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dissertation entitled

Development of a Modeling Approach to Analyze
Intersection Traffic Delay Under the Control
of a Real-Time Adaptive Traffic Signal System

presented by

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has been accepted towards fulfillment
of the requirements for

Ph.D. degree in Civil Engineering

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Date 3/14/97

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**DEVELOPMENT OF A MODELING APPROACH TO ANALYZE
INTERSECTION TRAFFIC DELAY UNDER THE CONTROL OF A
REAL-TIME ADAPTIVE TRAFFIC SIGNAL SYSTEM**

By

P. Brian Wolshon

A DISSERTATION

Submitted to
Michigan State University
in partial fulfillment of the requirements
for the degree of

DOCTOR OF PHILOSOPHY

Department of Civil and Environmental Engineering

1997

ABSTRACT

DEVELOPMENT OF A MODELING APPROACH TO ANALYZE INTERSECTION TRAFFIC DELAY UNDER THE CONTROL OF A REAL-TIME ADAPTIVE TRAFFIC SIGNAL SYSTEM

By

P. Brian Wolshon

The United States Department of Transportation has recently begun implementation of the national demonstration project for suburban Advanced Traffic Management (ATMS) and Advanced Traveler Information Systems (ATIS) in Oakland County, Michigan. As part of this project, the City of South Lyon has recently converted the control of its signalized traffic network from optimized fixed-time control to the Sydney Coordinated Adaptive Traffic System (SCATS). SCATS is an automated, real time, traffic responsive signal control strategy. Under SCATS, the timing of the signals is governed by a computer-based control logic. The system has the ability to modify signal timings on a cycle-by-cycle basis using traffic flow information collected at the intersection approach stop lines.

The expected benefit from such a system comes from its ability to constantly modify signal timing patterns to most effectively accommodate changing traffic conditions. While the potential benefits from this control structure may be significant, few research studies have used computer simulation modeling to document the effect of implementing this method of signal control. The objectives of this research study are to analyze and document the changes to certain traffic flow and delay parameters which have occurred in South Lyon as a result

of implementing SCATS signal control.

The study will make use of the “before/after” analysis technique to measure certain aspects of the traffic delay conditions in periods prior to and following the implementation of SCATS control. The research will be structured within a framework of several component segments including data collection, reduction, analysis, simulation model construction, and statistical testing.

*Dedicated to my wife Kelly,
my parents Paul and Susanne, and my brother Jeff*

ACKNOWLEDGMENTS

I would like to express my appreciation and gratitude to my advisor and committee chairman Dr. William C. Taylor, for his invaluable advice and guidance throughout my studies at Michigan State University and during the completion of this research. His patience, kindness, and insights will never be forgotten.

My appreciation and gratitude are also extended to Dr. Thomas Maleck, Dr. Richard Lyles, and Dr. Joseph Gardiner for serving as members of the guidance committee and for their assistance. My gratitude is also extended to current and former graduate students Dr. Sorowit Narupiti, Mr. Mohammed Saif, and Mr. Ahmed Abdel-Rachman in the Department of Civil and Environmental Engineering at Michigan State University. Their assistance, suggestions, and encouragement were also key to the completion of this research.

Words can not express my most sincere love and gratitude to my wife Kelly. Without her constant support, and patience I could not have completed this project. I wish to thank my brother Jeffrey to whose heights of creativity and intelligence I have always aspired. To my father, I wish convey my gratitude for his love, support, and constant encouragement throughout my life. Through his example of hard work and a sense of humor, I have learned that the most important achievements in life are happiness and the knowledge that I have always tried my best. Finally, I would like to express a debt of gratitude to my mother Susanne. I know that the completion of my Doctoral Degree means more to her than it could ever mean to me. It has been because of her continuous love, support, sacrifice, and unending devotion to her children that my brother and I have the confidence to strive for greatness.

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Chapter 1.

Introduction

The United States Department of Transportation has recently begun implementation of the national demonstration project for suburban Advanced Traffic Management (ATMS) and Advanced Traveler Information Systems (ATIS) in Oakland County, Michigan. As part of this project, the City of South Lyon has recently converted the control of its signalized traffic network from optimized fixed-time control to the Sydney Coordinated Adaptive Traffic System (SCATS). SCATS is an automated, real time, traffic responsive signal control strategy. Under SCATS, the timing of the signals is governed by a computer-based control logic. The system has the ability to modify signal timings on a cycle-by-cycle basis using traffic flow information collected at the intersection approach stop lines.

The expected benefit from such a system comes from its ability to constantly modify signal timing patterns to most effectively accommodate changing traffic conditions. While the potential benefits from this control structure may be significant, few research studies have documented the effect of implementing this method of signal control. The objectives of this research study are to analyze and document the changes to certain delay parameters which

have occurred in South Lyon as a result of implementing SCATS signal control.

