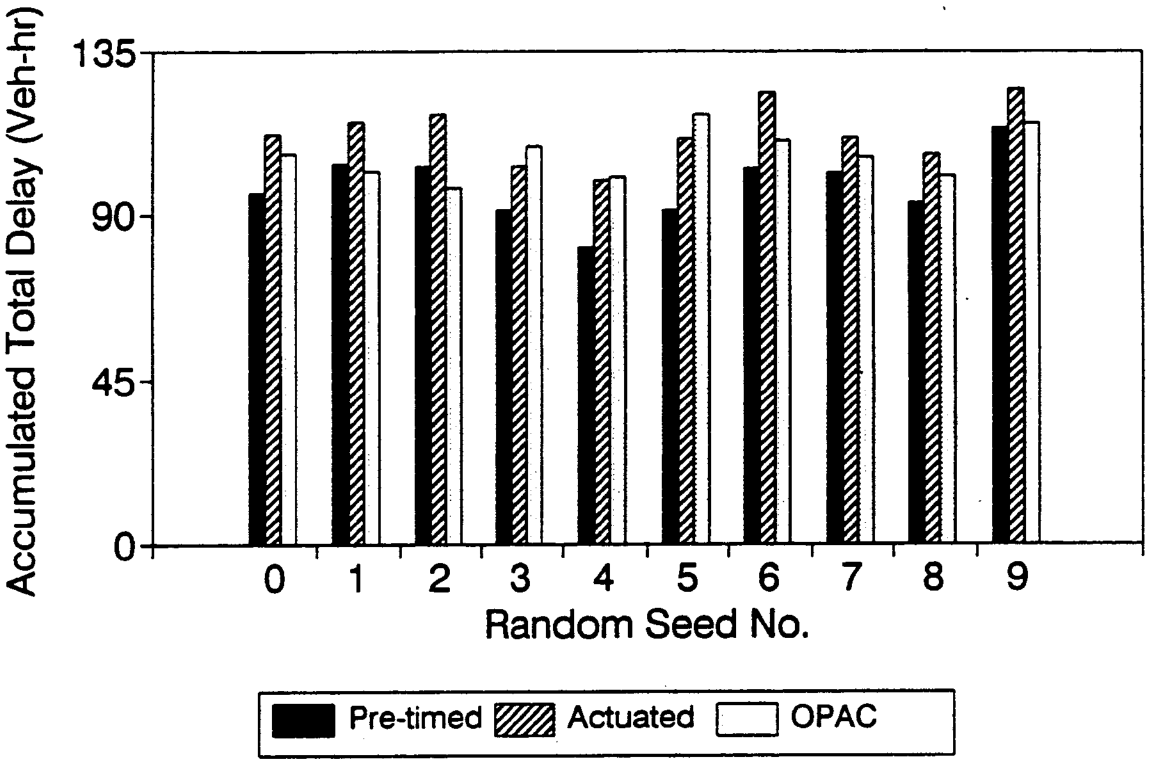


Fig. 5.8 Accumulated Total Delay Comparison (AM-peak)

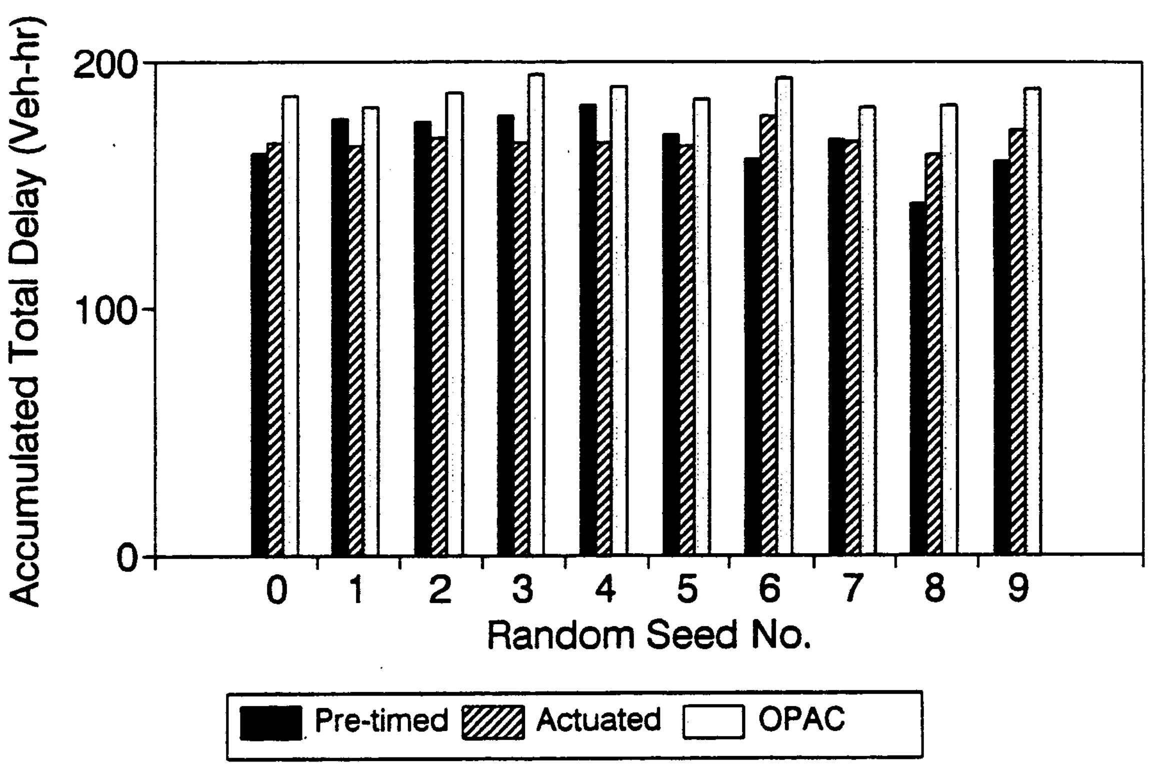


Fig. 5.9 Accumulated Total Delay Comparison (PM-peak)

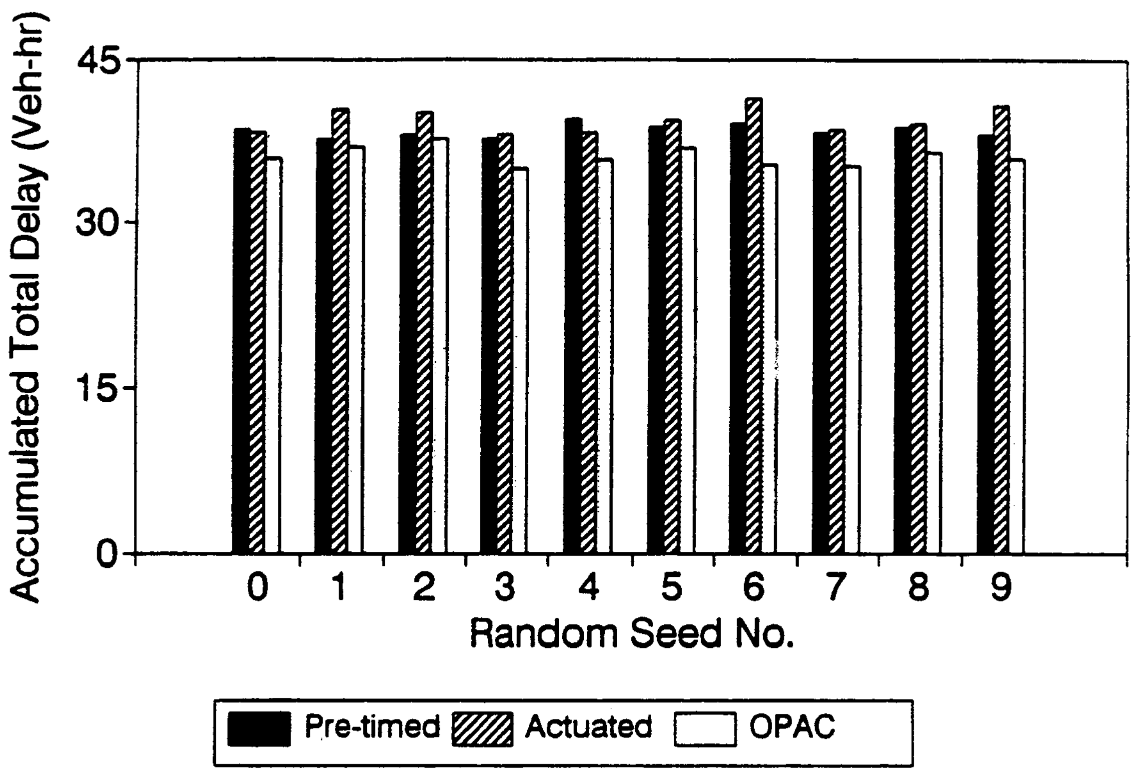


Fig. 5.10 Accumulated Total Delay Comparison (Off-peak)

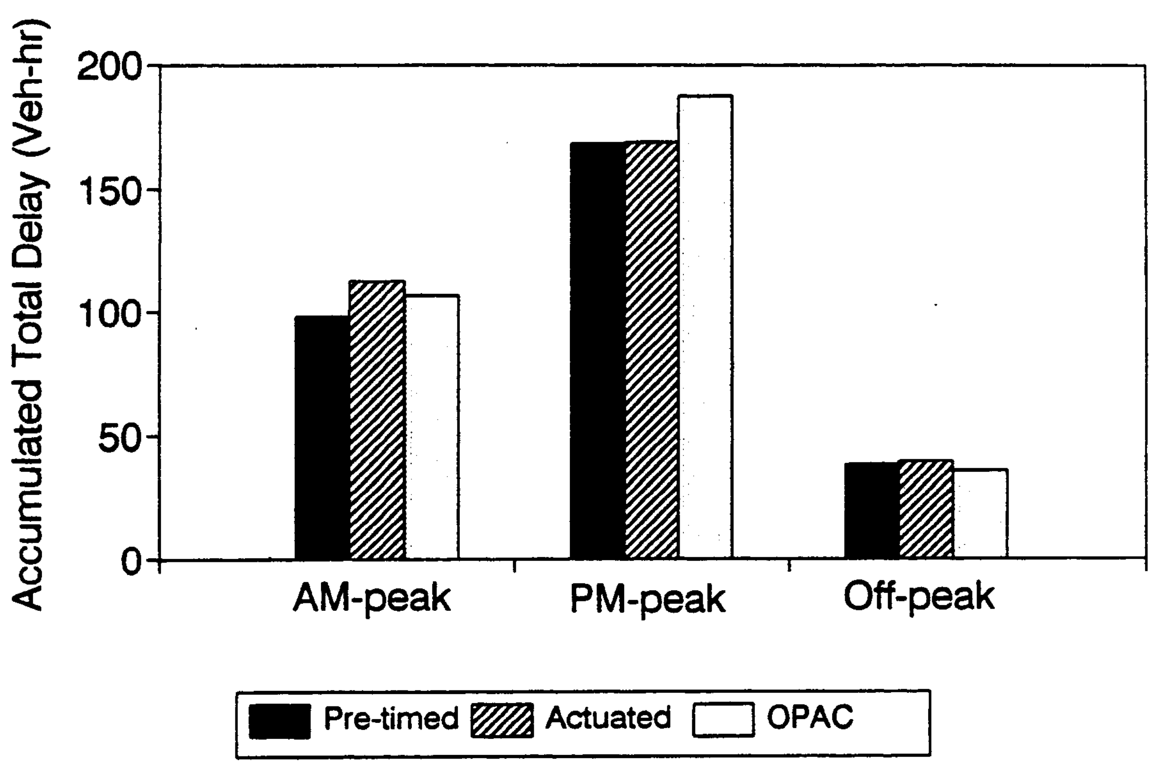


Fig. 5.11 Average Accumulated Total Delay Comparison

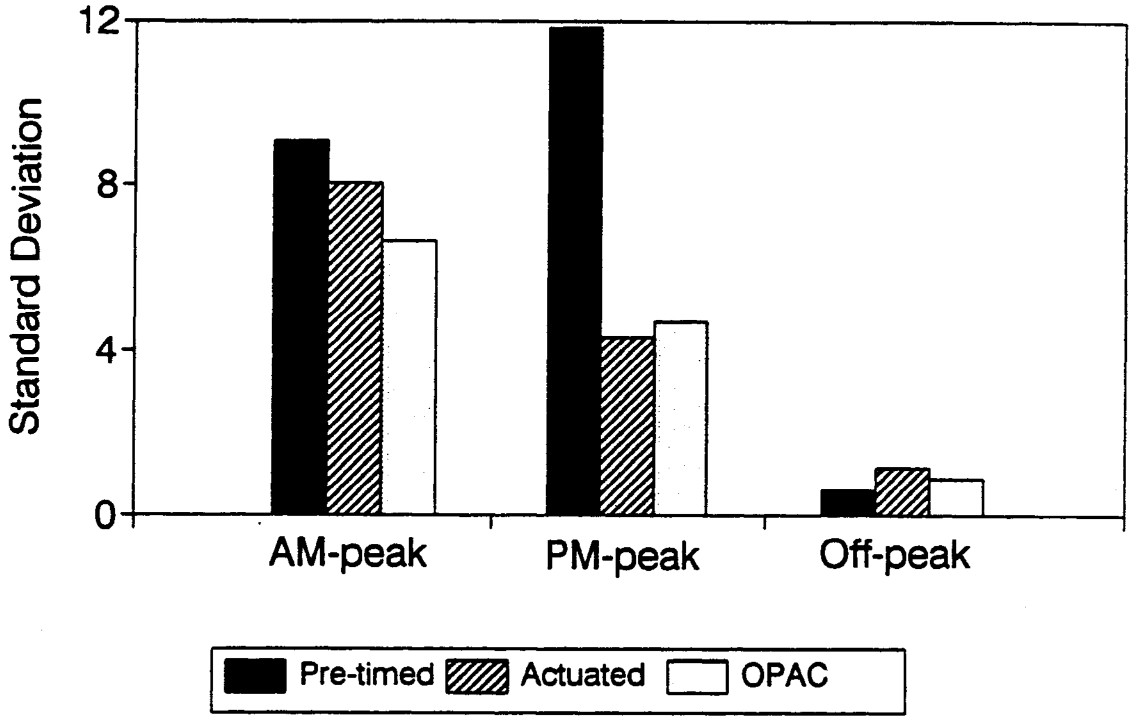


Fig. 5.12 Standard Deviations of Accumulated Total Delay

As the Tables indicate, at the low demand of the off-peak, OPAC performs best, with average accumulated delay 6.2% lower than in pre-timed control. Actuated control performs slightly worse than pre-timed, with average accumulated delay 2.5% higher. At high demand, both AM-peak and PM-peak, pre-timed control performs best. During the AM-peak, OPAC performs better than actuated control, with average accumulated delay 5.3% lower, though delays under both actuated control and OPAC increase 14.8% and 8.7 %, respectively, compared to pre-timed control. Further, during the PM-peak, when demand is the highest, actuated control performs almost the same as pre-timed control, but OPAC delay increases 11.6% compared to pre-timed control. Standard deviations are around 1 for off-peak and relatively larger for both AM-peak and PM-peak, ranging from 4 to 12.

Besides accumulated-total-delay (accumulated from the beginning of the first time period) that NETSIM provides at the end of each time period, it also gives delay-per-vehicle-per-trip and stop-percentage within that time period (thereafter called period delay-per-vehicle-per-trip and period stop-percentage). In this study 5-minute time period MOEs from runs with random seed No. 0 are given in Tables 5.9 to 5.11 and shown in Figures 5.13 to 5.21. As the Tables indicate, delay-per-vehicle-per-trip and stop-percentage are consistent with accumulated total delay, i.e., higher accumulated total delay corresponds to higher period delay-per-vehicle-per-trip and period stop-percentage.

V.4 Summary

This chapter described the evaluation results of pre-timed, actuated and OPAC control strategies in an isolated intersection. NETSIM was used to simulate the traffic with three demand patterns, i.e., AM-peak, PM-peak, and off-peak, on a typical weekday in February. Three MOEs were selected, i.e., accumulated total delay, period delay-per-vehicle-per-trip, and period stop-percentage.

Under each of three control strategies, ten simulation runs, each with a different random seed, were performed, for each of three demand patterns. There are a total of 90 runs (3 control strategies by 3 demand patterns by 10 random seeds). Test results on average accumulated total delay, the most important performance index, are mixed and no control strategy is clearly superior. Pre-timed control performs somewhat better than actuated control for all three demand patterns, and better than OPAC in peak periods, when demand is high. OPAC performs best when demand is low (off-peak) and worst when demand is the highest (PM-peak); this is consistent with the expected properties of OPAC, which was originally developed for undersaturated traffic flow. For the high demand pattern (AM-peak), OPAC performs better than actuated control, by 5.3%, but worse than pre-timed control, by 8.7%.

A possible reason for the mixed performance results of the three control strategies in this study is that both the percentage of turning movement and volume (shown in Fig. 5.5, 5.6 and 5.7) are substantially different across the three demand patterns. Another possible reason is that control strategy parameters were determined by trial-and-error, not by formal optimization.