This study will make use of the “before/after” analysis technique to measure certain aspects of the delay conditions in periods prior to and following the implementation of SCATS control. The research will be structured within a framework of several component segments including data collection, reduction, and analysis; simulation model construction; and statistical testing.

1.1 FAST-TRAC and SCATS

The South Lyon signal improvement project is a small segment of the FAST-TRAC (Faster and Safer Travel - Traffic Routing and Advanced Controls) project.⁽¹⁾ FAST-TRAC has involved the conversion of more than 1,000 pretimed and actuated signalized intersections in Oakland County to SCATS control and has established a county-wide, real-time route navigation system.^(2,3) While FAST-TRAC has been managed primarily by the Road Commission for Oakland County (RCOC), it has been a cooperative effort between many federal, state, county, and local government agencies; as well as private corporations and universities.

The SCATS system was developed in the 1970's by the Roads and Traffic Authority of New South Wales, Australia. The operational aspect of SCATS has been compared to the type of control “provided by a traffic control officer stationed at the intersection controlling traffic to insure that congestion is reasonably equal among the various approaches. The primary difference is that today’s real time adaptive control systems can anticipate the arrival of vehicles from preceding intersections and respond accordingly.”⁽⁴⁾ It functions by making constant modifications to traffic signal timings in real-time in response to the variations in traffic demand and system capacity. It has advantages over the police officer by evaluating and controlling the signal system on a system wide basis rather than on an isolated intersection by intersection basis. It operates by using traffic sensors to monitor flow

conditions and thus coordinate signal timings in order to minimize stops and delay time when the system is at or near capacity. SCATS attempts to maximize the system capacity and minimize the possibility of traffic jams by controlling the formation of queues. One of the ways that SCATS can accomplish this is by providing a progression of green signal phases to reduce stopped vehicle queues, thereby reducing delay and decreasing the network travel times.⁽³⁾

Input data for the SCATS system is collected via a system of traffic sensors. The sensors may be inductive loop detectors imbedded in the pavement or, as in the case of the South Lyon system, video image devices mounted overhead on the signal strain poles or attached on mast arms. The traffic information collected in the field involves the discharge characteristics (i.e., flow and occupancy during the green phase) on each intersection approach. This data is transmitted to a regional control center where the SCATS control program attempts to most effectively maintain the highest degree of saturation on the intersection downstream of the collected traffic data.

SCATS divides the network into systems and subsystems. Each subsystem contains a single “critical” intersection, usually where two high volume roadways intersect. SCATS control logic incorporates a dynamic process whereby intersection signal phasing is coordinated. This system is known as “marriage” and “divorce.” Married intersections coordinate timings to allow platoons of traffic to pass through. A divorce occurs when two intersections no longer require coordination to maximize traffic flow through the network. The divorce is implemented after three consecutive cycles warrant a divorce, insuring additional stability within the system.