Table 5.9. MOEs per 5-minute time period (AM-peak, random seed No. 0)

a. Pre-timed

Time (AM)	Accumulated total delay (veh-h)	Period delay per-veh-per-trip (min)	Period stop percentage (%)
7:20	2.74	0.61	67.5
7:25	6.20	0.65	70.8
7:30	10.32	0.72	75.4
7:35	14.74	0.77	78.0
7:40	19.71	0.81	79.8
7:45	25.69	0.88	81.2
7:50	34.07	0.98	81.9
7:55	42.94	1.07	83.1
8:00	50.59	1.12	84.4
8:05	57.78	1.15	84.8
8:10	63.18	1.14	84.6
8:15	68.21	1.13	84.8
8:20	72.60	1.11	84.6
8:25	78.32	1.11	84.4
8:30	83.82	1.11	84.7
8:35	88.03	1.09	84.0
8:40	92.60	1.08	83.7
8:45	95.98	1.06	83.5

Table 5.9. (Cont.)

b. Actuated

Time (AM)	Accumulated total delay (veh-h)	Period delay per-veh-per-trip (min)	Period stop percentage (%)
7:20	2.87	0.70	75.3
7:25	7.63	0.84	78.9
7:30	12.42	0.89	81.0
7:35	17.93	0.96	82.4
7:40	24.54	1.03	83.1
7:45	31.55	1.12	83.8
7:50	40.32	1.22	84.1
7:55	49.86	1.32	85.2
8:00	58.82	1.36	85.5
8:05	66.19	1.38	86.0
8:10	71.58	1.35	85.2
8:15	76.62	1.33	84.6
8:20	82.51	1.32	84.3
8:25	89.10	1.32	84.3
8:30	95.36	1.33	84.3
8:35	101.55	1.33	84.2
8:40	107.05	1.31	83.8
8:45	112.17	1.30	83.0

Table 5.9. (Cont.)

c. OPAC

Time (AM)	Accumulated total delay (veh-h)	Period delay per-veh-per-trip (min)	Period stop percentage (%)
7:20	3.31	0.74	80
7:25	6.86	0.71	80
7:30	10.91	0.76	80
7:35	15.67	0.82	80
7:40	20.84	0.85	80
7:45	27.63	0.93	80
7:50	34.83	1.00	80
7:55	42.47	1.06	80
8:00	50.34	1.12	80
8:05	57.72	1.16	80
8:10	64.90	1.18	80
8:15	71.49	1.19	80
8:20	78.22	1.20	80
8:25	86.33	1.22	80
8:30	93.90	1.24	80
8:35	99.61	1.24	80
8:40	103.49	1.21	80
8:45	106.65	1.18	80

Table 5.10. MOEs per 5-minute time period (PM-peak, random seed No. 0)

a. Pre-timed

Time (PM)	Accumulated total delay (veh-h)	Period delay per-veh-per-trip (min)	Period stop percentage (%)
3:50	5.48	1.10	91.9
3:55	12.05	1.13	91.0
4:00	18.15	1.16	91.0
4:05	24.91	1.20	89.4
4:10	32.29	1.25	89.1
4:15	41.87	1.35	89.3
4:20	53.13	1.49	90.1
4:25	63.50	1.55	90.6
4:30	75.14	1.63	90.9
4:35	87.19	1.71	91.5
4:40	96.66	1.71	91.8
4:45	106.34	1.73	91.5
4:50	117.62	1.76	91.7
4:55	126.14	1.76	91.5
5:00	136.91	1.80	91.3
5:05	146.81	1.81	91.1
5:10	154.58	1.79	90.8
5:15	163.06	1.79	90.6

Table 5.10. (Cont.)

b. Actuated

Time (PM)	Accumulated total delay (veh-h)	Period delay per-veh-per-trip (min)	Period stop percentage (%)
3:50	5.16	1.03	92.4
3:55	12.34	1.19	88.8
4:00	20.51	1.34	90.6
4:05	27.95	1.39	89.3
4:10	36.97	1.49	88.3
4:15	47.51	1.62	88.8
4:20	57.41	1.68	88.6
4:25	68.72	1.75	88.7
4:30	78.67	1.78	87.5
4:35	90.53	1.83	88.2
4:40	102.22	1.88	88.1
4:45	111.53	1.87	88.3
4:50	121.20	1.88	88.1
4:55	130.18	1.88	87.7
5:00	140.87	1.90	87.6
5:05	150.53	1.90	87.6
5:10	158.47	1.89	86.8
5:15	167.43	1.89	86.7

Table 5.10. (Cont.)

c. OPAC

Time (PM)	Accumulated total delay (veh-h)	Period delay per-veh-per-trip (min)	Period stop percentage (%)
3:50	6.21	1.14	90
3:55	13.09	1.16	90
4:00	21.97	1.28	90
4:05	31.75	1.39	90
4:10	42.41	1.51	90
4:15	53.47	1.59	90
4:20	65.02	1.65	90
4:25	76.15	1.70	90
4:30	88.45	1.76	90
4:35	100.71	1.80	90
4:40	112.15	1.83	90
4:45	123.87	1.85	90
4:50	134.98	1.86	90
4:55	145.98	1.86	90
5:00	156.45	1.87	90
5:05	167.06	1.88	90
5:10	176.66	1.87	90
5:15	185.99	1.87	90

Table 5.11. MOEs per 5-minute time period (Off-peak, random seed No. 0)

a. Pre-timed

Time (PM)	Accumulated total delay (veh-h)	Period delay per-veh-per-trip (min)	Period stop percentage (%)
7:35	1.85	0.53	65.4
7:40	3.61	0.54	66.6
7:45	5.54	0.54	67.6
7:50	7.67	0.56	69.2
7:55	9.61	0.55	69.3
8:00	11.53	0.55	68.9
8:05	13.63	0.56	69.0
8:10	15.58	0.55	69.3
8:15	17.50	0.55	69.1
8:20	19.59	0.56	69.1
8:25	22.38	0.57	69.9
8:30	25.68	0.59	71.2
8:35	28.32	0.59	71.5
8:40	30.66	0.60	71.9
8:45	32.73	0.59	71.6
8:50	34.70	0.59	71.3
8:55	36.82	0.59	71.3
9:00	38.62	0.59	71.2

Table 5.11. (Cont.)

b. Actuated

Time (PM)	Accumulated total delay (veh-h)	Period delay per-veh-per-trip (min)	Period stop percentage (%)
7:35	1.80	0.51	68.1
7:40	3.35	0.49	69.1
7:45	5.28	0.52	69.6
7:50	7.32	0.53	69.9
7:55	9.17	0.53	69.2
8:00	10.95	0.52	68.5
8:05	12.82	0.52	69.2
8:10	14.93	0.53	70.1
8:15	16.83	0.53	70.3
8:20	18.82	0.54	70.6
8:25	21.60	0.55	71.5
8:30	25.14	0.57	71.8
8:35	27.89	0.58	72.4
8:40	30.06	0.59	72.5
8:45	32.24	0.59	72.2
8:50	34.31	0.59	72.3
8:55	36.55	0.59	72.3
9:00	38.36	0.59	72.2

Table 5.11. (Cont.)

c. OPAC

Time (PM)	Accumulated total delay (veh-h)	Period delay per-veh-per-trip (min)	Period stop percentage (%)
7:35	11.88	0.55	70
7:40	33.57	0.53	70
7:45	55.30	0.52	70
7:50	77.29	0.53	70
7:55	99.21	0.53	70
8:00	11.11	0.54	70
8:05	13.12	0.54	70
8:10	15.03	0.54	70
8:15	16.99	0.54	70
8:20	18.86	0.54	70
8:25	21.49	0.54	70
8:30	24.31	0.55	70
8:35	26.35	0.55	70
8:40	38.29	0.55	70
8:45	30.53	0.55	70
8:50	32.33	0.55	70
8:55	34.30	0.55	70
9:00	35.88	0.55	70

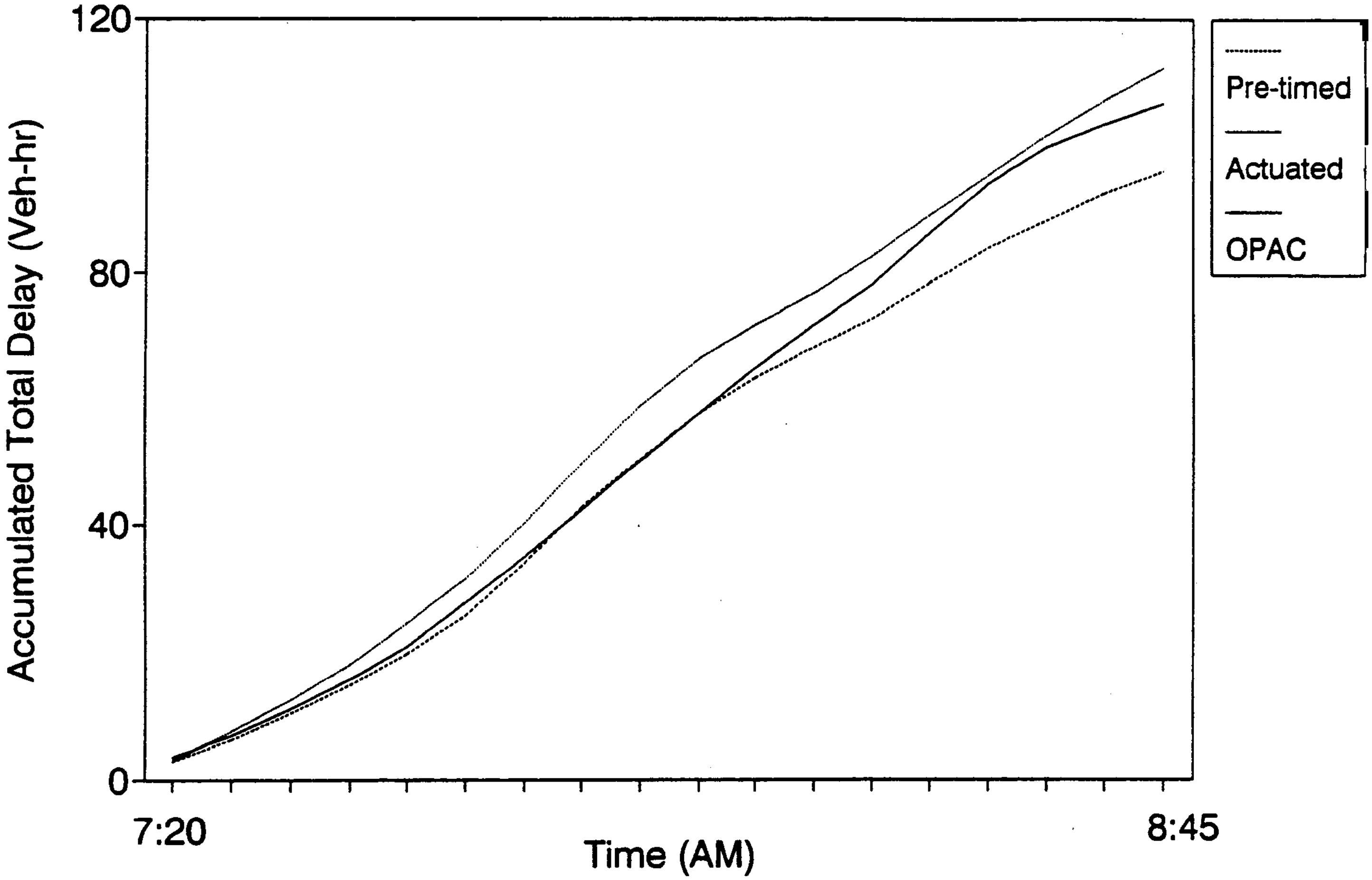


Fig. 5.13 Accumulated Total Delay Comparison (AM-peak)

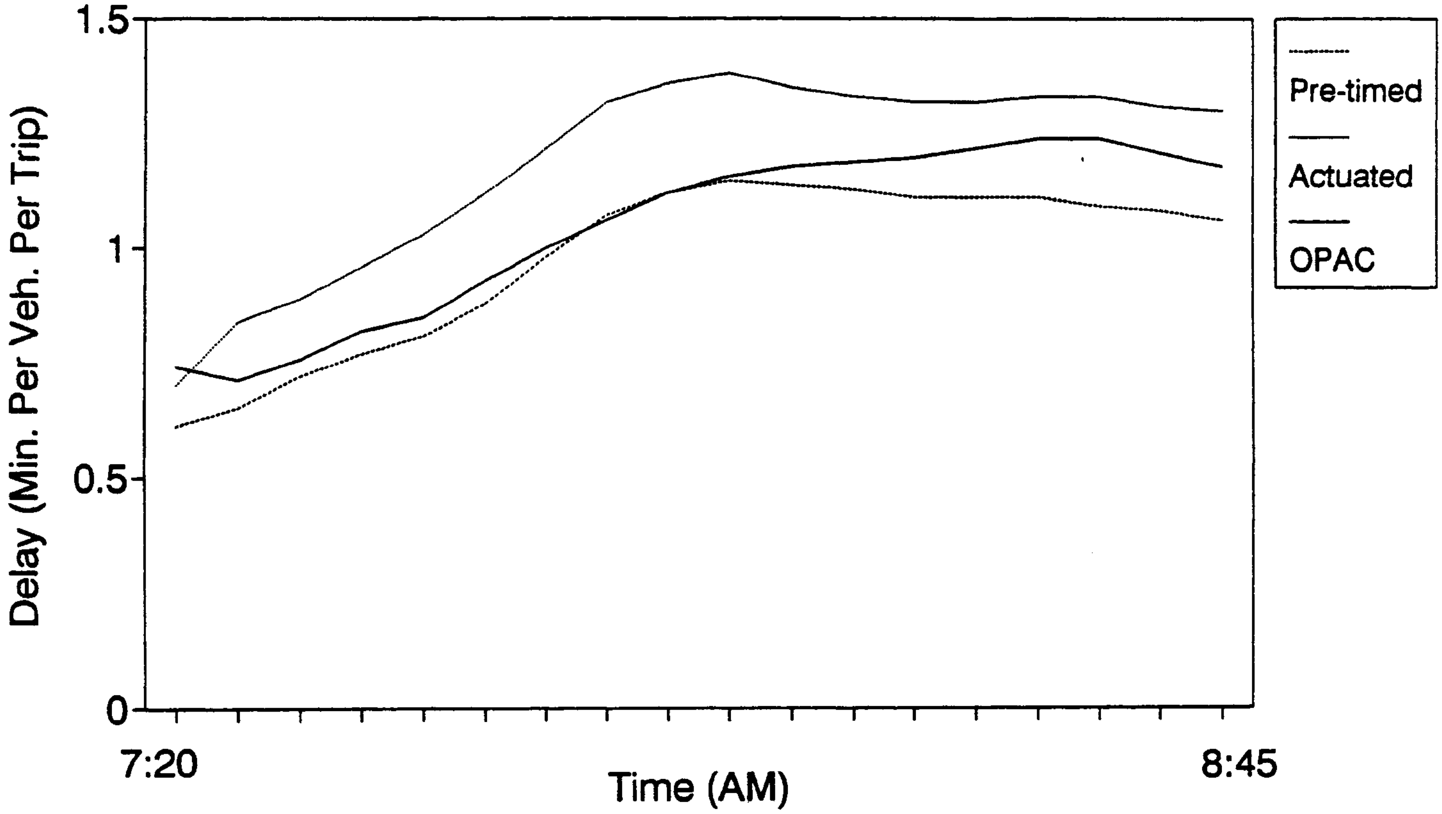


Fig. 5.14 Period Delay Comparison (AM-peak)

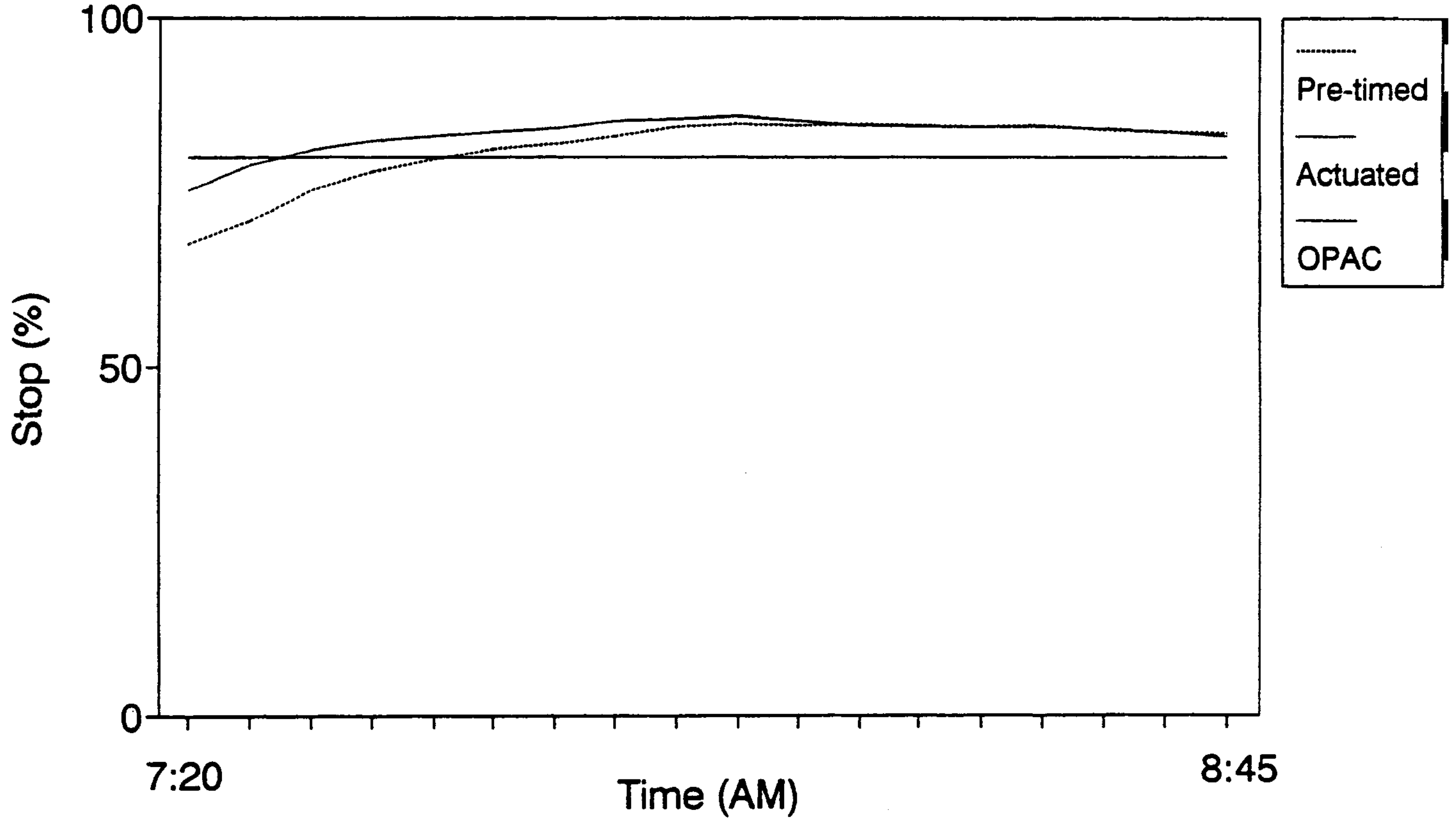


Fig. 5.15 Period Stop Percentage Comparison (AM-peak)

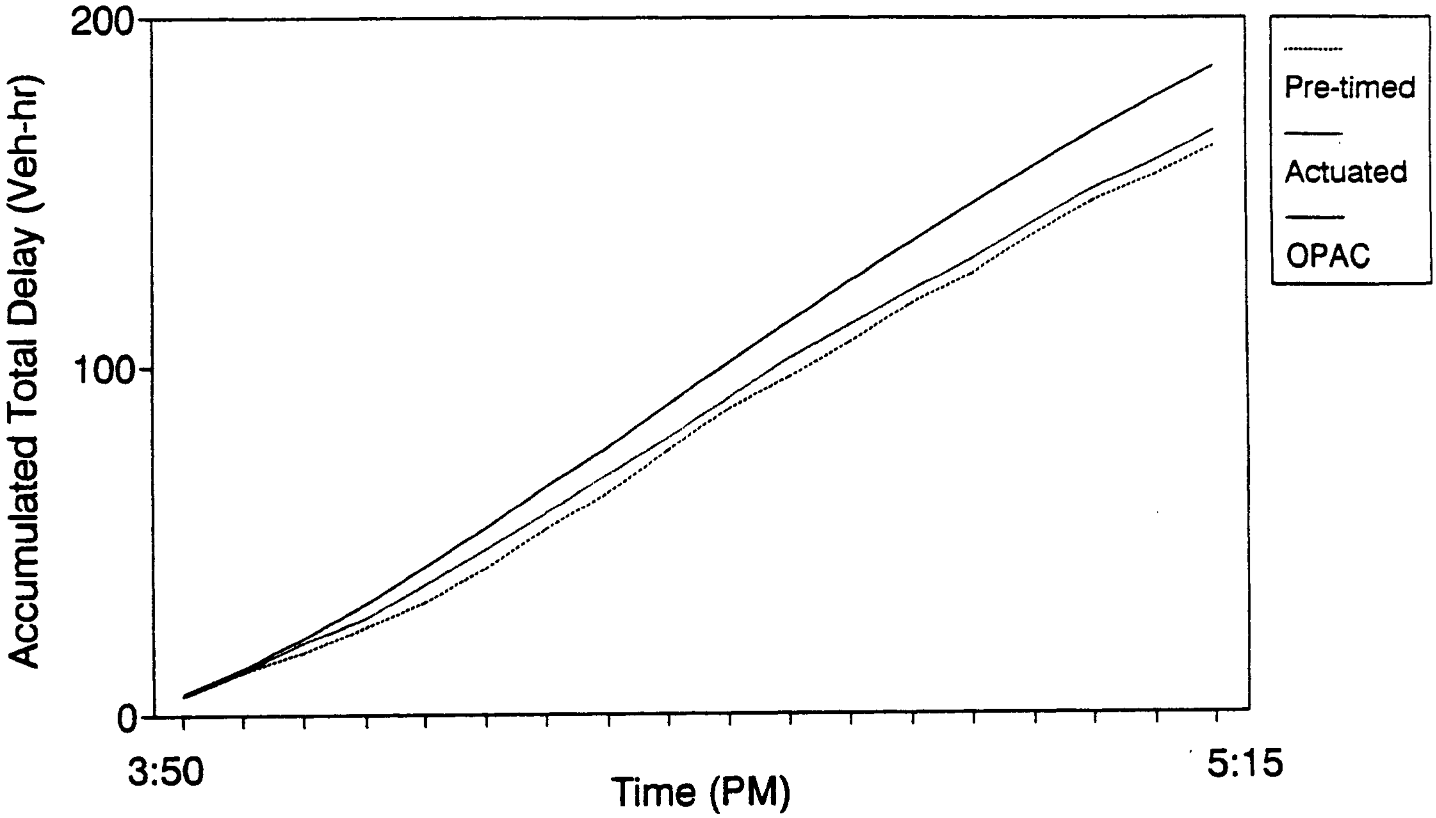


Fig. 5.16 Accumulated Total Delay Comparison (PM-peak)

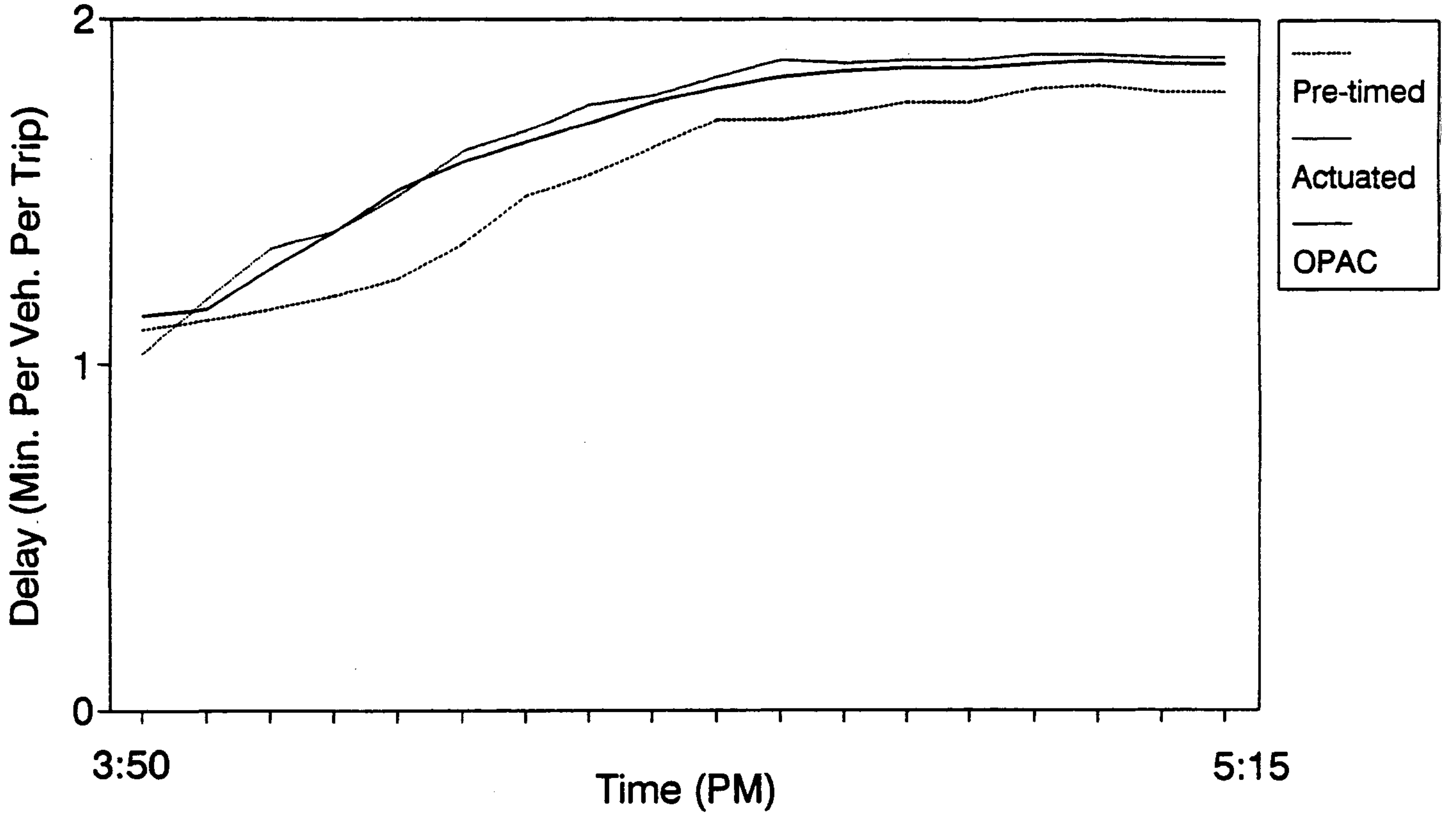


Fig. 5.17 Period Delay Comparison (PM-peak).

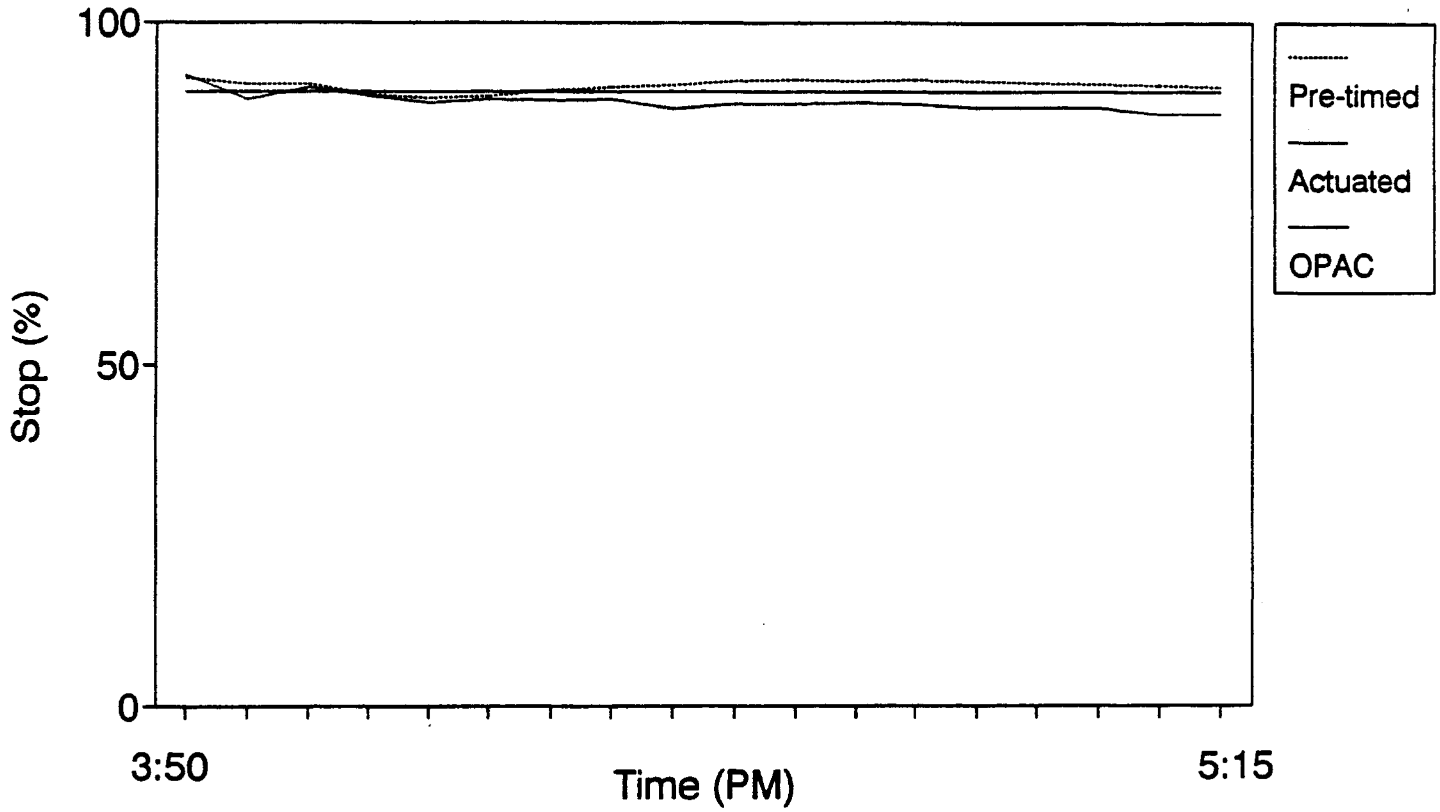


Fig. 5.18 Period Stop Percentage Comparison (PM-peak)

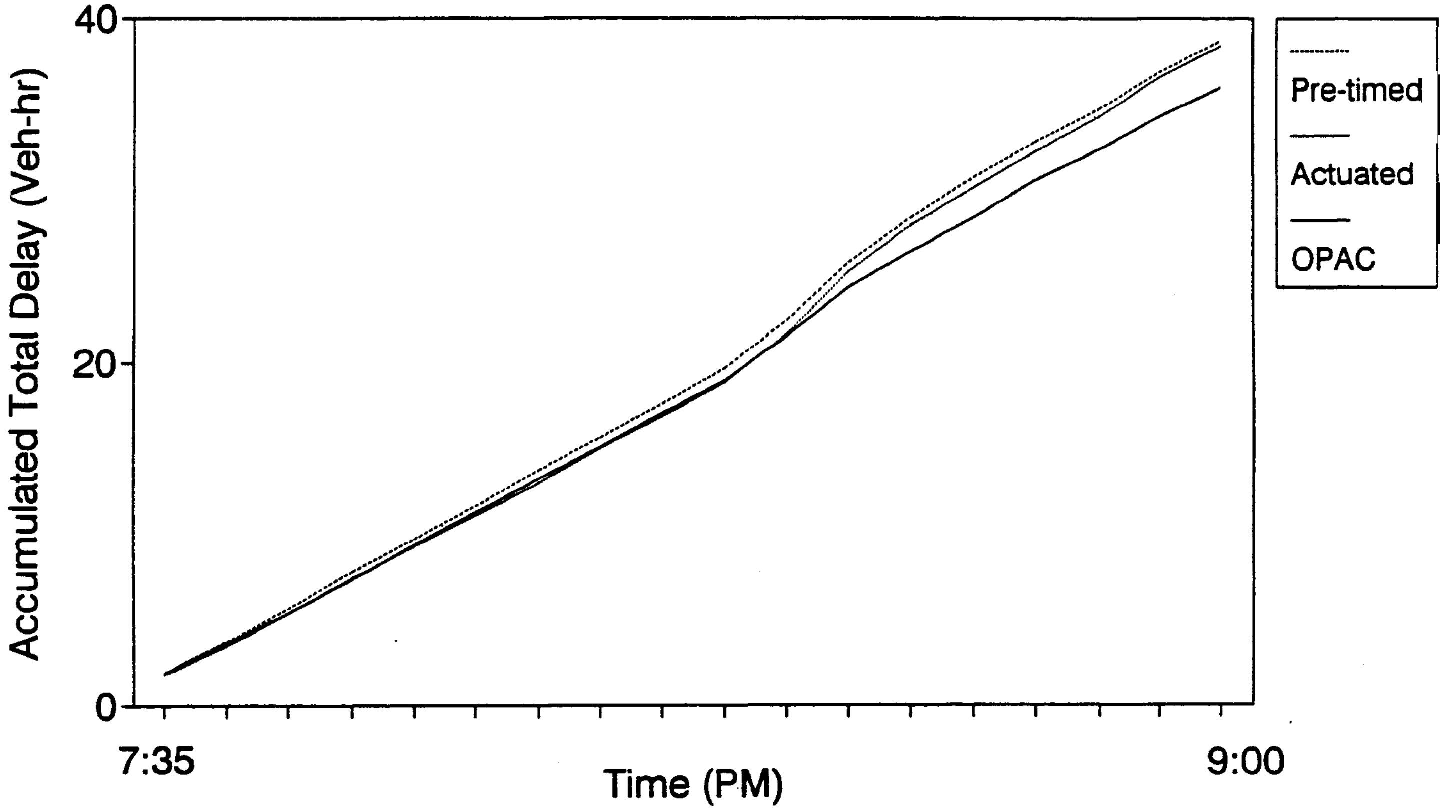


Fig. 5.19 Accumulated Total Delay Comparison (Off-peak)

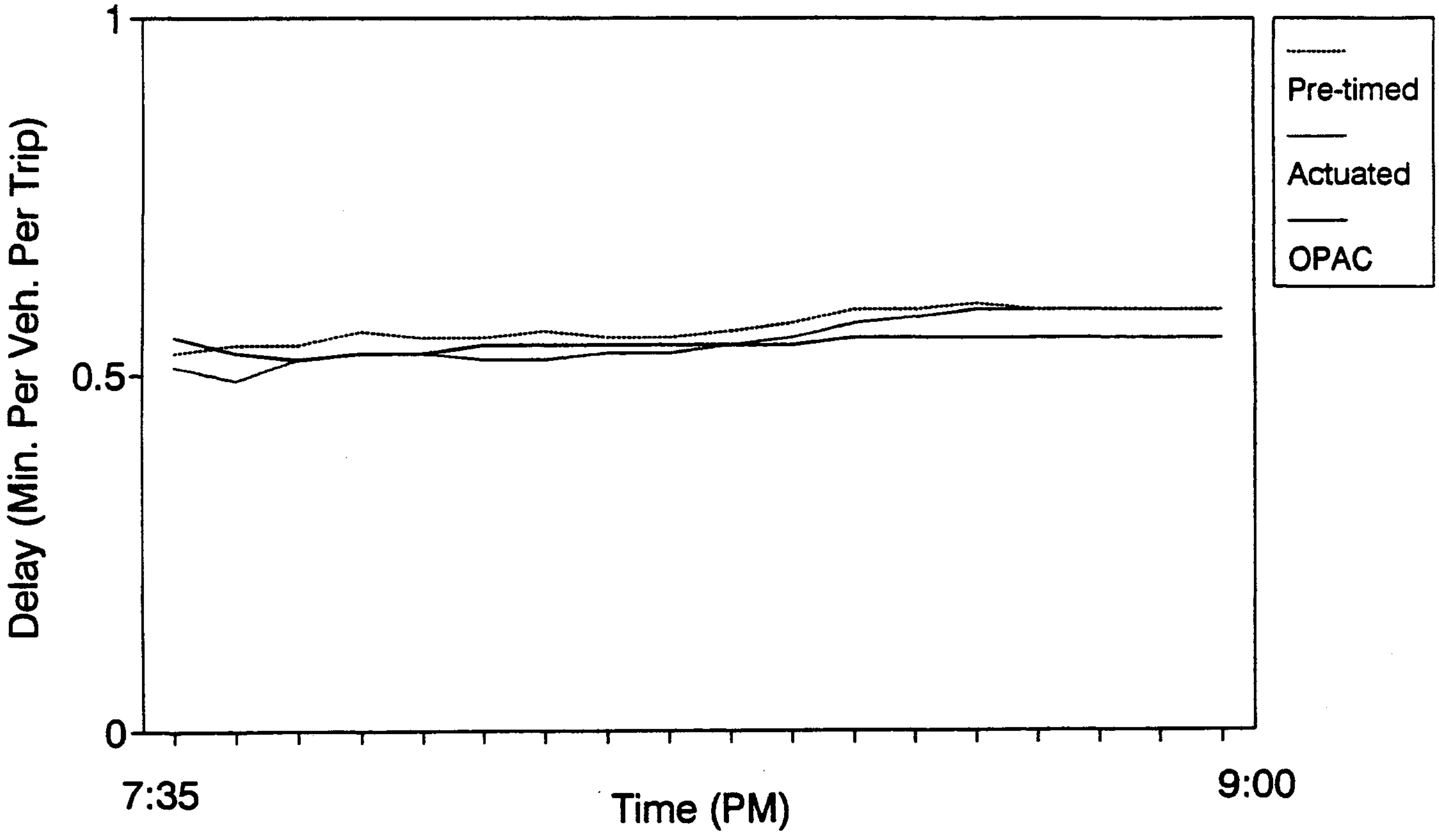


Fig. 5.20 Period Delay Comparison (Off-peak)

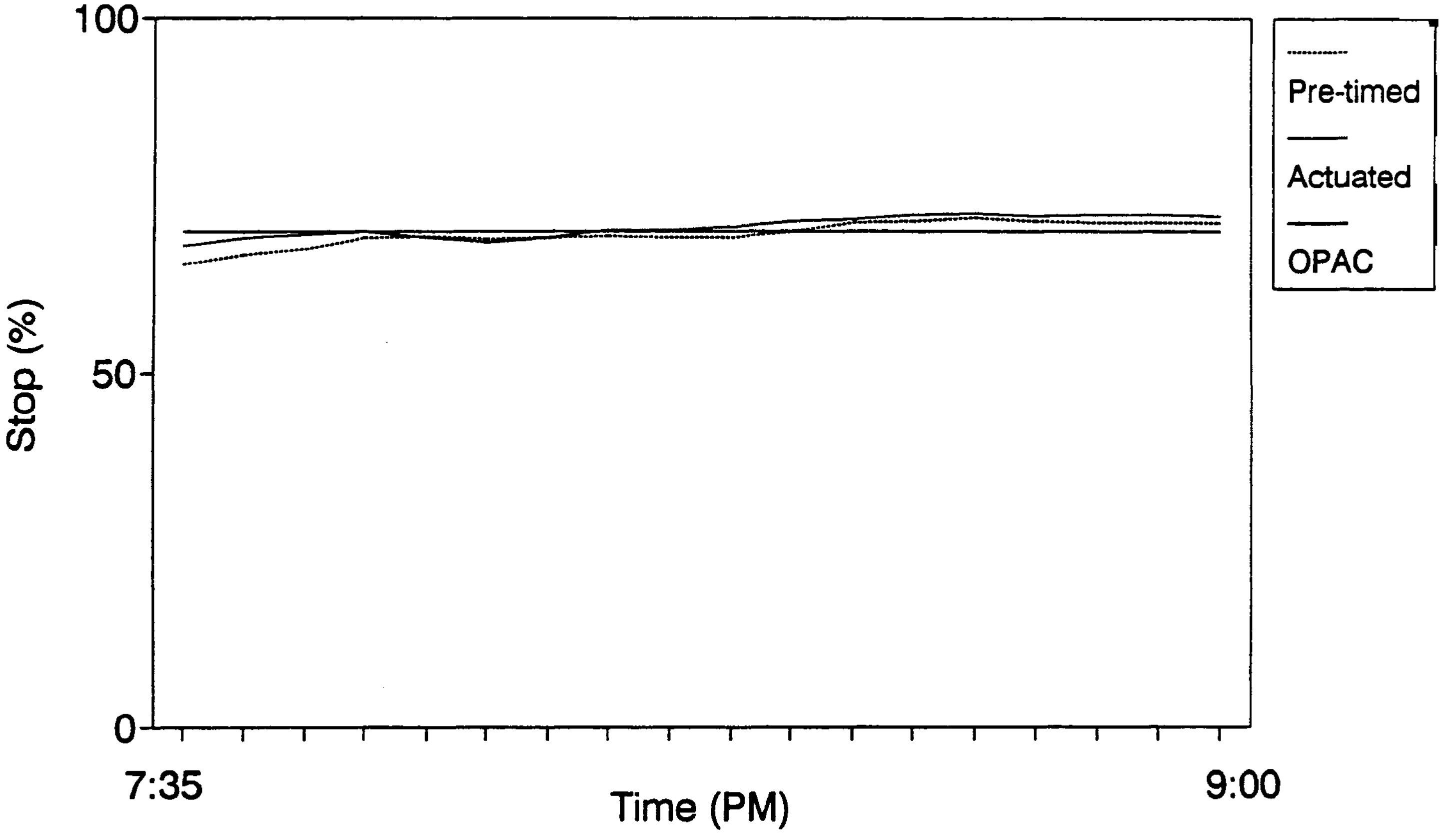


Fig. 5.21 Period Stop Percentage Comparison (Off-peak)

VI. INSTALLATION OF MACHINE-VISION DETECTION SYSTEM FOR DEVELOPMENT OF LIVE INTERSECTION LABORATORY

VI.1 Introduction

Testing new control strategies in a real traffic environment, and thus, refining the control schemes prior to full scale implementation is of critical importance in developing efficient and robust real-time control strategies. While evaluating new strategies off-line using simulation provides significant insights in terms of the performance of new control schemes, the inherent approximations in the traffic models embedded in a simulator and the random elements in traffic limit the effectiveness of off-line evaluation under a simulated environment. Developing a live intersection laboratory, where new control strategies can be tested with real traffic is one of the essential elements in developing comprehensive real time traffic management strategies.