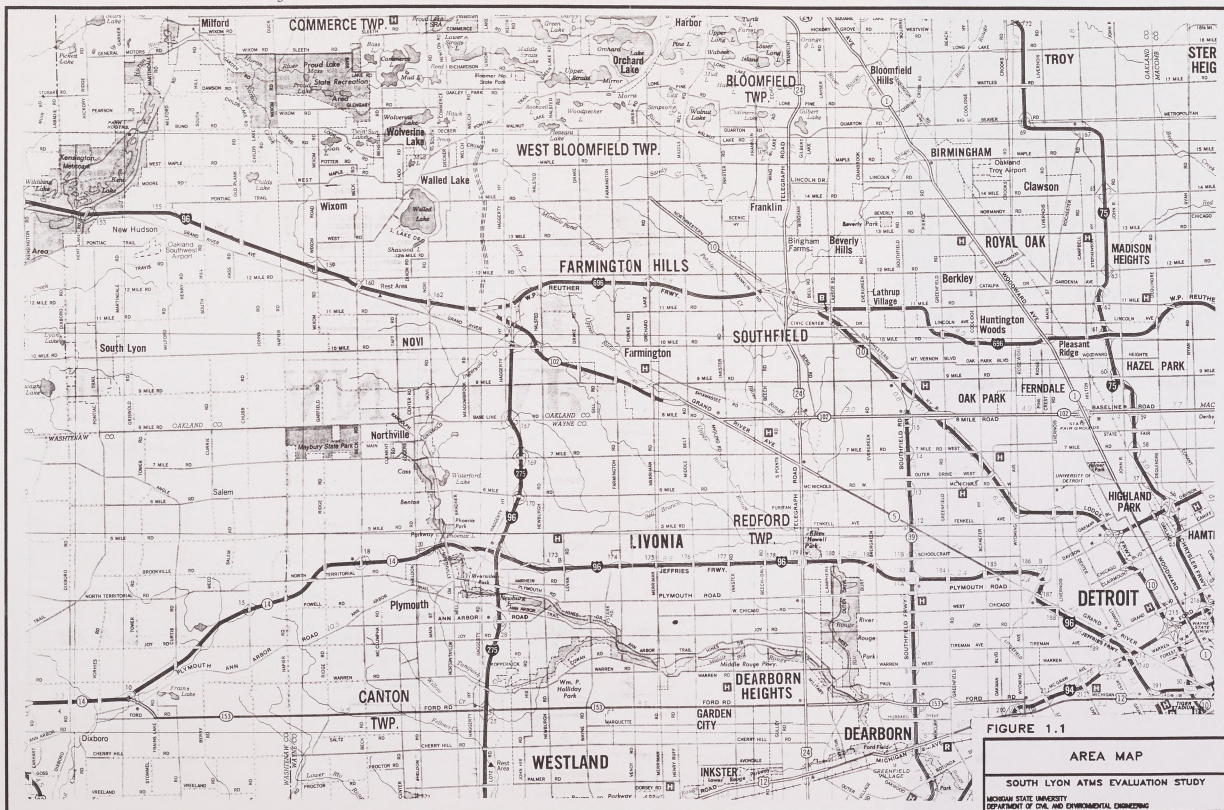
Other differences that separates SCATS from conventional fixed timed systems is its ability to modify timing strategies to fit various control philosophies and to collect, process, and maintain a history of traffic statistics for an area. Signal phases can be set to equalize saturation on all approaches or they can be arranged to give priority to a particular direction

of importance. Since the SCATS system requires the use of certain traffic data information it has the ability to record and store these statistics to monitor the strategic performance of the system, detect signal faults, and allow manual overrides of the signals under special operating circumstances.

1.2 The South Lyon Traffic Network

Oakland County is located in the southeastern corner of Michigan, immediately north of the City of Detroit. Throughout the past 15 to 20 years Oakland County has experienced an explosion in commercial and residential development. Accompanying the growth in development was an equally significant increase in traffic congestion.⁽⁵⁾ The City of South Lyon is located in the southwest corner of Oakland County, approximately 40 miles northwest of the City of Detroit. Figure 1.1 illustrates the location of South Lyon relative to the Detroit metropolitan area. It is presently a small, semi-rural/suburban community of approximately 25,000 people. The traffic congestion problems are comparatively minor compared to many cities in Oakland County. However, like the rest of Oakland County, the land within the City and surrounding Township is experiencing considerable commercial and residential development and increases in the amount of traffic congestion are expected to follow. It was expected that the introduction of the SCATS system of advanced traffic management will allow the community of South Lyon to accommodate the anticipated increases in traffic in a cost effective and efficient manner.

The layout of South Lyon road network is arranged in a perpendicular grid system of primary roadways. The major roads are spaced at approximately one mile intervals. The lone exception to the grid layout is Reynold Sweet Parkway. The Parkway serves as a bypass route for through traffic around the central business district. The layout of the South Lyon street system can be seen in more detail in Figure 1.2. The majority of the South Lyon traffic load is carried on Pontiac Trail and Ten Mile Road. Pontiac Trail is the main north-south arterial roadway in South Lyon, providing access to Interstate 96 which is located



approximately four miles north of town. The overwhelming majority of commercially developed land within South Lyon is located directly adjacent to Pontiac Trail. Ten Mile Road is the prime east-west arterial serving the traffic demand to the commercial centers located to the east.

The local street network is also arranged in an approximate grid layout. Its density is considerably greater than the primary road system. The area of greatest density is located within the vicinity of the central business district, surrounding the intersection of Ten Mile Road and Pontiac Trail. As a result of the dense commercial development, two minor street intersections with Pontiac Trail have been signalized. The South Lyon road network under study also incorporates two at-grade railroad intersections. One of these, to be described in detail later, forms an awkward triple intersection at a point where two roads and the railroad tracks all coincide.

There were six signalized intersections in operation within the South Lyon traffic network during the study period of 1995-1996. The installation, operation, and maintenance of these signals are under the jurisdiction of the Road Commission for Oakland County. The closest traffic signal outside of the study network is located approximately five miles away. Originally, all of these signals operated on a well coordinated, pre-timed basis. No traffic adaptive control measures, like actuated signal timing, were initially at work within South Lyon. The Oakland County ATMS project involved the conversion of all six signals to SCATS control. It was thought that the relative isolation of South Lyon and its small signal network would make it an ideal "laboratory" for an evaluation study of the SCATS system of advanced traffic management.

It has been hypothesized that the ATMS proposed for South Lyon will result in improvements to the traffic flow conditions within the controlled network. With the resources allocated for the design, implementation, testing, and research of FAST-TRAC and the potential worldwide implementation of adaptive traffic signal control systems, like

SCATS, there is a need to assess its benefits. The following research study has documented performance measures before and after the installation of the SCATS system, to address such questions.

Chapter 2.

Literature Review

To establish the current state of the art a literature review was completed. The literature search was performed to accomplish four primary goals. First, the current limits of knowledge in the field of traffic engineering research relative to SCATS signal control were explored. Second, the literature search lead to an understanding of the "gaps" resulting from past research. The research gaps included the absence of studies performed specifically on the comparative benefits gained from adaptive signal control. The literature review also established a base of knowledge from which to launch the proposed study and demonstrated certain techniques which have been successful in past research. Some of these were applied to the South Lyon evaluation study to aid in the accuracy and efficiency of the experiment. Finally, the review of past published literature gave insights into the way in which current theories, technology, and implementation of adaptive traffic signal systems have developed over the years. The search has shown how theories have been built from prior experiments and how and why some ideas of twenty and thirty years ago have now come into practice while others were unsuccessful in field applications.

The following sections of the literature review have been divided into the main areas of traffic research that relate to this study. They include the historical development of adaptive traffic signal control, the state of current and future practice of advanced traffic management systems, the development and use of computer simulation and analysis tools to model traffic related events, and an investigation into the experiments and theories which are under study in Intelligent Transportation Systems (ITS). The last two sections of this chapter will provide documentation of the results of recent comparative studies of adaptive signal control systems and a demonstration of the need for research into more advanced measurement and analysis techniques in this field.

2.1 Adaptive Traffic Control Systems

The majority of travel delay experienced on arterial roadways is governed by the intersections along the route. Reductions in stop delay at intersections can enhance the efficiency of a road and reduce the amount of time required to travel through a particular corridor or network. One of the best ways to achieve a reduction in delay is to provide an efficient progression of signals. A method of providing effective signal progression is to anticipate the arrival of vehicles and modify signal timings to match the arrival pattern. The Sydney Coordinated Adaptive Traffic System is one of several forms of advanced traffic management which are in operation or under development that use anticipatory and adaptive techniques to increase the efficiency of a road network.

Adaptive traffic control systems are traffic signal systems which have the ability to change the phasing and timing strategies and coordination of signals within a network to meet the demands placed upon them. These types of systems may take on many forms and levels of complexity and automation. Their primary purpose is to increase the efficiency of a system by maximizing the way traffic is managed.

The concept of traffic signal systems which could be modified to more efficiently move traffic has been studied for many years. The practice of traffic signal optimization began in the 1920's.⁽⁶⁾ As signal control technology became more advanced, signal systems began to use pretimed coordination plans. The original "traffic responsive" signal systems were merely pretimed signal control systems which could be modified to fit the anticipated traffic demand patterns.⁽⁷⁾ Such systems, still prevalent today, are designed to optimize traffic based on average time-of-day and day-of-week conditions. These types of control work well and are considerably less expensive to install, operate, and maintain than more complex computer controlled systems.

Real-time adaptive control is a fairly recent development. Past research publications have shown ongoing testing and development was underway in the early sixties. For real-time systems to be possible, accurate detection, rapid data processing, and effective and speedy transmission of data are necessary. One of the initial studies performed to evaluate the use of computer and video technology was published in 1967.⁽⁸⁾ The study was one of the first attempts to evaluate the feasibility of using video detection and recording equipment to chronicle traffic activities near roadway intersections, detect the occurrence of accidents, then record and store this data for further use. The system was not very sophisticated and required a technician to watch the video feed and look for incidents. The technology of the day did not make it possible to automatically search and record events for use on a real-time basis. However, the study was able to demonstrate the utility of incorporating automated technology to search for and record certain elements of the traffic stream.

Another advance toward today's advanced traffic management systems was made in 1967 with the development of a computer program and methodology to gather and process data from loop detectors placed near intersections to determine certain traffic flow parameters. This research and development project⁽⁹⁾ also demonstrated how such data could be used to determine queue lengths and delay at signalized intersections. By today's standards this model was primitive. However, the technology demonstrated in this project has evolved into

one of the integral elements which allow real-time adaptive control systems to function today.