The key element in developing such a live laboratory is a detection system that can support a wide range of control strategies by providing various types of traffic data from various locations. Although loop detectors permanently installed under the pavement have been commonly used in detecting traffic at intersections, their lack of flexibility in terms of detection location and type of available data significantly restricts their effectiveness as detection tool for the live laboratory. In this research, a machine-vision detection system is identified and installed at the intersection selected as the site for the live laboratory. The selected detection system, based on the machine-vision image processing technique, provides flexible detection capabilities without requiring the existence of any physical detector on a roadway. The rest of this chapter describes the laboratory site and installation of the machine-vision detection system.

VI.2 Selection of live laboratory site

The location of the live intersection laboratory was determined in consultation with the traffic engineers from the Minnesota Department of Transportation and the City of Minneapolis. Figure 6.1 shows the detailed layout of the selected intersection located at Franklin and Lyndale Avenues in downtown Minneapolis, Minnesota. This intersection is currently under pretimed control and has the following characteristics:

1) The traffic demand during peak hours is close to saturation flow and this results in frequent congestion and delays.

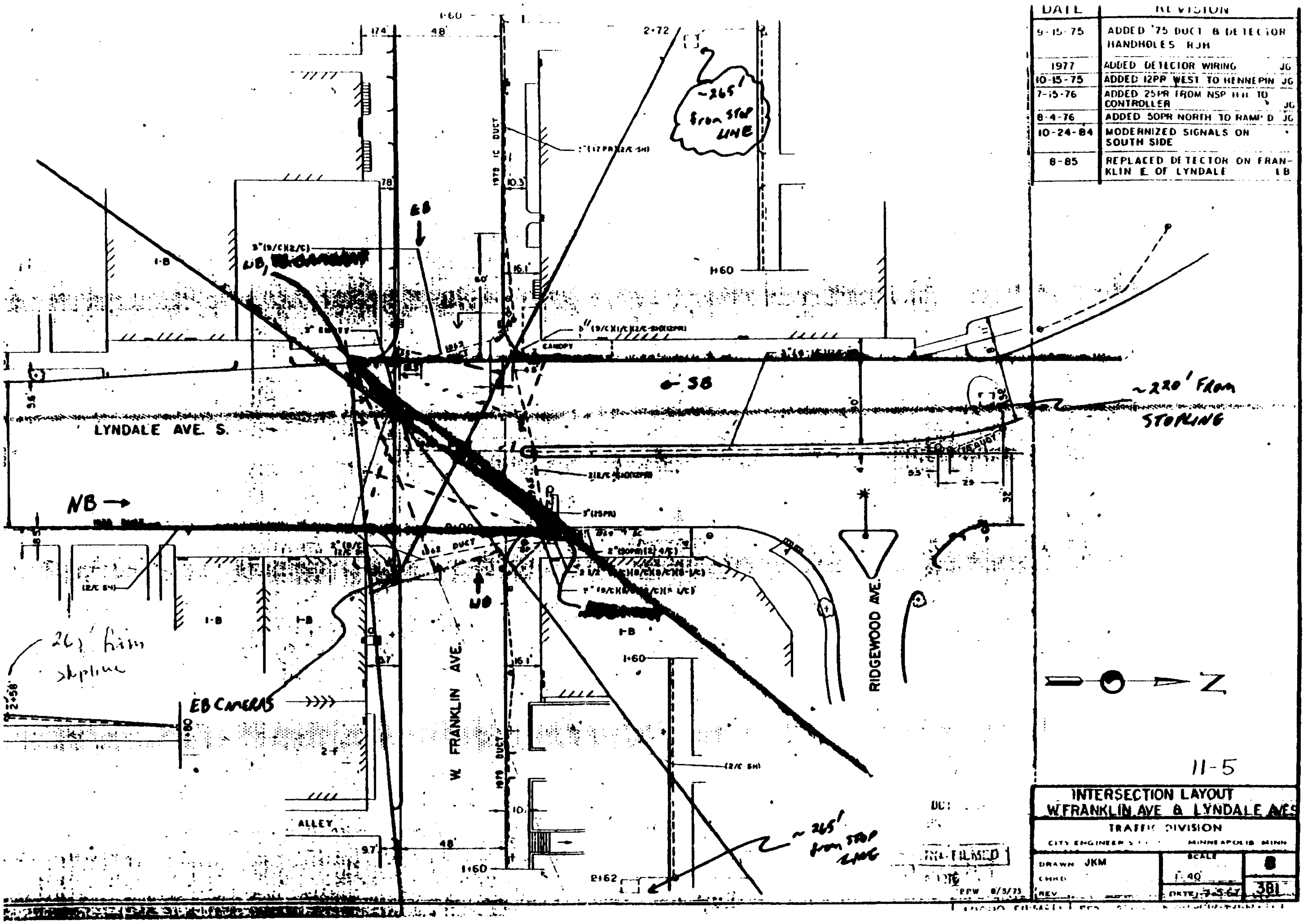


Figure 6.1 Camera location at intersection laboratory

2) The location and distance of the intersection from the adjacent intersections make it possible to operate it as an isolated intersection, but it can be easily incorporated into coordinated network control.
3) The incident rate at the intersection proper is relatively high, and this can provide valuable data for future development of intersection incident detection strategies.

VI.3 Development of machine-vision detection system requirements

In this section, a generic technical specification for a machine-vision, video detection system to be installed at the live laboratory is developed by incorporating future detection needs of new control strategies as much as possible. Since the detection requirements can vary depending on the specific needs of the control strategies to be tested in the laboratory, it is important to define basic functional requirements of the machine-vision system to meet as many future detection needs as possible. The technical specification developed in this section covers various requirements including real-time vehicle detection, measured or derived traffic parameters, electrical and environmental performance of hardware, software capabilities, camera and interface requirements. The specification is attached in Appendix B.

VI.4 Purchase and installation of machine-vision detection system

Based on the technical specification developed in the previous section, a machine-vision detection system was purchased through an open bid process. The selected system can handle up to six cameras; to date, only four cameras have been installed and these cover four approaches at the intersection laboratory. The locations of the cameras were determined at a joint meeting by personnel from the University of Minnesota, City of Minneapolis and the vendor in January, 1993, after a visit to the site. In determining the location of each camera, special attention was given to the following:
1) Existing poles or other structures upon which cameras might be mounted.
2) Location of control cabinet that will house the machine-vision detection system.
3) Obstructions that might block the field of camera view.
Further, several video tapes were recorded and reviewed at various positions using the signal pole from a bucket truck before the location of each camera was determined. The final camera locations determined for each approach are as follows:

Southbound Lyndale and westbound Franklin

The cameras were to be mounted on pole extensions added to the signal poles. The cameras for the southbound Lyndale and westbound Franklin approaches were mounted on the same pole at the southeast corner of the intersection. Existing power lines prohibit the use of the poles located at the northwest corner.

Eastbound Franklin

The camera to cover eastbound Franklin was mounted on an extension pole located at the southeast corner.

Northbound Lyndale

The camera for northbound Lyndale could be ideally located at the northeast corner power pole. However, to avoid mounting on power poles, it was decided to install the camera on a 9' luminaire arm mounted to an extension pole above the existing signal pole. The camera was positioned to minimize obstruction by the power lines in the field of view.

While the above locations were identified as the best locations under the current circumstances, it is recommended that, in the future phase, more cameras be added to cover the full intersection and the upstream southbound Lyndale approach (currently, only 200 feet from the stopline can be covered because of the bend in the roadway).

The four cameras and detection system were installed in February, 1994, by the traffic engineers of the City of Minneapolis. Figure 6.1 shows the camera location and the field of view of each camera installed at the intersection laboratory.

VI.5 Summary

Developing a live intersection laboratory where new control strategies can be tested and refined in a real traffic environment prior to full scale implementation is of critical importance in developing efficient real time control strategies. The key element in developing such a live laboratory is a traffic detection system that can provide a variety of data from various locations, so that new control strategies can be implemented and evaluated. This chapter described the installation of a machine-vision detection system at the intersectionselected as the site for the live intersection laboratory. A generic technical specification to select a machine-vision detection system was developed and a machine-vision detection system was selected. The installation of the cameras and the machine-vision system was conducted by the traffic engineers in the City of Minneapolis, and the location of each camera was determined in consultation with the traffic engineers from the City of Minneapolis and the University of Minnesota. The data collected from the machine-vision detection system will be used to analyze the performance of the intersection in the current phase, and a comprehensive operational plan for the live laboratory will be developed in the next phase.

VII. EVALUATION OF TRAFFIC PERFORMANCE BASED ON MACHINE VISION

VII.1 Introduction

Intersection delay time is a well accepted indicator of performance of traffic management strategies at intersections. Using intersection delay as a performance indicator in "before" and "after" studies, traffic engineers can assess the effects of improvements such as changes in the road geometry, signal optimization, introduction of traffic control devices and other traffic management schemes. Intersection delay is particularly useful for evaluating the effectiveness of traffic control strategies, so that the most effective strategy can be implemented. Unfortunately, reliable estimates of delay at intersections are not easily available. Many MOE collection processes involve a great deal of tedious (and, therefore, error prone and expensive) manual labor. As a result, traffic performance monitoring is rarely carried out.

In this chapter, we propose a simple delay estimation algorithm that is used for traffic performance evaluation, and is tested with data collected by a machine vision system installed as part of this project (see Chapter VI). Description of data collection and analysis follow, including detector layout, traffic demand and turning movements. Finally, performance results under the current pre-timed control strategy are presented.

VII.2 Delay estimation algorithm [42]

The delay estimation algorithm is a discretized version of the standard input/output traffic model. This model defines a section of the roadway to be the current section of analysis. It monitors the number of vehicles that enter and exit the roadway segment in each lane and time slice, using the count detectors at upstream boundaries and stoplines.

Detectors do not provide continuous monitoring of traffic. Rather, at each time slice, each detector only provides the number of accumulated cars and average speed (if detector is a speed trap) in that time slice. Therefore, delay can only be estimated under the assumption of a certain distribution of the input and output in a time slice. In this study we assume the distributions of both input and output are Poisson. Delay per segment per time slice is defined as the difference between the total time that all vehicles occupy the segment and the time that the output vehicles would occupy the segment if they traversed it at the pre-defined free flow speed.

Let the length of roadway segment k be L_k, and denote the input (vehicles) to and output from that segment in time slice i by $I_{k,i}$ and $O_{k,i}$, respectively. By the end of time slice i $S_{k,i}$ (vehicles) are stored in the segment, and

$$S_{k,i} = I_{k,i} - O_{k,i-1}, + S_{k,i-1}, \quad 0 \leq S_{k,i} \leq S_{k,max}, \tag{1}$$

where $S_{k,max}$ is the maximum number of vehicles that segment k can store; it is calculated by assuming the segment is evenly spaced along the lane and an average effective vehicle length is 22 feet. This assumption is based on the statistical measurement of the length that a stopped vehicle occupies in a queue.

Therefore, delay $D_{k,i}$ in time slice i and segment k is calculated as follows, depending on the relative value of $O_{k,i}$ and $S_{k,i-1}$:

i) $O_{k,i} <= S_{k,i-1}$

$$D_{k,i} = O_{k,i} * T_s / 2 + (S_{k,i-1} - O_{k,i}) * T_s + I_{k,i} * T_s / 2 - O_{k,i} * T^F_k \tag{2}$$

where T_s is the length of the time slice and T^F_k is the time any vehicle takes to traverse segment k at the pre-defined free flow speed.

On the right hand side of equ. (2), the first term is the time that output vehicles ($O_{k,i}$) occupied the segment in this time slice; the second term is the time that vehicles which were stored at the previous time slice but still did not exit by the end of this time slice ($S_{k,i-1} - O_{k,i}$) occupied the segment in this time slice; the third term is the time that input vehicles ($I_{k,i}$) occupied the segment in this time slice; the last term is the time that output vehicles ($O_{k,i}$) would occupy the segment if they traversed it at the pre-defined free flow speed.

ii) $O_{k,i} > S_{k,i-1}$

$$D_{k,i} = S_{k,i-1} * T_s /2 + (O_{k,i} - S_{k,i-1}) * (L_k / V_{k,i}) +$$

$$(I_{k,i} + S_{k,i-1} - O_{k,i}) * T_s /2 - O_{k,i} * T^F_k \tag{3}$$

where $V_{k,i}$ is the average speed at which vehicles $O_{k,i} - S_{k,i-1}$ traversed the segment in the time slice.

On the right hand side of equ. (3), the first term is the time that vehicles that were stored at the previous time slice but exited in this time slice ($S_{k,i-1}$) occupied the segment in this time slice; the sencond term is the time that vehicles that entered and exited the segment in the time slice ($O_{k,i}$- $S_{k,i-1}$) occupied the segment in this time slice; the third term is the time that vehicles that have entered the segment but did not exit by the end of the time slice ($I_{k,i}$ + $S_{k,i-1}$ - $O_{k,i}$) occupied the segment in this time slice; and the last term is the same as the last term in equ. (2).

The total accumulated delay is

$$D = \sum_{k,i} D_{k,i} \ . \tag{4}$$

The delay estimation algorithm is sensitive to false detection and lane changes, since any estimation error will accumulate in the segment over time. These problems can be addressed by introducing appropriate bounds in equ. (1) if the traffic is frequently heavy; for instance, if the number of stopped vehicles is larger than the segment can store, the upper bound might be used to avoid the error accumulation. The worst case would occur in light traffic when the upper bound is not frequently used. One way to improve the estimation in light traffic is by checking the traffic signal status. If there is no output when the signal is green, the number of vehicles stored in a segment should be set to 0 to avoid error accumulation. Another way is by decreasing the segment length, in which case, the maximum number of vehicles the segment can store is small and the upper bound can be frequently used in light traffic. However, short segment length results in a large number of segments and a requirement for installation of a large number of detectors.

VII.3 Traffic data collection and analysis

VII.3.1 Machine-vision detector layout

The machine-vision detector layout at the intersection is given in Figures 7.1 to 7.4, and summarized in Appendix D. It was determined for the purposes of collecting traffic demand, measuring turning movements and obtaining accurate delay estimation, and was subject to the limitations of geometry and the number of detectors.

A total of 44 virtual detector stations have been installed. These include two directional detectors that detect the east- and westbound left-turn vehicles, 17 speed trap stations that detect the average speed of traffic every time slice, and 25 count detector stations that detect the traffic flow, turning movements, and the input and output of each road segment every time slice. The time slice is selected as 20 seconds; it cannot be shorter since

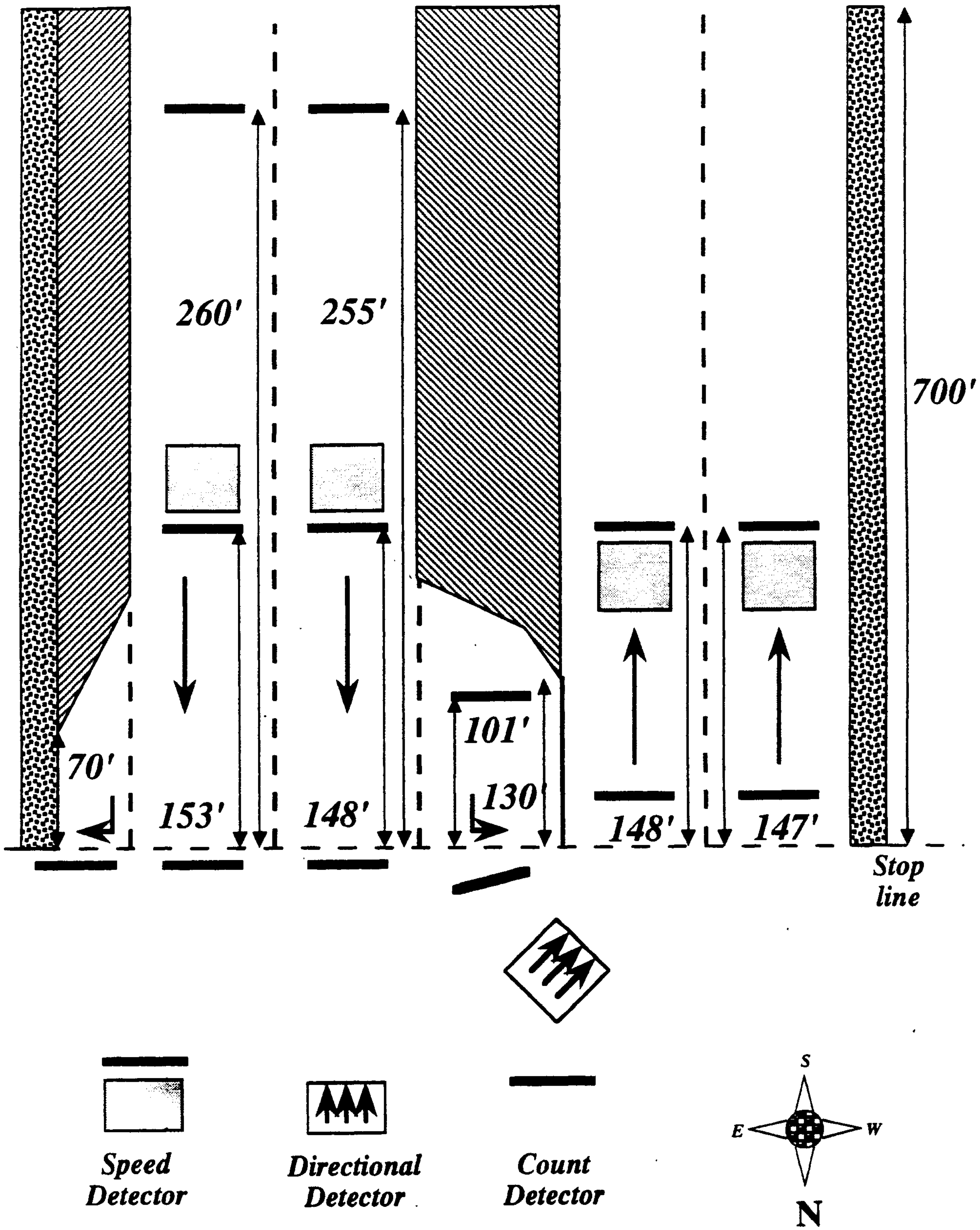


Figure 7.1 Northbound detector layout (not to scale).