The development and implementation of adaptive control systems have become possible over the past five to ten years due to a number of very important factors. Two of the most important are concerns about the increased levels of congestion and advancements in computer technology and data processing efficiency. The number of annual vehicle miles traveled is increasing at a steady rate and it is not economically, environmentally, nor spatially possible to construct new roads or expand existing ones to meet the anticipated traffic. Therefore, the answer to improving transportation efficiency lies in the effective management of existing systems. Real-time adaptive traffic management systems allow traffic professionals to more effectively manage the existing transportation infrastructure.

Several types of advanced control systems are currently in operation, serving in experimental traffic control management roles. Two such systems, the Sydney Co-Ordinated Adaptive Traffic System (SCATS) and the Split, Cycle and Offset Optimising Technique (SCOOT), have developed into the most prevalent real time adaptive traffic signal control systems and are poised to become the automated traffic management systems for the next century.

The SCOOT system was developed in Great Britain in the mid 1970's.⁽⁶⁾ The main idea of the SCOOT system was to take an "off-line" model, like the fixed time signal optimization program TRANSYT, and have it operate "on-line." Specifically, the system uses traffic data measurements collected from the existing stream and makes short and long term decisions regarding the traffic signal settings. The great advantage to a real time, on-line system like SCOOT is that it can respond to the current traffic conditions with almost no lag time and it greatly reduces the need for constant human interaction in adjusting the signal timings. Traffic stream measurements are collected automatically and adjustments to the timing plans are made automatically. This is in contrast to fixed time, non-automated systems where there is a need for traffic engineers and field technicians to study the traffic conditions and

implement the changes.

SCOOT is currently in operation throughout Great Britain as well as in Thailand, Hong Kong, China, the Philippines, and Canada. The first SCOOT implementation project in the United States occurred in Oxnard, California in 1992.⁽¹⁰⁾ Studies performed by the Transportation Road Research Laboratory in London, England found that, under certain conditions, the SCOOT system provided a 20% improvement over a standard fixed time signal system.⁽⁶⁾

While the SCOOT system represented a major advance in the management of signal timing, it had some shortcomings (especially in its earlier forms) that made the parallel development and implementation of another real time adaptive traffic control system even more desirable. The SCATS system was developed in Australia during the same time as the SCOOT system. SCATS, like SCOOT, is an automated traffic control system whereby traffic signal timings are adjusted in response to variations in traffic demand. The SCATS system operates on a real-time basis, using the current traffic flow information to modify and coordinate signal timing. To minimize stops and delay time when the system is at or near capacity, SCATS attempts to maximize the system capacity and minimize the possibility of traffic jams by controlling the formation of queues.^(2,3,11) SCATS accomplishes this by providing a progression of green signal phases to reduce stopped vehicle queues, thereby reducing delay and decreasing the network travel times.⁽²⁾

The SCATS system also offered some distinct advantages over SCOOT. Primary among these was its ability to omit individual signal phases from the signal cycle if the traffic demand did not warrant them. For example, a protected left turn phase could be eliminated from the cycle if no vehicles were present; as detected by the sensors. The other advantage of the SCATS system was its ability to readjust the phase sequence pattern to best take advantage of the traffic conditions. This feature requires drivers to be more vigilant because one cycle may start with a leading protected left turn phase, while the next cycle might

feature a lagging protected left turn phase.

Development of yet another advanced traffic control project is currently underway in Europe. The research and development associated with the HERMES (High Efficiency Roads with Rerouting Methods) project has taken place in parallel with the testing, development, and implementation of SCATS in Australia and North America. The HERMES project relies on the origin-destination characteristics of the network and automatic incident detection information to execute the advanced traffic management process.⁽¹²⁾ The HERMES system utilizes origin-destination algorithms to determine traffic flows within the control system. The origin-destination information is used to set strategies for arterial signal control and freeway ramp metering. One of the primary advantages of the HERMES system is that it seeks to go a step further than SCATS or SCOOT by searching the network for the occurrence of disruptions or incidents which can restrict the flow of traffic. Then it implements new routing strategies, based on the location and severity of the incidents, to most efficiently route vehicles around the effected area.

The automatic incident detection element of the HERMES system is contained in the MONICA (Monitoring Incidents and Congestion Automatically) algorithm.^(13,14) Once an incident is detected in the system, a process of rerouting the traffic is enacted. The difficulties of implementing a fully integrated system like HERMES mean that some aspects of the project remain in the simulation and development stage. However, work continues since the integration of an automatic incident detection and traffic rerouting system within an advanced traffic signal control system remains a desirable goal.

Another form of advanced traffic control under study and development is the OPAC (Optimization Policies for Adaptive Control) demand-responsive traffic signal control for individual intersections.^(15,16) This ATMS structure uses a dynamic programming approach to determine an optimal signal control strategy. It then compares the optimized timing to a more conventional optimized signal timing pattern, based on volumes and past experience.

The research study indicated that the OPAC strategy demonstrated a significant improvement over fixed time control. The conclusions were drawn from simulation trials and analyses using Highway Capacity Manual⁽¹⁷⁾ criteria. The study did not include field verification of the simulation trials. The obvious limitation of the OPAC system is that it optimizes signalized intersections in isolation, in contrast to SCATS and SCOOT, which seek system optimization.

2.2 Traffic Simulation and Model Tools

As the volume of traffic increased and individual signals were coordinated into signal networks, the need to measure the effect of signals on the efficient movement of traffic within networks became more important. Advanced technologies have allowed more sophisticated analysis techniques for the study of traffic control. The advanced methods to study traffic control have been researched and developed concurrent with the advanced controls themselves. Studies to measure the performance of traffic signals have been underway, in one form or another, since the invention of the signalized traffic control.

Research into the principles of how signals contribute to delays began to take shape in the 1940's and 50's. Many of the early studies of signal control analyzed intersections in isolation. They focused on the effect of signals on the approach traffic arriving at an intersection. One of the earliest available studies used mathematical equations to evaluate starting delay and how it could impact the capacity of an intersection.⁽¹⁸⁾

As technology levels increased and the need to study and understand the effects of signalized traffic control became more apparent, more complex study methods were employed. During the 1960's, efforts were made to test mathematical models of various timing controls with the assistance of computers. One of the earliest published studies to investigate the use of computer simulation, lauded the anticipated results that it could bring to the field of traffic engineering research.⁽¹⁹⁾ It was hoped that the use of computer simulation would also help

spur the development of more complex mathematical models constructed to describe the behavior of traffic flow. This study attempted to describe the physical characteristics of the intersection, the generation of vehicles, and the acceptance of left turning gaps, in terms of mathematical models. It was correctly assumed at the time that computer simulation models could be used to study hours of traffic conditions without effecting actual operating conditions in the streets. The procedures of these models were coded and simulation trials executed by a computer to determine the accuracy of the model predictions. The early research also demonstrated how the state of computer technology at that time did not allow this study to be completed. The lack of research computers and the frequent breakdown of existing equipment hampered many early efforts.

A study published in 1963 that continued the initial computer simulation project was more successful in gaining some output results. The research study was one of the first to use the results of computer simulation to evaluate various patterns of signalized control.⁽²⁰⁾ The project involved the simulation of some 60,000 hours of traffic behavior to compare some of the basic relationships between traffic volumes and vehicular delay under various traffic control and volume conditions.

The lessons learned from early computer simulation studies remain valid today. For example, the occurrence of rare events such as accidents, especially if they were not recognized, could effect studies involving field observed data. Computer simulation allowed such events to be included by the use of probability distributions. Experiments that contained rare events could be tested over and over to focus on different aspects of traffic behavior. The study pointed out that computer simulation could also prove to be an extremely valuable tool for the completion of “before” and “after” studies because of the extreme difficulty in obtaining similar conditions to evaluate a change in control.

Later research studies continued to advance the knowledge base and complexity of computer simulation applications to traffic engineering. A simulation study completed in England in

the 1960's attempted to assess the implementation of certain signal control improvements to an area before it went into operation.⁽²¹⁾ The study was also one of the first to make use of simulation to model an area wide network rather than just an isolated intersection. Another interesting research technique documented in this study involved the use of events which were observed in the field but not reflected in the original simulation output. The events were used to reprogram the model to allow it to more realistically simulate the observed behavior.

The use of computerized traffic simulation and analysis programs have developed from use as strictly a research device, to very valuable tools in modern traffic engineering practice. Two programs, SOAP and TRANSYT-7F, were developed independently during the 1970's. After years of separate use the two programs are often used together for the evaluation and analysis of traffic signal plans. TRANSYT was developed in England to analyze coordinated progression of traffic signals on arterial roadways. It helps a users to evaluate various signal cycle lengths which will promote the movement of traffic through a particular corridor. The system attempts to promote the formation of traffic platoons and minimize the number of stops at red lights. The program will also produce space-time diagrams which are also helpful in the analysis of traffic flow. The Signal Operation and Analysis Package (SOAP) was developed for the analysis of single isolated signalized intersections. It was originally coded at the University of Florida in the 1970's and, like TRANSYT, has undergone numerous modifications to upgrade it accuracy and usefulness. It can be used to evaluate traffic signal design alternatives at four-legged intersections with or without protected left turning phase intervals in the signal sequence, including fixed time, semi-actuated, and fully actuated control. One of the benefits of the SOAP program is that it allows the operating characteristics of an individual intersection to be expressed in terms of specific measures of effectiveness (MOE). SOAP MOE's include the calculation of various vehicle approach delays, number of stopped vehicles, fuel consumption, queue lengths, and other flow characteristics.⁽²²⁾ Its primary limitation, however, is the lack of a mechanism to adjust vehicle arrival distributions. The SOAP delay analysis algorithms assume a random

arrival pattern in all analyses.