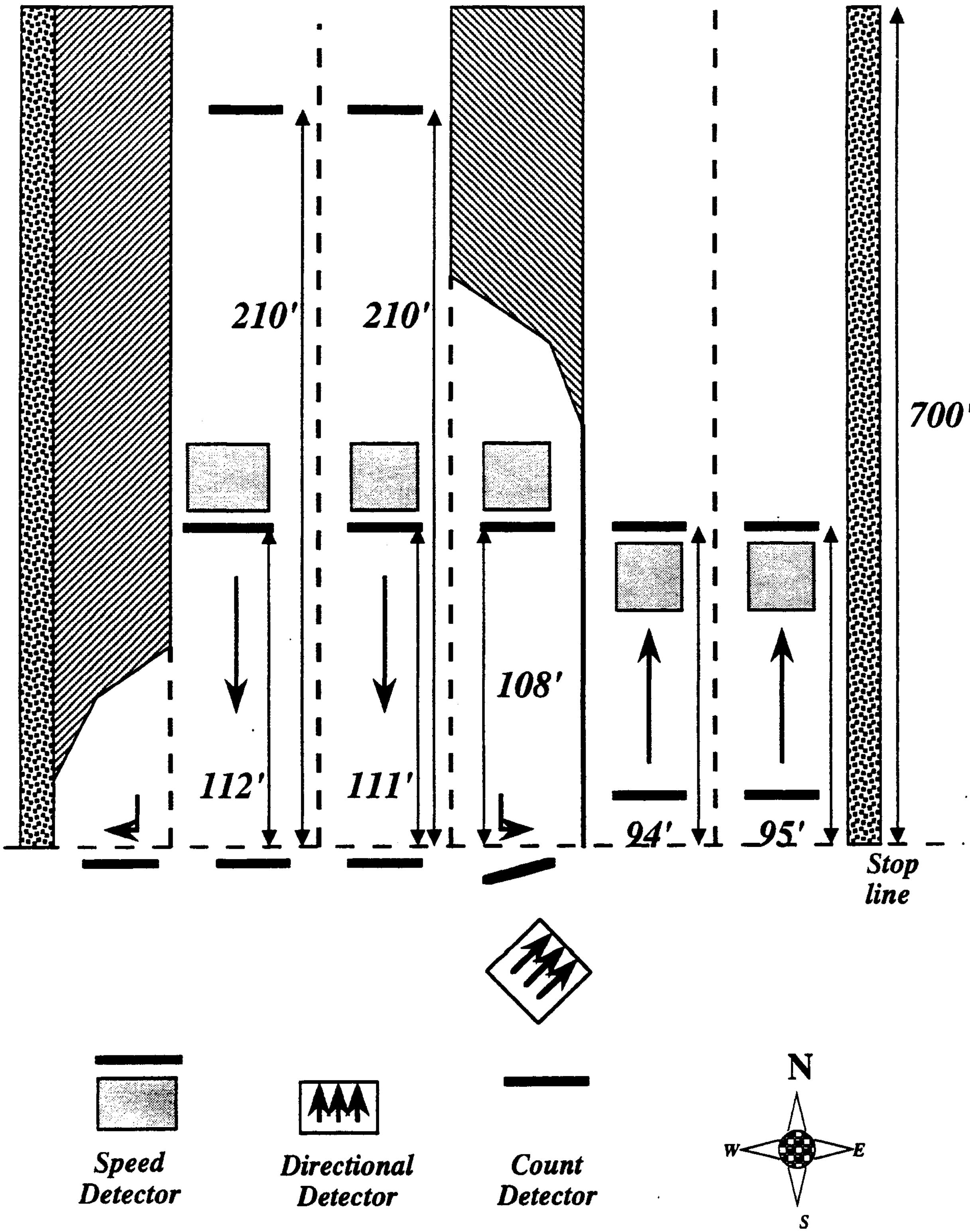


Figure 7.2 Southbound detector layout (not to scale).

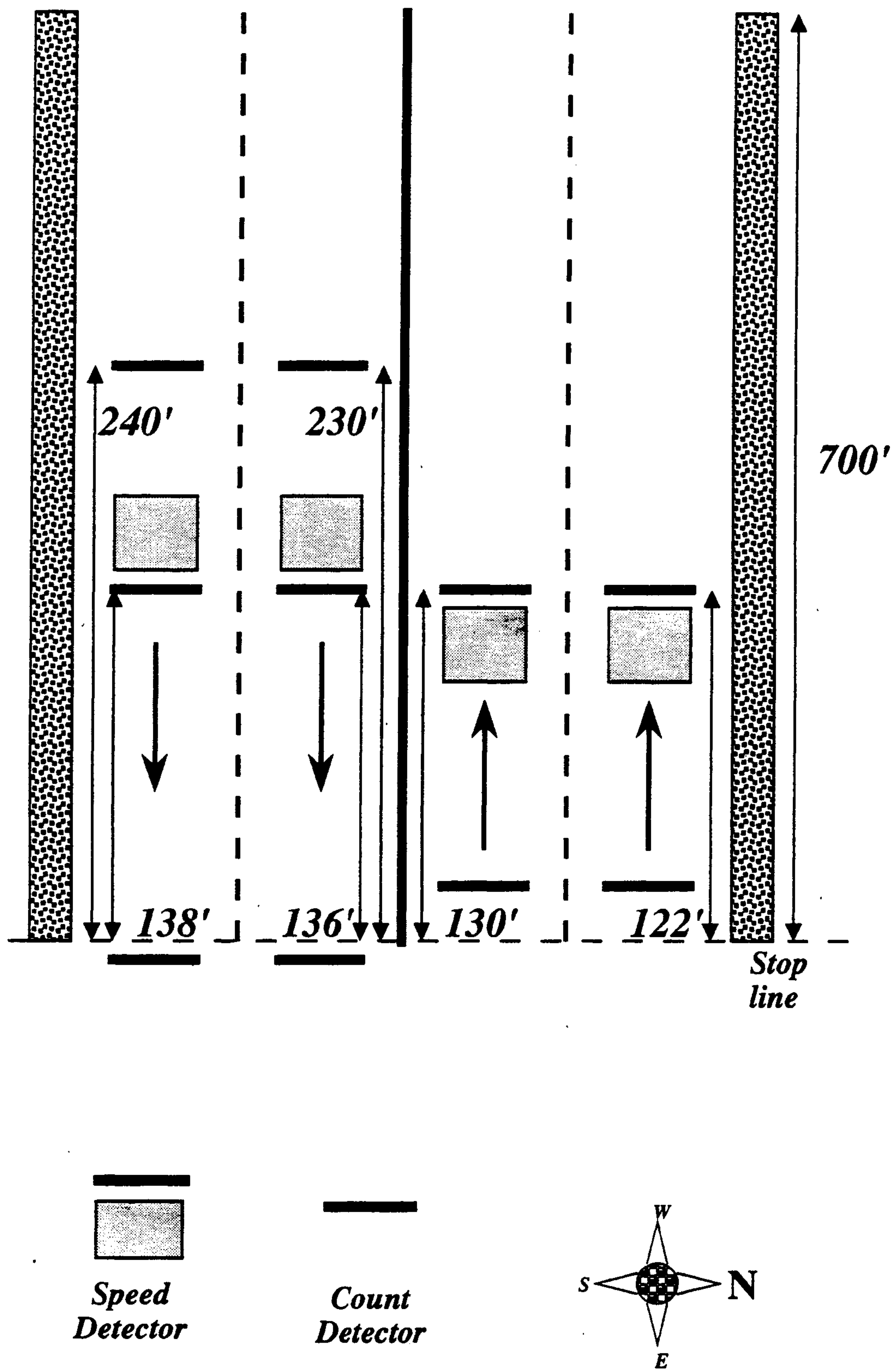


Figure 7.3 Eastbound detector layout (not to scale).

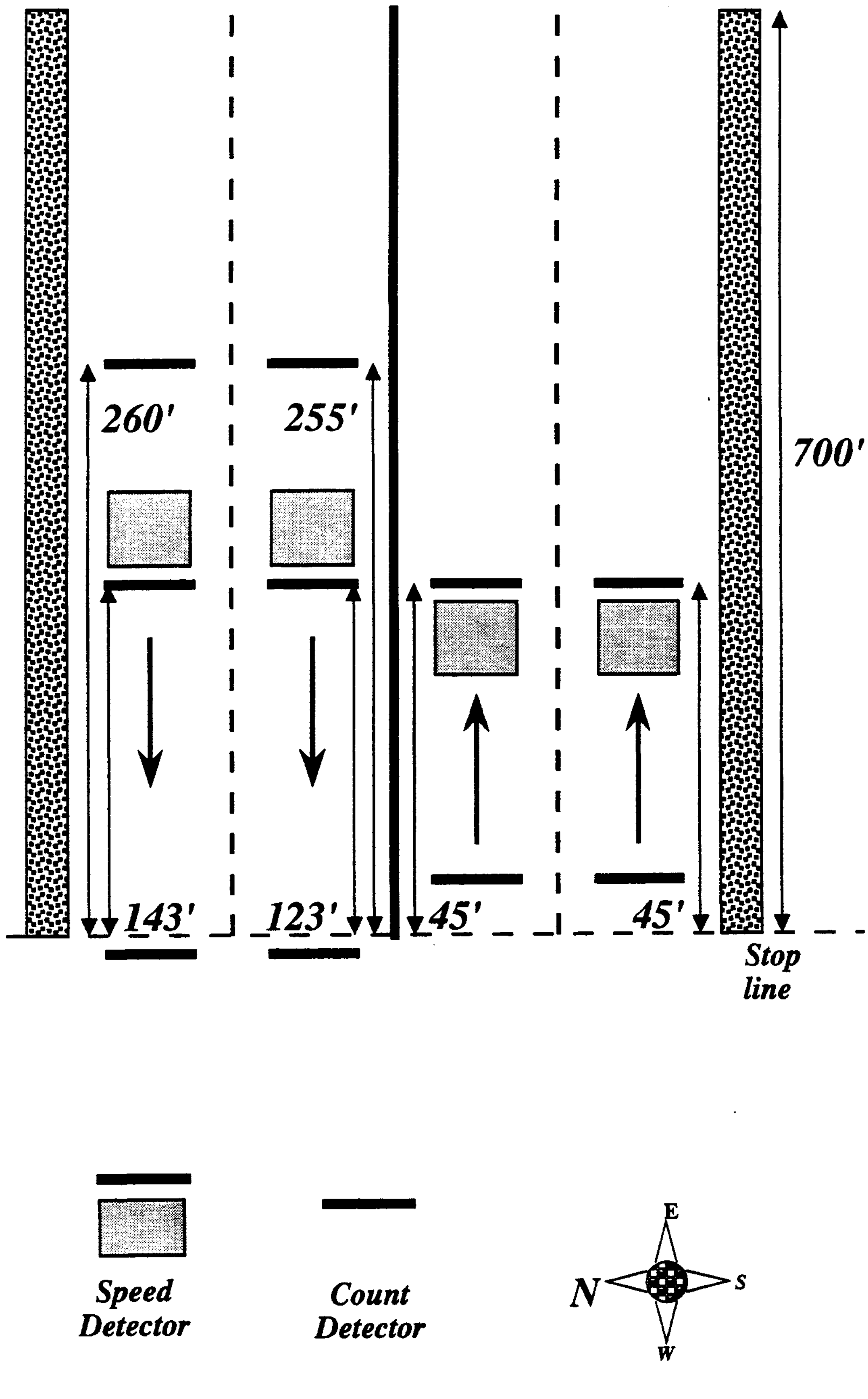


Figure 7.4 Westbound detector layout (not to scale).

Autoscope memory is limited and we have to collect traffic data for at least three hours before Autoscope memory is full.

At the intersection, each camera was mounted at a very small horizontal angle with respect to the approach it monitors, so that vehicles traveling in one lane do not actuate detectors in the adjacent one.

VII.3.2 Traffic flow and turning movements

The detector layout was finalized on April 14, 1994 after about two weeks of testing. Since April 15 data have been collected over three time periods on a daily basis on weekdays. These include AM-peak 6:00 - 9:00, off-peak 10:30 - 13:30, and PM-peak 15:30 - 18:30. As the city of Minneapolis is interested in the state of traffic within a two-hour period in each of the above three-hour periods, our analysis in this chapter is based on the data of AM-peak 6:30 - 8:30, off-peak 11:00 - 13:00, and PM-peak 16:00 - 18:00. A total of 15 sets of data were analyzed, three periods for each of 5 weekdays. The outputs from a typical count detector and a typical speed detector are shown in Figures 7.5 and 7.6, respectively.

For each of the 15 data sets, the traffic demand and turning movements of each approach are given in Tables 7.1 to 7.6. The average traffic demand and turning percentage of each approach are also included in Table 7.1 to 7.6 for each of the three periods. Further, the average turning percentage for each period is shown in Figures 7.8 to 7.10.

VII.4 Performance evaluation

We have applied the delay estimation algorithm to the analysis of the 15 sets of data described in the previous section. The evaluation results are summarized in Tables 7.7 to 7.10. Average accumulated delay for each approach in each of the three 2-hour periods is shown in Figure 7.11. Average delay per vehicle for each approach in each of the three periods is shown in Figure 7.12. Total intersection average accumulated delay and average delay per vehicle are also included in the tables and shown in the figures.

VII.4.1 AM-peak

As the results indicate, in the AM-peak period northbound average accumulated delay is slightly higher than southbound (Table 7.7), but northbound demand is substantially higher than southbound (Table 7.1). The reason is that southbound left-turn percentage is very high