Development of increasingly more detailed and sophisticated traffic simulation continued through the 1970's and 80's. Simulation has developed into a standard application tool for the modern traffic engineer. One of the most widely used traffic simulation programs today is the NETSIM computer model.⁽²³⁾ NETSIM, as its name suggests, is a microscopic road network simulation program. It was initially developed by the Federal Highway Administration in the mid-1970's as a method of modeling traffic events on arterial road networks. It is extensively used by transportation engineers and planners to analyze various highway design and traffic planning scenarios. The NETSIM program has continued to evolve and add more complex features to keep pace with advancements in traffic control technology. More advanced versions of NETSIM, currently under development, will also include features to assist in the modeling of adaptive signal control. Unfortunately, these systems were not available to assist in the completion of this study.

Recently, NETSIM has been incorporated into the TRAF family of traffic simulation programs. The TRAF modeling family encompasses a variety of independent freeway, arterial, and rural road simulation programs. The programs within TRAF are ROADSIM, a two lane roadway simulation model, FREFLO, a macroscopic freeway simulation model, NETFLO 1 and 2, macroscopic urban network simulation models, and FRESIM, a microscopic freeway simulation model. The central concept of the TRAF system is a compatible format of data exchange which allows them to be compatible with one another. This compatibility allows the various programs to be linked together to form broad-based multi-level traffic simulation models. These multi-program TRAF models allow the simulation of large scale traffic networks that may include both freeways and arterial roadways.

While the TRAF system allows a compatible format for the simulation of separate arterial roadway and freeway sub-networks, the most advanced simulation tool for the coordinated

modeling of arterial and freeway traffic systems is the INTEGRATION simulation program.⁽²⁴⁾ The INTEGRATION model was developed in Canada in the 1980's and incorporates many concepts which are very useful for the analysis of urbanized traffic flow. Primary among these is a strategy to model various forms of traffic assignment. The INTEGRATION program allows users to assign traffic volumes to a road network based on various conditions. These could include shortest travel distance, shortest travel time, or special conditions such as traffic rerouting due to incidents and congestion. Research is also underway to investigate the addition of dynamic route guidance in the INTEGRATION model.⁽²⁵⁾ A dynamic route guidance simulation model would be a very valuable tool to advance research in the area of intelligent traveler information systems.

The continued development of more advanced methods of computer simulation has played a key role in the study and cultivation of many traffic engineering theories. Current simulation models are able to very accurately predict detailed traffic stream parameters such as delay at signalized intersections, if the appropriate traffic flow data are known.^(15,26) A detailed assessment of current traffic simulation modeling was documented in research papers by Wang and Hsin⁽²⁶⁾ and Wang and Niedringhaus.⁽²⁷⁾ These papers documented some of the needs and requirements necessary in the next generation of traffic management simulation programs. The later presented the development process of the THOREAU (Traffic and Highway Objects for Research, Analysis, and Understanding) program. The THOREAU model appears to present a promising platform for the construction of complex traffic simulation models. It makes use of many innovative concepts in the field of computer programming and data processing, including object oriented programming and parallel processing. These allow for more detailed simulations of real world events and allow for faster construction and execution of the simulation models. THOREAU can also be used to model adaptive traffic signal control.⁽²⁸⁾

The recent interest and funding dedicated to Intelligent Transportation Systems has also allowed new simulation models to be developed at a more rapid pace. A recent study

sponsored by the United States Department of Energy identified some of the best available traffic simulation models.⁽²⁹⁾ These include freeway and arterial simulation models like INTEGRATION and the TRAF family of simulation programs. The study also pointed out the importance of the development of more sophisticated simulation models and some of the critical requirements that future generations of traffic simulation models should include. These ranged from the simulation of traffic flow, to the modeling of driver route selection behavior, to the environmental impacts of traffic activities. The authors indicated that future models will need to be more “user friendly” and allow users to quickly and accurately model complex systems which may involve very sophisticated traffic control and guidance activities. The text stressed the need and importance for such models and the need for further research into these and related computer simulation programs.