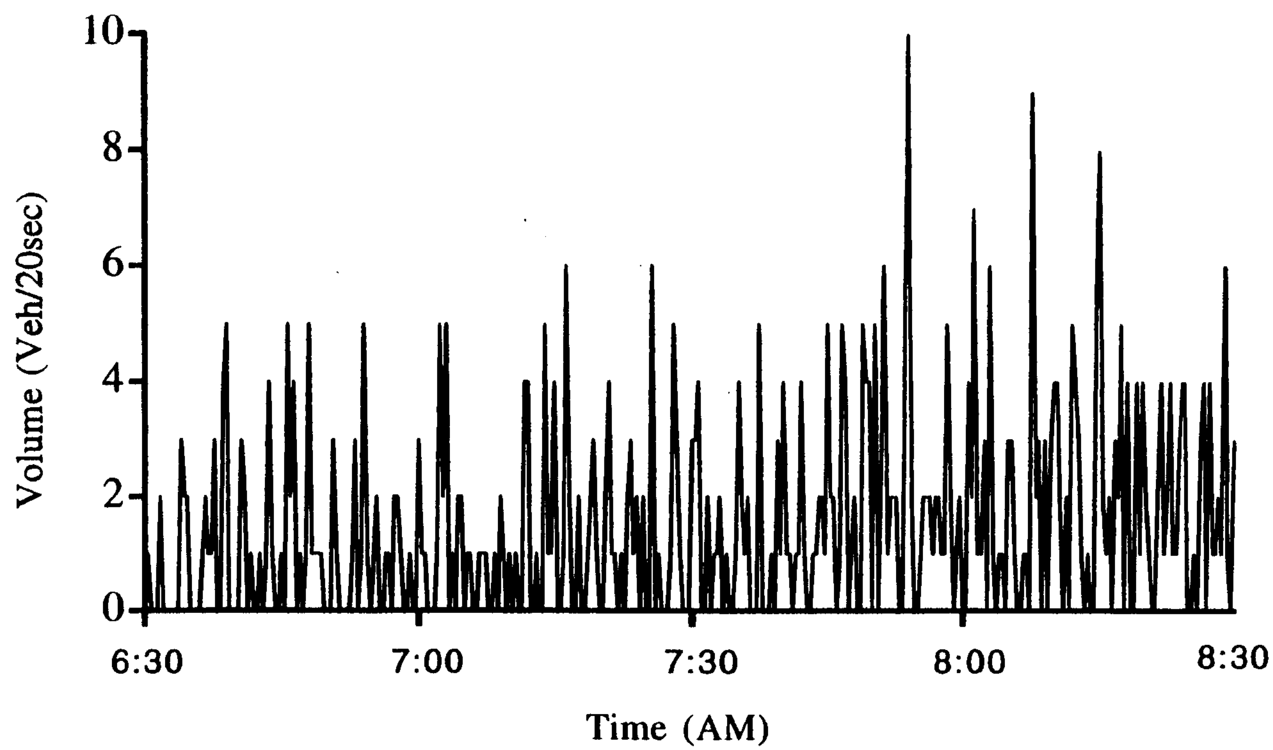


Fig. 7.5 Output from a southbound count detector

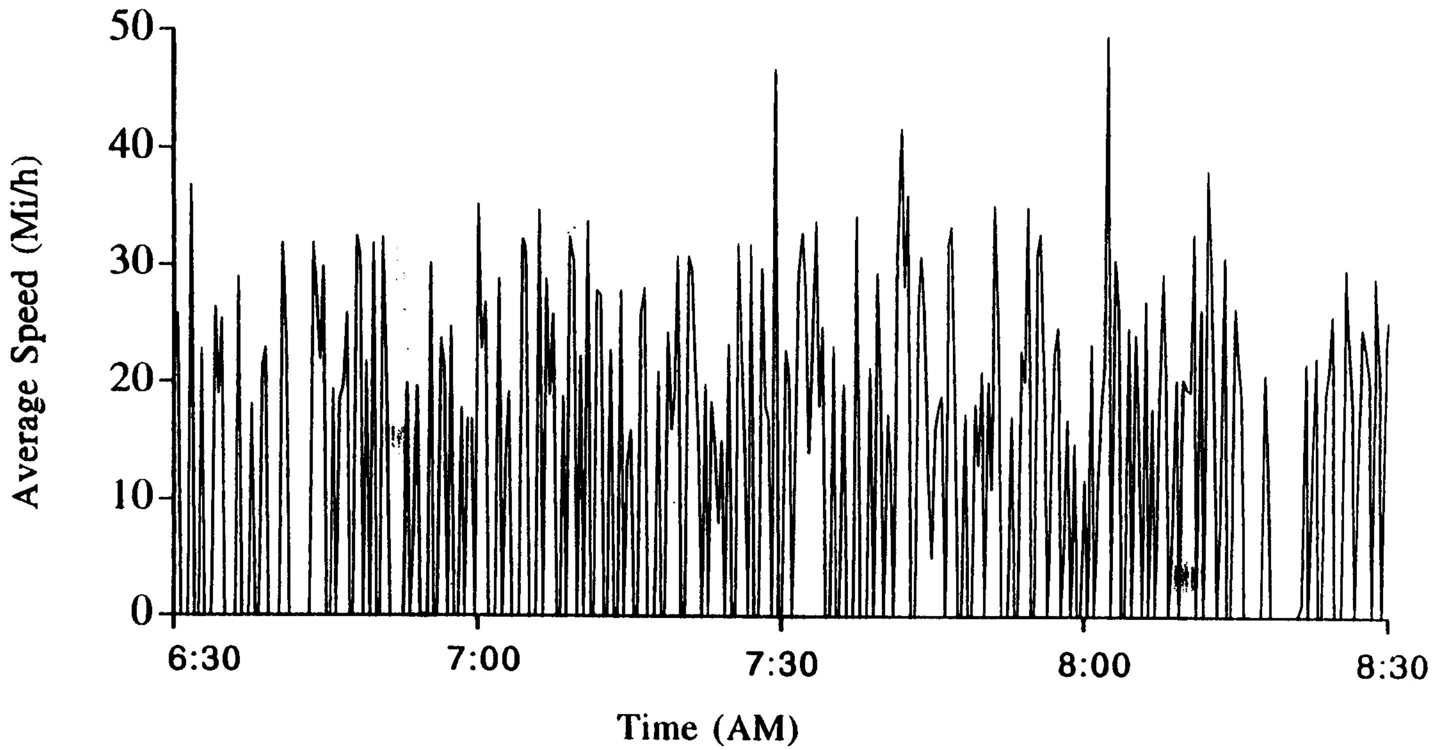


Fig. 7.6 Output from a southbound speed detector

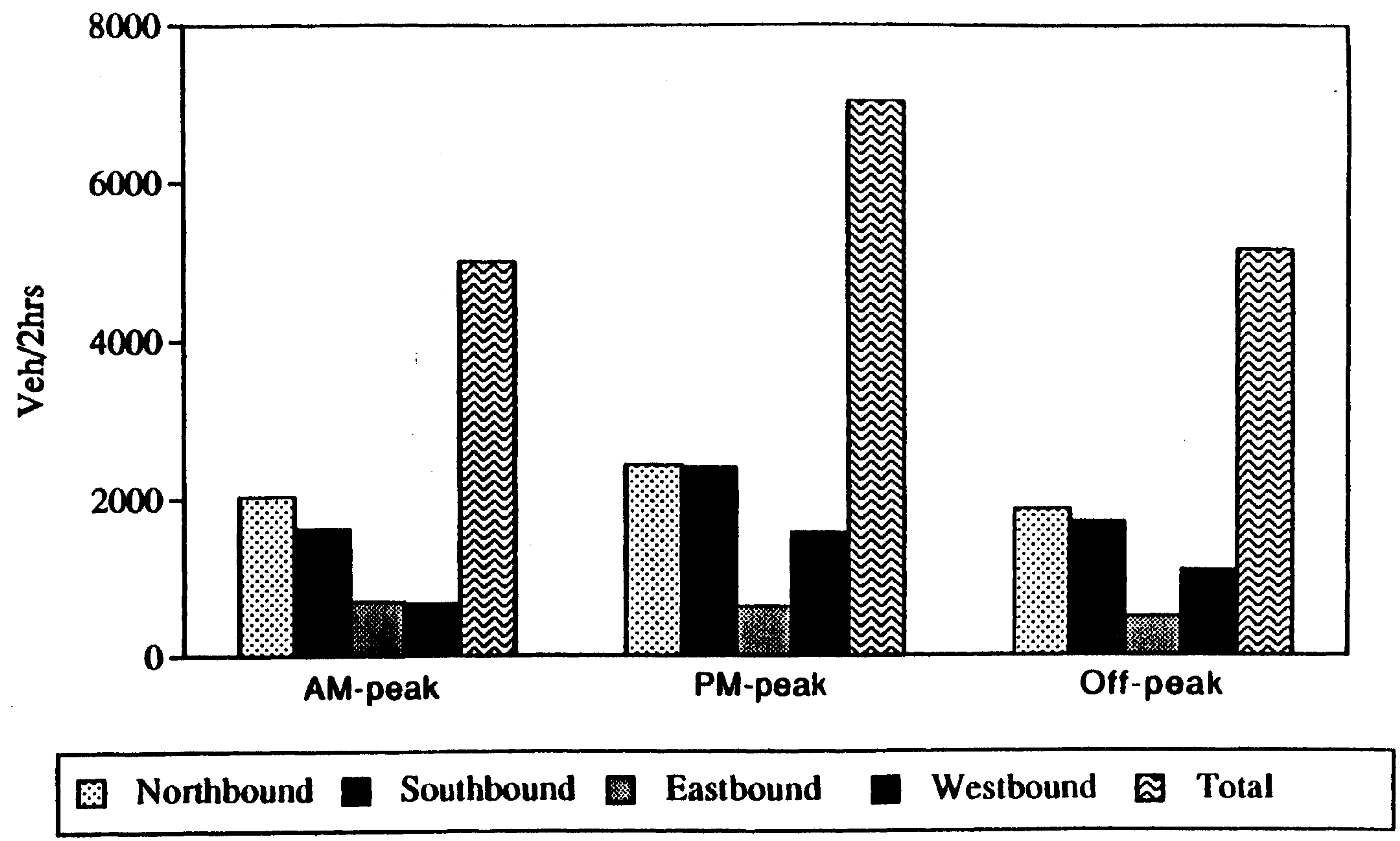


Figure 7.7 Average demand

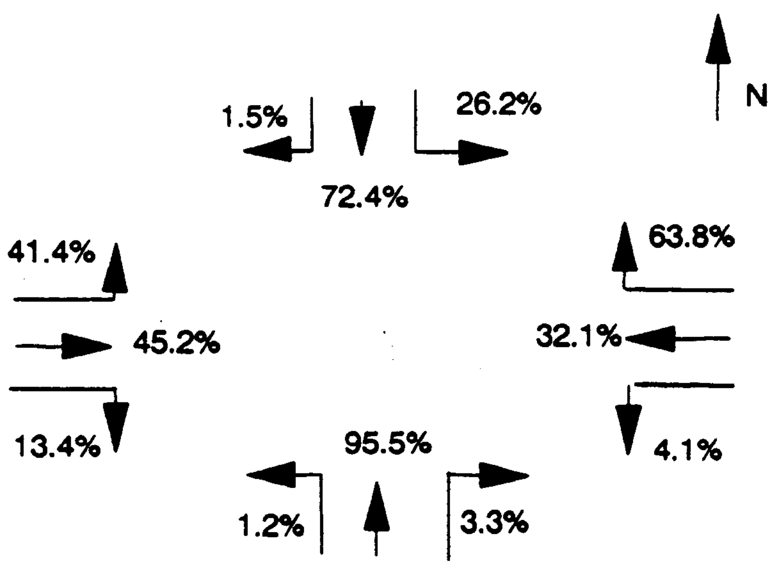


Fig. 7.8 Turning movements during AM-peak

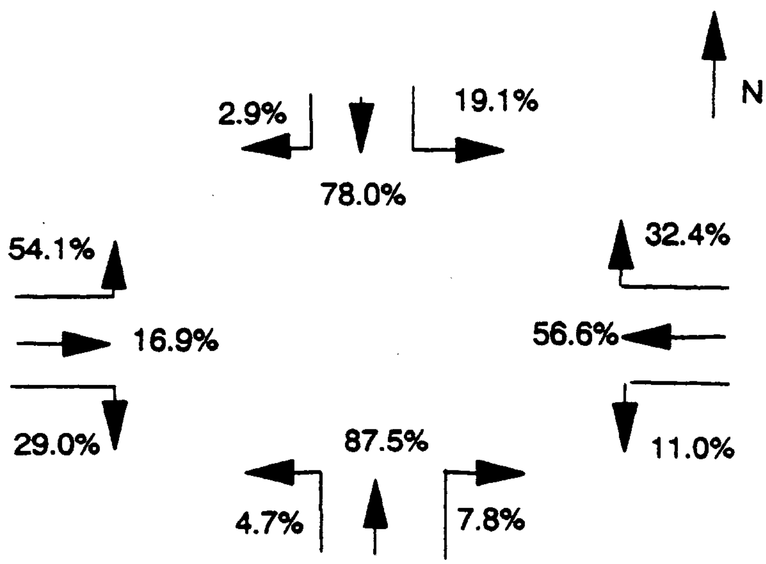


Fig. 7.9 Turning movements during PM-peak

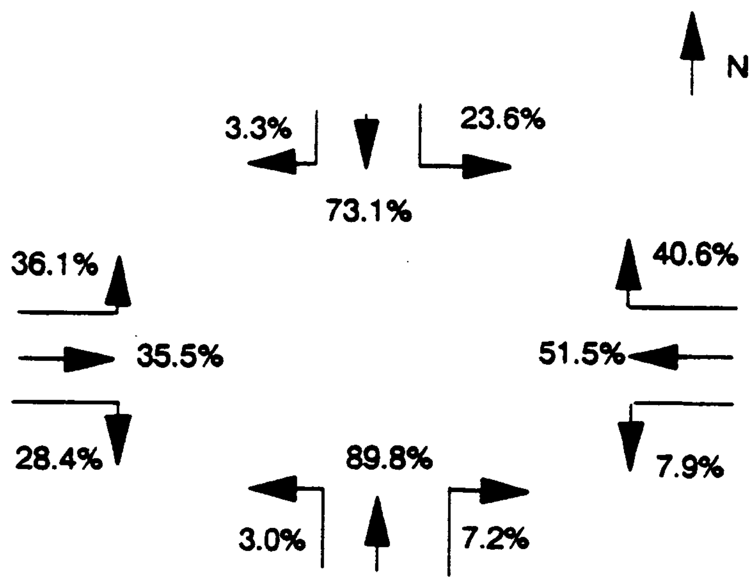


Fig. 7.10 Turning movements during Off-peak

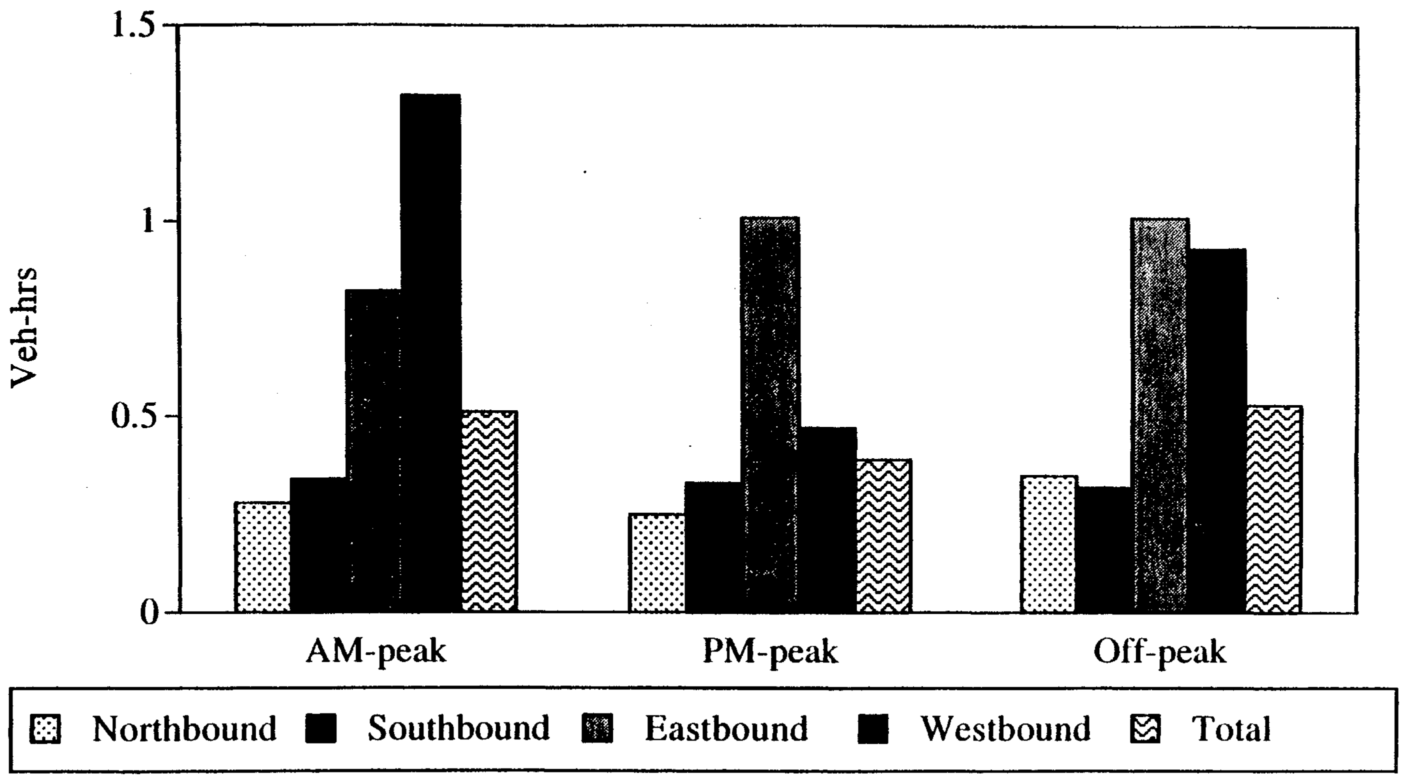


Figure 7.11 Accumulated delay

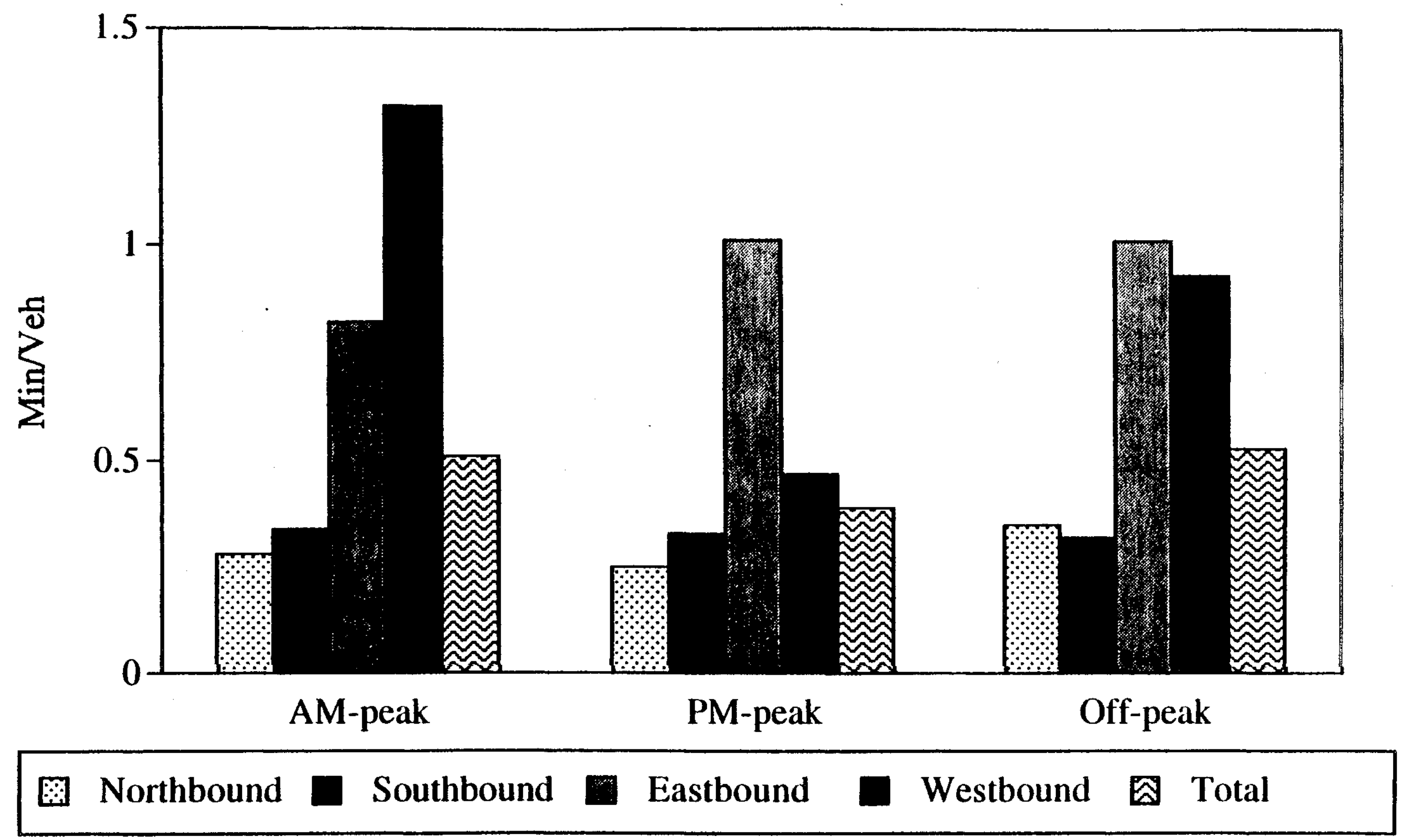


Figure 7.12 Average delay

Table 7.1 AM-Peak Demand (Vehicles/2hrs)

Date	Northbound	Southbound	Eastbound	Westbound	Total
4/21/94	2140	1642	682	605	5069
4/22/94	2071	1578	670	567	4886
4/25/94	1957	1592	655	736	4940
4/26/94	1971	1647	745	747	5110
4/27/94	2013	1650	672	671	5006
Average	2030	1622	685	665	5002

Table 7.2 PM-Peak Demand (Vehicles/2hrs)

Date	Northbound	Southbound	Eastbound	Westbound	Total
4/18/94	2679	2296	743	1597	7315
4/21/94	2457	2431	608	1701	7197
4/22/94	2584	2672	685	1698	7639
4/26/94	2189	2297	577	1516	6579
4/27/94	2235	2344	522	1380	6481
Average	2429	2408	627	1578	7042

Table 7.3 Off-Peak Demand (Vehicles/2hrs)

Date	Northbound	Southbound	Eastbound	Westbound	Total
4/18/94	1797	1735	513	1119	5164
4/21/94	1928	1756	490	1127	5301
4/22/94	1900	1723	523	1179	5325
4/26/94	1834	1680	465	1066	5045
4/27/94	1855	1638	460	986	4939
Average	1863	1706	490	1095	5155

Table 7.4 AM-Peak Turning Movements

Date	Northbound			Southbound			Eastbound			Westbound		
	Left	Through	Right	Left	Through	Right	Left	Through	Right	Left	Through	Right
4/21/94	25	2028	87	375	1237	30	402	214	66	25	179	401
4/22/94	34	1963	74	365	1183	30	371	228	71	33	124	410
4/25/94	20	1867	70	435	1137	20	323	256	76	28	286	422
4/26/94	19	1896	56	475	1148	24	356	305	84	30	277	440
4/27/94	23	1935	55	470	1163	17	303	284	85	20	201	450
Average	24	1937	68	424	1173	24	235	257	76	27	213	424
% of total	1.2	95.5	3.3	26.2	72.4	1.5	41.4	45.2	13.4	4.1	32.1	63.8

Table 7.5 PM-Peak Turning Movements

	Northbound			Southbound			Eastbound			Westbound		
Date	Left	Through	Right	Left	Through	Right	Left	Through	Right	Left	Through	Right
4/18/94	159	2218	302	437	1791	68	383	154	206	200	933	464
4/21/94	153	2116	188	515	1831	85	368	91	149	200	984	517
4/22/94	130	2255	199	489	2098	85	397	125	163	208	917	573
4/26/94	75	1977	137	437	1809	51	283	73	221	130	853	533
4/27/94	56	2054	125	421	1861	62	314	11	197	130	777	473
Average	114	2124	190	459	1878	70	349	109	187	173	892	512
% of total	4.7	87.5	7.8	19.1	78.0	2.9	54.1	16.9	29.0	11.0	56.6	32.4

Table 7.6 Off-Peak Turning Movements

	Northbound			Southbound			Eastbound			Westbound		
Date	Left	Through	Right	Left	Through	Right	Left	Through	Right	Left	Through	Right
4/18/94	55	1613	129	431	1245	59	182	193	138	80	587	452
4/21/94	58	1720	150	404	1306	46	185	174	131	98	588	441
4/22/94	60	1708	132	412	1249	62	190	182	151	93	607	479
4/26/94	62	1648	124	384	1238	58	170	173	173	77	546	443
4/27/94	44	1668	143	382	1197	59	177	163	120	83	496	407
Average	55	1671	135	402	1247	56	180	177	142	86	564	444
% of total	3.0	89.8	7.2	23.6	73.1	3.3	36.1	35.5	28.4	7.9	51.5	40.6

Table 7.7 AM-Peak Total Delay (Veh-hrs)

Date	Northbound	Southbound	Eastbound	Westbound	Total
4/21/94	8.74	7.85	9.54	11.36	37.48
4/22/94	8.98	7.96	9.31	15.93	42.18
4/25/94	5.98	10.87	8.33	14.60	39.78
4/26/94	9.76	8.80	8.54	15.81	42.91
4/27/94	13.32	10.31	11.34	15.35	50.31
Average	9.36	9.16	9.41	14.61	42.53

Table 7.8 PM-Peak Total Delay (Veh-hrs)

Date	Northbound	Southbound	Eastbound	Westbound	Total
18	10.22	12.72	11.22	9.38	43.53
21	8.98	13.77	10.21	12.27	45.23
22	8.64	11.70	9.03	9.50	38.86
26	11.92	12.96	10.89	16.79	52.56
27	10.38	14.41	11.47	13.30	49.56
Average	10.03	13.11	10.56	12.25	45.95

Table 7.9 Off-Peak Total Delay (Veh-hrs)

Date	Northbound	Southbound	Eastbound	Westbound	Total
4/18/94	9.42	8.49	8.29	15.94	42.15
4/21/94	11.96	8.63	8.54	16.93	46.07
4/22/94	10.30	9.19	8.00	15.27	42.77
4/26/94	10.69	9.51	7.64	17.52	45.36
4/27/94	12.48	9.65	8.90	18.89	49.91
Average	10.97	9.09	8.27	16.91	45.25

Table 7.10 Average Delay (Min/Veh)

Demand	Northbound	Southbound	Eastbound	Westbound	Total Average
AM-peak	**0.28**	**0.34**	**0.82**	**1.32**	**0.51**
PM-peak	0.25	0.33	1.01	0.47	0.39
Off-peak	**0.35**	**0.32**	**1.01**	**0.93**	**0.53**

(26.2%), whereas northbound left-turn percentage is very low (1.2%), consistent with the result that southbound has higher average delay per vehicle than northbound.

On the other hand, eastbound and westbound average accumulated delays are greater compared with those of north- and southbound, though the traffic demands are substantially lower. One reason is that the green time assigned to this phase is much shorter than that of phases for north- and southbound traffic. Another reason might be that the accumulated errors are larger because of lower demand (light traffic). In particular, westbound average accumulated delay is substantially greater than eastbound though their demands are almost the same. The reason is that eastbound left-turn percentage is much higher than westbound left-turn percentage (41.4% vs. 4.1%), whereas westbound right-turn percentage is much higher than eastbound right-turn percentage (63.8% vs. 13.4%), so westbound traffic is very light and accumulates a larger error.

VII.4.2 PM-peak

In the PM-peak period, north- and southbound traffic demands are almost the same (Table 7.2), but southbound delay is 30% higher than northbound delay (Table 7.8). The reason is the same as in AM-peak period, i.e., southbound left-turn percentage is higher. For east- and westbound traffic, westbound demand is more than twice that of eastbound, but westbound average accumulated delay is less than 20% higher than eastbound. This is because eastbound left-turn percentage is very high (54.1%).

Comparing westbound demand and average accumulated delay in PM-peak period to those in AM-peak period, demand in PM-peak period is more than twice that in AM-peak period; in contrast, average accumulated delay in PM-peak period is less than that in AM-peak period. This may confirm that a large error can be accumulated in light traffic.

VII.4.3 Off-peak

In the off-peak periods, north- and southbound traffic are almost the same as the traffic in the AM-peak period. However, east- and westbound traffic are almost the same as the traffic in the PM-peak period, except that westbound demand is lower but accumulated delay is greater in off-peak period than in PM-period. Westbound average delay per vehicle is lower than the delay in the AM-peak period but greater than the delay in the PM-peak period.

In summary, the estimated delays for north- and southbound are reasonable in the three periods. However, estimated delays for east- and westbound are not always consistent with their demand patterns. A possible reason is that east- and westbound traffic is often light, and the estimation algorithm may accumulate large errors in light traffic. This should be further addressed in the next phase of this study.

VII.5 Summary

In this Chapter we described the data collection process and analyzed traffic demand and turning movements at the test intersection. A delay estimation algorithm was proposed based on the machine-vision system to evaluate traffic performance. Performance results under the current pre-timed control strategy were presented. The proposed delay algorithm is sensitive to false detection, lane changes, and temporal detector failure, since any estimation error will accumulate in the segment over time. The algorithm works well in heavy (store-and-forward) traffic, but may result in large errors in light traffic. The problem will be further addressed in the next phase of this study.

VIII. CONCLUSIONS AND FUTURE RESEARCH

The most advanced concept for signalized network management employs demand-responsive control using on-line timing generators with adaptive features. Software developed for this type of control include SCOOT, SCATS, PRODYN and OPAC. While individual tests of each software have been conducted by various agencies, no comprehensive effort has been made to evaluate and quantify the performance of the state-of-the-art control software, especially in terms of their applicability to detection both with loops and machine-vision image processing.

This report documented the final results of the current phase of this research, which seeks to evaluate various intersection control strategies in a simulated environment, and to develop a live laboratory that can be used in the subsequent phase of the research for the development and testing of new control strategies. First, major intersection control strategies developed to date were briefly reviewed including state-of-the-art strategies with adaptive and on-line timing generation features. Owing to the availability of the control software, the OPAC control strategy was selected as the initial control algorithm to be evaluated in this research. The evaluation of other control strategies, such as CARS, will also be considered in a future phase depending on their availabilty. Second, a simulation environment was developed using the NETSIM simulator, and a test network located in downtown Minneapolis, in which all intersections are being controlled in pretimed mode.

As a first step towards a comprehensive evaluation of intersection control strategies, a hypothetical actuated control operation was simulated in the test network and its performance was compared with that of the current pretimed operation, which was also simulated with NETSIM. The evaluation results indicate that actuated control could provide better performance than the current pretimed control operation. However, prior to drawing conclusions regarding the effectiveness of the actuated control in the test network, comprehensive testing with additional pretimed operations must be conducted. The OPAC control strategy was next evaluated in the simulated environment using an intersection located in the Minneapolis downtown as the test intersection. The performance of OPAC was compared with that of pretimed and actuated control simulated with the same demand pattern at the same intersection. The comparison results indicate that OPAC performs best with low traffic demand, and pretimed control was most effective during peak periods when the traffic demand was near capacity.

Another important accomplishment of the current project is the selection of the site for the live intersection laboratory and the installation of a machine-vision video detection system at the laboratory intersection, located in downtown Minneapolis. The location of the live laboratory was determined in consultation with the traffic engineers from the City of Minneapolis and the Minnesota Department of Transportation. Further, the installation of the video system was conducted by the City traffic engineers. Using the data collected from the newly installed machine-vision detection system, the traffic performance of the intersection was quantified and analyzed. A performance index quantifying the traffic delay at the intersection was developed and delay was estimated using the data from the machine-vision detection. The Minneapolis laboratory will be used as a test site for new control strategies prior to full scale implementation in subsequent phases of this research.

Future work includes the development of a comprehensive operational plan for the live intersection laboratory, installation of additional cameras at the laboratory to fully cover the intersection for incident detection research, and development of new control strategies that take advantage of machine-vision detection features, such as type of data that can be collected and detector location flexibility. The new control strategies will be tested and refined at the live laboratory after performing off-line evaluation using simulation. A new intersection simulator that can simulate machine-vision detection-based control strategies needs to be developed. Further, the effort to obtain additional advanced control strategies, such as CARS, will continue; once such strategies are available, their performance will be analyzed and compared with that of OPAC and other available control strategies.

REFERENCES

REFFERENCES

1. U.S. DOT (1984). TRANSYT-7F User's Manual, UF-TRC-U32 FP-06/07, June.
2. U.S. DOT (1992). TRAF User's Manual, FHWA-RD-92-060, May.
3. U.S. DOT (1983). SIGOP-III, User's Manual, FHWA-IP-82-19, July.
4. U.S. DOT (1982). Arterial Analysis Package, FHWA-IP-82-8.
5. Bretherton, R.D. and Bowen, G.T. (1990). Recent enhancements to SCOOT - SCOOT Version 2.4, IEE: Third International Conference on Road Traffic Control, 1-3, May, pp. 95-98.
6. Hounsell, N.B., McLeod, F.N. and Burton, P. (1990). SCOOT : A traffic database, IEE: Third International Conference on Road Traffic Control, 1-3, May, pp. 99-103.
7. Peck, C. and Gorton, P.T.W. (1990). The application of SCOOT in developing countries, IEE: Third International Conference on Road Traffic Control, 1-3, May, pp. 104-109.
8. Robertson, D.I. and Bretherton, R.D. (1991). Optimising networks of traffic signals in real time - The SCOOT method, IEEE Transactions on Vehicular Technology, Vol. 40, No. 1, February, pp. 11-15.
9. Hunt, P.B., Robertson, D.I., Bretherton, R.D. and Winton, R.I. (1981). SCOOT - A Traffic Responsive Method of Coordinating Signals, TRRL Laboratory Report 1014.
10. Henry, J.J., Farges, J.L., and Tuffal, J. (1983). The PRODYN real time traffic algorithm, Control in Transportation Systems, 4th IFAC/IFIP/IFORS Conference, Baden Baden, Germany, April 20-22, pp. 307-312.
11. Barriere, J.F., Farges, J.L., and Henry, J.J. (1986). Decentralisation vs. hierarchy in optimal traffic control, Control in Transportation Systems, 5th IFAC/IFIP/IFORS Conference, Vienna, Austria, July 8-11, pp. 321-326.
12. Henry, J.J. (1989), PRODYN tests and future experiments on ZELT, VNIS'89: Vehicle Navigation and Information Systems, IEEE Conference, Toronto, Canada, September 11-13.
13. Henry, J.J., and Farges, J.L. (1989). PRODYN, CCCT'89: Control, Computers, Communications in Transportation, 6th IFAC/IFIP/IFORS Symposium on Transportation, Paris, France, September 19-21.
14. Kessaci, A., Farges, J.L., and Henry, J.J. (1989). On-line estimation of turning movements and saturation flows in PRODYN, CCCT'89: Control, Computer, Communications in Transportation, 6th IFAC/IFIP/IFORS Symposium on Transportation, Paris, September 19-21.
15. Kessaci, A., Farges, J.L., and Henry, J.J. (1990). Upper level for real time urban traffic control systems, 11th World Congress of IFAC, Tallin, Estonia, August 13-17.
16. Farges, J.L. (1990). Optimal control of pedestrian crossings, 8th Congresso Brasileiro de Automatica, Belem, Brazil, September 10-14.

17. Farges, J.L., Khoudour, L., and Lesort, J.B. (1990). PRODYN : On site evaluation, IEE Third International Conference on Road Traffic Control, 1-3 May, pp. 62-66.
18. de la Breteque, Amy L., and Jezequel, R., (1976). Adaptive control of an isolated intersection, a comparative study of some algorithms, Traffic Engineering and Control.
19. Luk, J.Y.K. (1984). Two traffic responsive area traffic control methods: SCAT and SCOOT, Traffic Engineering and Control, January, pp. 14-18, 22.
20. Cornwell, P.R., Luk, J.Y.K., and Negus, B.J. (1986). Tram priority in SCATS, Traffic Engineering and Control, November, pp. 561-565.
21. U.S. DOT (1989). Evaluation of the Optimised Policies for Adaptive Control Strategy, Federal Highway Administration, Publication No. FHWA-RD-89-135, May.
22. Lowrie, P.R. (1990). SCATS - Sydney Co-Ordinated Adaptive Traffic System - A traffic responsive method of controlling urban traffic, Roads and Traffic Authority NSW, Australia.
23. Rutherford, G.S., Jacobson, L.N., Schroeder, M., and Hallenbeck, M.E. (1990). Arterial Control and Integration, Research Project GC 8286, Task 30, Washington State Department of Transportation, March.
24. Chen, H., Cohen, L.C., Nathan, H.G., and Liu, C.C. (1987). Simulation study of OPAC: A demand-responsive strategy for traffic signal control, Tenth International Symposium on Transportation and Traffic Theory, M.I.T., Cambridge, Massachusetts, July, pp. 233-249. 25.Luk, J.Y.K. (1989). Estimation of turning flows at an intersection from traffic counts, Research Report ARR No 162, Australian Road Research Board, June.
26. Vincent, R.A. and Peirce, J.R. (1988). MOVA: Traffic Responsive, Self Optimizing Signal Control for Isolated Intersections. TRRL Report No. 170, Transport and Road Research Laboratory, Crowthorne, Berkshire, England.
27. Lines, C.J., Vincent, R.A. and Crabtree, M.R. (1990). MOVA Data Set-Up Guide. Application Guide No. 11, Transport and Road Research Laboratory, Crowthorne, Berkshire, England.
28. Vincent, R.A., Peirce, J.R. and Webb, P.J. (1990). MOVA Traffic Control Manual. Application Guide No.10, Transport and Road Research Laboratory, Crowthorne, Berkshire, England.
29. Vincent, R.A., and Young, C.P. (1986). Self optimizing traffic signal control using microprocessors - The TRRL MOVA strategy for isolated intersections. Traffic Engineering and Control, Vol. 27, Aug., pp. 385-387.
30. Peirce, J.R. and Vincent, R.A., (1989). Repeated stage signal and control using MOVA. Traffic Engineering and Control, Vol. 30, Jan., pp. 6-9.
31. Richard, David B. (1983). Metropolitan Toronto's New System. Engineer's Foundation Conference on Traffic Monitoring and Control Systems, Henniker, New Hampshire.

32. Greenouth, John L. and Quon, Brenda Y., (1991). The Metropolitan Toronto SCOOT Demonstration Project - The Next Frontier. Draft report to Publication Committee, Urban Traffic Engineers Council, Institute of Transportation Engineers.
33. Row, Edwin (1991). The Los Angeles Automated Traffic Surveillance and Control (ATSAC) System. IEEE Transactions on Vehicle Technology, Vol. 40, No. 1, pp. 16-20.
34. Rowe, Edwin (1990). The Los Angeles Automatic Traffic Surveillance and Control (ATSAC). Report for the Los Angeles Department of Transportation, Los Angeles, California.
35. Koski, David R. and Hildebrand, Dallas W. (1978). Minneapolis Computerized Traffic Signal Control System. Report for the Minneapolis Department of Public Works, Minneapolis, Minnesota.
36. Fortron Signal Systems Limited (1991). T2000L Traffic Signal Control System, Summary of Features and Functions. Fortron Signal Systems Limited Fact Sheet for T2000 System. Scarborough, Ontario, Canada, pp. 1-20.
37. Stephanedes, Y.J., Kwon E. and Michalopoulos, P. (1992). Development and Application of On-Line Strategies for Intersection Control, Phase I, Final Report, University of Minnesota, Minneapolis, Minnesota, December 1992.
38. Wong, S. Y. (1990). TRAF-NETSIM: How it works, what it does, ITE Journal, April, pp. 22-27.
39. Grubba, J., Allyn, D., Barbareso, J. and Beaubien, R. (1993). Selecting real time adaptive traffic control for Oakland County, Michigan, Presented at 72nd Annual Transportation Research Board Meeting, Washington D.C., January 10-14.
40. Barcelo, J., Grau, R., Egea, P. and Benedito, S., (1991). CARS: A demand-responsive traffic control system, Applications of Advanced Technologies in Transportation Engineering, ASCE, August, pp. 91-95.
41. U.S. DOT (1979). Urban Traffic Control System First Generation FORTRAN IV Overlay Software (Extended Version). FHWA, Implementation Package, FHWA-IP-79-4, May.
42. Pettersson, B.A. (1992). Using Video Detection Data for Extraction of Intersection and Highway Segment Measures of Effectiveness, M.S. Thesis, January, University of Minnesota, Minneapolis.

APPENDIX A

INPUT DATA FOR THE TEST NETWORK

APPENDIX A: INPUT DATA FOR THE TEST NETWORK

Table A.1. Network Geometry Details

LINK NO.	LINK LENGTH (Feet)	NUMBER OF LANES	LEFT TURN POCKET? Feet	RIGHT TURN POCKET? Feet
(8007,297)	0	2	N	N
(8008,295)	0	4	N	N
(8010,293)	0	3	N	N
(8011,220)	0	3	N	N
(8013,275)	0	3	N	N
(8040,253)	0	3	N	N
(8042,259)	0	3	N	N
(8043,259)	0	2	N	N
(8044,261)	0	2	N	N
(8045,280)	0	3	N	N
(8047,297)	0	2	Y, 132	N
(297,295)	421	2	N	N
(297,281)	361	2	N	N
(281,280)	528	2	N	N
(280,278)	392	3	N	N
(280,261)	362	2	N	N
(280,281)	528	2	N	N
(261,259)	479	1	N	N
(259,255)	422	3	N	N
(295,297)	421	2	Y, 140	N
(295,293)	490	3	Y, 140	N
(295,282)	381	4	N	N
(282,281)	410	2	Y, 140	N
(282,278)	479	4	N	N
(278,277)	479	3	N	N
(278,262)	381	4	N	N
(255,253)	490	3	N	N
(253,275)	479	3	N	N
(275,262)	485	3	N	N
(275,277)	391	3	N	N
(277,220)	459	3	Y, 135	N
(220,293)	425	3	Y, 140	N
(293,295)	490	3	Y, 130	N
(220,282)	495	3	N	N
(259,261)	479	3	N	N
(261,280)	362	2	N	N
(281,297)	361	3	N	N

Note: By NETSIM specifications, entry links (8XXX - XXX) must be assigned a length equal to ZERO; no statistics are provided for these links.

Table A.2. TRANPLAN Turning Volumes for NETSIM Network

Intersection & Link Name	Left Turn(VPH)	Through Movement(VPH)	Right Turn(VPH)
2nd & Washing-ton Ave(297)			
(8007,297)	1	87	86
(295,297)	849	1041	0
(281,297)	0	22	206
1st & Washing-ton ave(295)			
(8008,295)	106	497	526
(297,295)	0	1486	25
(293,295)	304	1376	0
Hennepin & Wa-shington(293)			
(8010,293)	0	1583	294
(295,293)	720	897	0
(220,293)	67	608	84
2nd Ave & 3rd ST. (281)			
(297,281)	0	243	697
(282,281)	150	1309	150
(280,281)	236	236	0
1st Ave & 3rd ST. (282)			
(295,282)	0	405	463
(220,282)	158	1065	0
Hennepin & 3rd ST. (220)			
(8011,220)	0	1103	37
(277,220)	132	713	0

Table A.2. TRANPLAN Turning Volumes for NETSIM Network (Continued)

	Left(VPH)	Through(VPH)	Right(VPH)
2nd Ave & 4th ST.(280)			
(8045,280)	54	678	295
(281,280)	78	214	0
(261,280)	0	390	209
1st Ave & 4th ST. (278)	80	507	0
(280,278)	0	956	18
Hennepin & 4th ST. (277)			
(278,277)	49	987	0
(275,277)	0	796	105
2nd Ave & 5th ST. (261)			
(8044,261)	382	0	286
(259,261)	55	55	0
(280,261)	0	274	231
(262,261)	3	998	162
1st Ave & 5th ST. (262)			
(278,262)	0	249	276
(275,262)	50	875	0
Hennepin & 5th ST. (275)			
(8013,275)	0	732	116
(253,275)	162	669	0
2nd Ave & 6th ST. (259)			
(8043,259)	3	10	0
(261,259)	0	563	0
1st Ave & 6th ST. (255)			
(262,255)	96	273	0
(259,255)	0	415	299
Hennepin & 6th ST. (253)			
(255,253)	129	493	0
(8040,253)	0	703	293

Table A.3. TRANPLAN Hourly Arrivals from Entry Links

LINK(SOURCE,DESTINATION)	ARRIVALS (VPH)
(8007,297)	174
(8008,295)	1128
(8010,293)	1607
(8011,220)	1140
(8013,275)	848
(8040,253)	996
(8042,259)	191
(8043,259)	2
(8044,261)	669
(8045,280)	1036
(8047,297)	1390

Table A.4. Current Offsets and Splits for Each Pretimed intersection

INTER-SECTION	SPLIT PLAN #	OFFSET	PHASE				
			1	2	3	4	
297	2	12	68	32			2ND AVE/WASHINGTON AVE
	6	82	68	32			AS ABOVE
	12	82	68	32			AS ABOVE
295	2	20	50	35	15		EB & WB WASHINGTON AVE /
	6	82	50	36	14		1ST AVE N./WB WASHINGTON
	12	82	50	35	15		(GREEN BALL & LEFT ARROW)
293	6	82	45	40	15		WASHINGTON / HENNEPIN AVE
							/SE-B WASHINGTON WITH LEFT ARROW
281	2	70	50	50			2ND AVE. N. / 3RD ST. N
	6	39	44	56			AS ABOVE
	12	39	45	55			AS ABOVE
282	2	76	50	50			1ST AVE N. / 3RD ST. N.
	6	27	45	55			AS ABOVE
	12	27	50	50			AS ABOVE
220	6	13	35	10	45	10	1,2:HENNEPIN AVE 3,4: 3RD ST.
280	2	4	70	30			4TH ST. / 2ND AVE
	6	88	40	60			AS ABOVE
	12	68	50	50			AS ABOVE
278	2	19	50	50			4TH ST. / 1ST AVE.
	6	73	50	50			AS ABOVE
	12	73	55	45			AS ABOVE
277	6	25	50	10	30	10	1,2:HENNEPIN AVE. 3,4: 4TH ST. N.
261	2	26	45	40	15		WB & EB 5TH AVE / 2ND
	6	7	50	35	15		AVE. N. / EB 5TH ST. N.
	12	17	45	40	15		(GREEN BALL WITH LEFT)

Table A.4. Current Offsets and Splits for Each Pretimed Intersection (Continued)

INTER-SECTION	SPLIT PLAN #	OFFSET	PHASE				
			1	2	3	4	
262	2	79	50	50			1ST AVE N./5TH ST. N.
	6	47	50	50			AS ABOVE
	12	47	45	55			AS ABOVE
275	6	14	40	10	40	10	1,2:HENNEPIN AVE 3,4:5TH ST.
259	2	22	75	25			2ND AVE N./6TH ST.
	6	82	75	25			AS ABOVE
	12	82	75	25			AS ABOVE
255	2	68	60	40			1ST AVE N./6TH ST.N.
	6	89	75	25			AS ABOVE
	12	89	75	25			AS ABOVE
253	6	1	50	10	30	10	1,2:HENNEPIN AVE. 3,4:6TH ST. N.

NOTE: Only P.M. peak hour data are available for Hennepin Avenue.

Table A.5. Initial values assumed for actuated control

Nodes Timing	Node 282 First Avenue & Third Street	Node 278 First Avenue & Fourth Street	Node 262 First Avenue & Fifth Street
Phase 1:			
Minimum Green time(sec)	8	8	8
Maximum Extension Time(sec)	35	30	30
Phase 2:			
Minimum Green time(sec)	8	8	8
Maximum Extension Time(sec)	30	25	25

APPENDIX B

TECHNICAL SPECIFICATION FOR MACHINE-VISION VEHICLE DETECTION SYSTEM

APPENDIX B

TECHNICAL SPECIFICATION FOR MACHINE-VISION VEHICLE DETECTION SYSTEM

1.0 GENERAL

This specification sets forth the minimum requirements for a system that monitors vehicles on a roadway via processing of video images and provides detector outputs to a traffic controller.

1.1 SYSTEM HARDWARE

The system shall consist of one to four synchronous closed-circuit television (CCTV) camera(s) or other synchronous video source(s), an automatic control unit (ACU), and a supervisor computer with a VGA video monitor.

1.2 SYSTEM SOFTWARE

The system shall be able to detect vehicles in multiple traffic lanes. A minimum of 48 detection zones shall be user-definable through interactive graphics by placing lines and/or boxes in an image on a video monitor. The user shall be able to redefine previously defined detection zones. The ACU shall calculate traffic parameters in real-time and provide local non-volatile data storage for later down-loading and analysis.

2.0 FUNCTIONAL CAPABILITIES

2.1 REAL-TIME VEHICLE DETECTION

2.1.1 The ACU shall be capable of simultaneously processing information from a minimum of four (4) synchronous CCTV video cameras, video tape players or other video sources.

2.1.2 The system shall be able to detect the presence of vehicles in a minimum of 48 detection zones within the combined field of view of the cameras.

2.1.3 Different detector types shall be selectable via software. Detector types shall include stop-line detectors, presence detectors, directional passage detectors and speed trap detectors. The speed trap detectors shall report vehicle speed and vehicle type based on length. Three length categories shall be user-definable in software.

2.1.4 Once the ACU has been properly set up using the supervisor computer with a VGA monitor, it shall be possible to disconnect the supervisor computer and video monitor. The ACU shall then detect vehicles as a stand-alone unit, calculate traffic parameters in real time, and store traffic parameters in its own non-volatile memory.

2.2 LOCAL DATA STORAGE

2.2.1 The ACU shall count vehicles in real time and compute the average of traffic parameters over user-defined time intervals (or time slices), as follows:

a. VOLUME
Number of vehicles detected during the time interval.

b. OCCUPANCY
Occupancy per lane measured in percent.

c. VEHICLE CLASSIFICATION
Number of automobiles, single unit trucks or tractor trailers, as defined by length.

d. FLOW RATE
Vehicles per hour per lane.

e. TIME HEADWAY
Average time interval between vehicles.

f. SPEED
Average vehicle speed during each time interval specified by user.

2.2.2 The duration of the time intervals (or time slices) shall be user-selectable as 20, 30, seconds or 1, 5, 10, 15, 30 or 60 minutes.

2.2.3 The time-interval data shall be retained in non-volatile EEPROM flash memory within the ACU for later downloading and analysis. The amount of memory shall be 2 MB or 4 MB, as specified. The base memory of 2 MB shall allow the accumulation of 15-minute time-interval traffic data for 48 detection zones data for a minimum of seven days.

2.2.4 Retrieval of data stored in the non-volatile memory of the ACU shall be via a serial communications port. Provision shall be made for downloading of data via a modem and dial-up telephone lines, via private cable or fiberoptic network, or via direct connection to another computer by cable.

2.3 OPERATION WITH SUPERVISOR ON-LINE

2.3.1 Once the detector configuration has been downloaded from the supervisor computer into the ACU, it shall be possible to operate the video detection system either with the supervisor computer disconnected or on-line.

2.3.2 When the supervisor computer is on-line, it shall be possible to view vehicle detections in real-time as they occur on the VGA video monitor.

2.3.3 It shall be possible to automatically save time-interval traffic data on hard disk following completion of each time interval. These traffic data shall include volume, flow rate, lane occupancy, headway, speed, and vehicle classification based on length category. It shall also be possible to save on hard disk the complete time data for each vehicle detection. The collected traffic and detection data shall be made available in readily-accessible ASCII format. The video detection software of the host computer shall provide file management routines for efficiently filing, retrieving and reporting of the collected traffic data.

2.3.4 It shall be possible to display the captured traffic data on the VGA screen of the supervisor computer in both numeric and graphic formats. The data to be displayed shall be selected by pull-down menus and shall be in the form of windows under the Windows 3.1 graphics operating environment.

3.0 VEHICLE DETECTION

3.1 DETECTION ZONE PLACEMENT

The video detection system shall provide flexible detection zone placement anywhere and at any orientation within the combined field of view of the cameras. Preferred presence detector configurations shall be lines placed across lanes of traffic or lines placed in-line with lanes of traffic. A single detector line shall be able to replace multiple conventional detector loops connected in series.

3.2 DETECTION ZONE PROGRAMMING

3.2.1 Placement of detection zones shall be by means of a supervisor computer operating in the Windows 3.1 graphics environment, and a mouse. The VGA video monitor of the supervisor computer shall show images of the detection zones superimposed on the video image of traffic.

3.2.2 The detection zones shall be created by using the mouse to draw detection lines on the VGA video monitor. It shall be possible to save detector configurations on disk, to download detector configurations to the ACU, and to retrieve the detector configuration that is currently running in the ACU.

3.2.3 It shall be possible to use the mouse to edit previously defined detector configurations so as to fine-tune the detection zone placement. Once a detection configuration has been created, the supervisor computer system shall provide a graphic display of the new configuration on its VGA screen that also shows traffic.

3.2.4 It shall be possible to individually adjust sensitivity, persistence and shadow compensation for each detection zone in the system.

3.2.5 When a vehicle is under a detection zone, the detection zone shall change in color or intensity on the VGA video monitor, thereby verifying proper operation of the detection system.

3.3 OPTIMAL DETECTION

The video detection system shall reliably detect vehicle presence when the camera is mounted 35 feet (11 m) or higher above the roadway, when the camera is adjacent to the desired coverage area, and when the length of the detection area or field of view (FOV) is not greater than ten (10) times the mounting height of the camera. The camera shall not be required to be mounted directly over the roadway. A single camera placed at the proper mounting height and with the proper lens shall be able to monitor eight (8) traffic lanes simultaneously.

3.4 DETECTION PERFORMANCE

Overall performance of the video detection system shall be comparable to inductive loops. Using standard camera optics and in the absence of occlusion, the system shall be able to detect vehicle presence with 98% accuracy under normal conditions (day & night) and 96% accuracy under adverse conditions (fog, rain, snow).

4.0 ACU HARDWARE

4.1 ACU MOUNTING

The ACU shall mount into a 19" EIA equipment rack assembly or be shelf-mountable. Nominal outside dimensions excluding connectors shall be 5-1/2" x 17-1/4" x 10-1/8" or 140 x 438 x 257 mm (H x W x D).

4.2 ACU ENVIRONMENTAL

The ACU shall be designed to operate reliably in the adverse environment found in the typical roadside traffic cabinet. It shall meet the environmental requirements set forth by the NEMA (National Electrical Manufacturers Association) TS1 and TS2 specifications as well as the environmental requirements for Type 170 and Type 179 controllers. Operating temperature shall be from -35 to +74 degrees C at 0% to 95% relative humidity, non-condensing.

4.3 ACU ELECTRICAL

4.3.1 The ACU shall be modular in design and provide processing capability equivalent to the Intel 486SX microprocessor. The bus connections used to interconnect the modules of the ACU shall be gold-plated DIN connectors.

4.3.2 The ACU shall be powered by 95 - 135 VAC, 60 Hz, single phase, and draw less than 2 A, or by 180 - 265 VAC, 50 Hz, single phase and draw less than 1 A. Surge ratings shall be as set forth in the NEMA TS1 and TS2 specifications.

4.3.3 Serial communications to the modem or supervisor computer shall be through an RS-232/RS-422 serial port. This port shall be able to download traffic data stored in non-volatile memory as well as the real-time detection information needed to show detector actuations. A 9 pin "D" subminiature connector on the front of the ACU shall be used for serial communications.

4.3.4 The ACU shall be available with a NEMA TS1 detector interface for 32 or 64 detector outputs. Output levels shall be compatible with the NEMA TS1, NEMA TS2 Type 2, Type 170 and Type 179 standards. Subminiature 37 pin "D" connectors on the front of the ACU shall be used for discrete detector outputs.

4.3.5 The ACU shall be available with a NEMA TS2 Type 1 detector interface for 32 or 64 detector outputs, where the detector information is transmitted serially via RS-485. A "D" subminiature connector shall be used for the serial detector output.

4.3.6 The ACU shall be available with two or four RS-170 (NTSC) composite video inputs, so that signals from two or four synchronous video cameras or other synchronous video sources can be processed in realtime. BNC connectors on the front of the ACU shall be used for video input.

4.3.7 The ACU shall be available with one RS-170 (NTSC) composite video output, which correspond to one of four video inputs, as selected remotely via Supervisor or front panel switch on the ACU. BNC connectors on the front of the ACU shall be used for video output.

4.3.8 As an alternative to RS-170 (NTSC) video format, the ACU shall be available with video inputs and outputs in the PAL/CCIR format.

5.0 CAMERA SYSTEM

5.1 The video system shall use medium-resolution, color or monochrome CCD cameras as the video source for real-time vehicle detection. Each camera shall provide 380 lines of resolution. It shall have automatic iris and absolute black reference. The limits of gain, iris and sensitivity shall be adjustable to prevent blooming during nighttime hours.

5.2 The NTSC version of the camera shall be a Burle Model TC651EA or approved equal. Modifications of the gain, sensitivity and iris limits, as may be required for optimum performance with the video detection system, shall be completed prior to installation. The camera lens shall provide zoom capability from 8 to 48 mm, or a fixed focal length as required for the application. The auto-iris capability of the lens shall operate reliably at -30 degrees C.

5.3 The camera and lens assembly shall be housed in an environmental enclosure that is waterproof and dust-tight to NEMA-4 specifications. A 20-watt heater shall be attached to the lens of the enclosure to avoid ice and condensation in cold weather. The enclosure shall be light-colored and shall include a sun shield to minimize solar heating. The enclosure shall be a Burle Model TC9393 or equivalent.

5.4 A galvanized steel junction with approximate measurements 12" x 10" x 6" (30 x 25 x 15 cm) shall be provided for each pole used for camera mounting. Each junction box shall contain a terminal block, a ground-fault interrupt circuit and tie points for the coax cable.

5.5 A video interface panel measuring 12" x 12" (30 x 30 cm) shall be provided for the inside of the traffic cabinet. The panel shall provide a terminal block and a lightning arrester for each camera.

5.6 The supplier shall provide 4 camera system packages to work with the video detection system; this includes the cameras, enclosures, optics, associated mounting hardware and junction box.

5.7 SUPERVISOR COMPUTER SYSTEM

5.7.1 The minimum supervisor computer system, as needed for detector setup and viewing of vehicle detections, shall consist of a supervisor computer and a video digitizer board.

Minimum specifications for the supervisor computer shall be the following:

IBM PC-compatible
386 processor
MS-DOS 3.3, MS-DOS 5.0 or higher
Microsoft Windows 3.1
One full-size AT-compatible expansion slot
VGA monitor
Keyboard
Mouse
4 MB of RAM
1.44 MB floppy disk drive
60 MB hard disk drive

5.7.2 The University will supply the supervisor computer, while the supplier of the video detection system shall provide the video digitizer and the software necessary for supervision and data communication.

5.7.3 A video digitizer board shall be installed in the supervisor computer to capture video images. This board shall fit in the full-size AT-compatible expansion slot specified for the supervisor computer and shall be modified by the supplier as needed for operation with the vehicle detection system; the output of the digitizer board shall drive the VGA monitor of the supervisor computer to display scenes of moving traffic with superimposed actuating detection zones.

5.7.4 A 2400 or 9600 baud modem, which is to be supplied by the University, shall be used with the supervisor computer to allow remote detector setup and retrieval of data stored in the ACU.

6.0 INSTALLATION AND TRAINING

6.1 At the option of the buyer, the supplier of the video detection system shall supervise the installation and testing of the video detection and computer equipment; a technically-qualified representative from the supplier shall be on-site for a minimum of one day.

6.2 At the option of the buyer, two days of training shall be provided to personnel of the contracting agency in the operation, setup and maintenance of the video detection system: Instruction and materials shall be provided for a maximum of 20 persons and shall be conducted at a location selected by the contracting agency; the contracting agency shall be responsible for any travel, room and board expenses for its own personnel.

7.0 WARRANTY, MAINTENANCE AND SUPPORT

7.1 The video detection system shall be warranted by its supplier for a minimum of one (1) year.

7.2 Ongoing software support by the supplier shall include updates of the ACU and supervisor software. These updates shall be provided free of charge during the warranty period.

7.3 The supplier shall maintain a program for technical support and software updates following expiration of the warranty period. This program shall be made available to the contracting agency in the form of a separate agreement for continuing support.

APPENDIX C

GLOSSARY

APPENDIX C

GLOSSARY

Time Period

A time period is the amount of time during which data describing traffic flow remain constant. The total time to be simulated may be segregated into as many as 19 time periods or may be modeled in as few as 1.

Link Length

Distance from the stop line of the upstream feeder link to the stop line of the subject link.

Free Speed

Speed attained by traffic in the absence of any impedance that is due to other vehicles, pedestrians or control devices.

MOE (Measure of Effectiveness)

Measures of effectiveness are statistics, such as mean speed, vehicle trips, and delay time, which are computed during execution of the simulation model. They provide a means for evaluating traffic performance over the network. Measures of effectiveness are computed for links, intersection, and the entire network.

Moving Time

The idealized travel time that would exist if all vehicle trips were performed at the mean free-flow speed of the link without any signal or other delay. This is computed as:

$$\frac{\text{Vehicle Trips} * \text{Link Length (ft)}}{\text{Mean Free-Flow Speed (ft/sec)}}$$

Delay Time

The difference between the actual total travel time accumulated on the link and the idealized moving time that would exist if vehicles always moved at the mean free-flow speed without slowing for other vehicles or stopping in response to intersection control. This is computed as:

Total Travel Time (Veh-Min) - Moving Time (Veh-Min)

Total Travel Time (Veh-Min)

Cumulative travel time on a link of all vehicles which have traversed the link plus the cumulative travel time of all vehicles present on the link when the statistic is computed.

Vehicle Miles

This is equivalent to:

$$\frac{\text{Vehicle Trips} * \text{Link Length (ft)}}{5280 \text{ (ft/mile)}} - V$$

where V = adjustment for vehicles which entered the link via a right turn movement and, therefore, did not traverse the length of the upstream intersection.

Vehicle Trip

One vehicle trip is counted when a vehicle travels the full length of a link, i.e., enters the link and discharges from the link.

Accumulated-Total-Delay (Veh-hours)

Sum of delay time of all vehicles on both approach and departure links of the intersection, accumulated from the beginning of the first time period.

Period Delay-Per-Vehicle-Per-Trip (Min)

Average delay experienced by a vehicle in completing one vehicle trip on a link.

Period Stop-Percentage (%)

The percentage of all vehicle trips in which a vehicle is forced to come to a complete stop at least once in the time period.

APPENDIX D

DETECTOR LAYOUT

APPENDIX D
DETECTOR LAYOUT

Detector No.	Position (from stopline, ft)	Type
128	WB R Stopline	Count
129	WB L Stopline	Count
130	WB R Upstream (143)	Speed
131	WB L Upstream (123)	Speed
132	EB L Downstream (45)	Speed
133	EB R Downstream (45)	Speed
134	EB Both Downstream Stopline	Count
139	WB R Upstream (260)	Count
140	WB L Upstream (255)	Count
234	SB R Stopline	Count
235	SB RC Stopline	Count
236	SB LC Stopline	Count
237	SB L Stopline	Count
238	SB RC Upstream (112)	Speed
239	SB LC Upstream (111)	Speed

240	SB L Upstream (108)	Speed
241	NB L Downstream (94)	Speed
242	NB R Downstram (95)	Speed
244	NB Both Downstream Stopline	Count
249	EB-to-NB	Directional
255	SB R Upstream (210)	Count
256	SB L Upstream (210)	Count
325	NB R Stopline	Count
326	NB RC Stopline	Count
327	NB LC Stopline	Count
328	NB L Stopline	Count
329	SB Both Downstream Stopline	Count
330	NB RC Upstream (153)	Speed
331	NB LC Upstream (148)	Speed
332	NB L Upstream (101)	Count
333	SB L Downstream (148)	Speed
334	SB R Downstream (147)	Speed
346	WB-to-SB	Directional

353	NB R Upstream (260)	Count
354	NB L Upstream (255)	Count
424	EB R Stopline	Count
425	EB L Stopline	Count
426	WB Both Downstream Stopline	Count
427	EB R Upstream (138)	Speed
428	EB L Upstream (136)	Speed
429	WB L Downstream (130)	Speed
430	WB R Downstream (122)	Speed
433	EB R Upstream (240)	Count
434	EB L Upstream (230)	Count

All count detectors at stoplines were set to measure the demand and count the vehicles exiting road links. In particular, detectors 328 and 325 count northbound left- and right-turn vehicles, respectively. Directional detectors 249 and 346 count east- and westbound left-turn vehicles, respectively. Detectors 134 and 426 at east and westbound downstream stoplines count vehicles entering the downstream links, whereas detectors 244 and 329 at north and southbound downstream stoplines count vehicles coming from east- and westbound only. Subtracting the count of detector 249 from that of detector 244 results in westbound right-turn vehicles, whereas subtracting the count of detector 346 from that of detector 329 results in eastbound right-turn vehicles.

All speed detectors at downstream measure speed of vehicles leaving the intersection, with reasonable distances from downstream stoplines. All speed detectors at upstream were set as far from the stopline as possible to measure the speed of vehicles approaching the intersection, subject to the field of view of the camera and the requirement of speed detector length. In particular, speed detector 240 was set in southbound left-turn pocket, while count detector 332 was set in northbound pocket.

In addition, one count detector was set for each approaching lane as far upstream as possible to measure upstream demands.