2.3 FAST-TRAC and Related Intelligent Highway Projects

SCATS hardware and computer technology have been implemented on the road network within Oakland County, Michigan.^(30, 31) The signal improvements are part of the FAST-TRAC (Faster and Safer Travel - Traffic Routing and Advanced Controls)⁽¹⁾ system, the national demonstration project for Advanced Traffic Management Systems (ATMS)/Advanced Traveler Information Systems (ATIS). The project involves the conversion of over 1,000 pretimed and actuated signalized intersections to SCATS control. In 1995, there were about 200 SCATS controlled intersections operating within the Oakland County system. Traffic flow data are gathered at each intersection and transmitted to a central control center. This center serves as the heart of the traffic management system. It houses the SCATS computer program and the various control systems required to execute the modifications to the signal controllers.

An evaluation study is currently underway of the Troy FAST-TRAC network.⁽⁴⁾ One of the primary goals is to document the impact of SCATS control on intersection delay. While the study is not complete, some preliminary data have been compiled. It appears that the SCATS

method of ATMS has some tangible benefits over fixed time signals, under certain traffic conditions. The Troy evaluation study, involved a “before” and “after” technique to evaluate the system performance. The measure of effectiveness used to compare the “before” and “after” periods was average stop delay per vehicle at the intersections. Autoscope video image detectors⁽³²⁾ were used to record traffic volumes and video taped data were used to record the stopped vehicle queues on the approach legs. Various recording and simulation methods were employed to determine the delay. One method involved the use of video camera data to calculate an average delay per vehicle by timing the stop delay experienced by the first, last, and “middle” vehicles in the stopped queues on each of the approaches.

The FAST-TRAC project is only one of several ITS projects which are in operation or under development in the State of Michigan.⁽³³⁾ The SCANDI (Surveillance Control And Driver Information) project is another ATMS project which has been in operation since the 1960's. It is comprised of a system of loop detectors, closed circuit cameras, and changeable message signs located at various positions on three major freeways within the City of Detroit. The system was installed to assist drivers in anticipating congestion and give information on events such as road construction. An extension of the existing system is currently under contract. The upgrade will involve the addition of systems for automatic incident detection and motorist aid. Other Michigan ITS projects include DIRECT (Driver Information Radio using Experimental Communication Technologies) and MACS (Mainline Automated Clearance System). These projects involve the implementation of systems for advanced traveler information and commercial vehicle operations.

Although the primary application of advanced technology for the improvement of highway transportation has been focused on congested urban settings, the use of emerging ITS technology has also been proposed for rural areas. One such project is currently under development in Minnesota. It involves the use of advanced traveler information systems and advanced transit information services.⁽³⁴⁾ The deployment of ATIS systems are of particular value to tourist traffic. Visiting drivers are in greater need of travel information services

because they are often unfamiliar with the local road system. They are also in frequent need of special interest information like the location of specific points of interest, gas stations, and road construction zones. Recent studies have also stressed the need for intelligent transportation systems in rural areas to assist with advanced warning for unexpected road hazards, speed enforcement, and commercial vehicle navigation and safety.⁽³⁵⁾ The 1992 Intelligent Vehicle Highway System (IVHS) Strategic Plan prepared by the United States Department of Transportation outlined the application of advanced technologies in rural areas for the identification of hazardous weather conditions on roadways and the coordination of public transportation services for lower mobility individuals.

2.4 Comparative Studies of Adaptive Traffic Signal Systems

Many studies have been completed which claim to have evaluated adaptive signal traffic signal systems. Several of the more recent studies have involved the two most widely used real-time traffic responsive signal systems, SCATS and SCOOT. Past studies have completed comparisons of these systems against various forms of less sophisticated forms of signal control like coordinated fixed time actuated control. The depth and level of detail incorporated into these comparative studies has varied, although none of the previous studies has used simulation nor stopped delay as a performance measure.

2.4.1 SCATS

Many studies of adaptive control have been carried out by the creators of SCATS, the Australian Road Research Board (ARRB) and the Department of Main Roads in New South Wales. One study evaluated SCATS against various forms of non-adaptive forms of signal traffic control.⁽³⁶⁾ The study measured the performance of SCATS against the control characteristics afforded by systems with isolated fixed time signal phasing and TRANSYT optimized fixed time control with and without local vehicle actuation. The study, however, documented solely the results of the performance comparison of SCATS and TRANSYT optimized timings.

The ARRB study made their comparison using the floating car travel time estimation technique to record the “journey” or travel time on each link, the number of stops in each link, the stopped time in each link, and the amount of fuel used in each trip. The recorded stopped times were later found to be unreliable, so they could not be used in the analysis. The accuracy and reliability of the fuel meters also prevented a valid analysis of fuel consumption data. The study was able to compare the different signal systems in terms of travel time, number of stops, and a derived “Performance Index.” The Performance Index was a weighted measure of travel time incorporating the number of stops during the trip. The study found that on one arterial highway, SCATS resulted in a 23% reduction in travel time and a 46% reduction in stops over isolated fixed time signals. In the central business district (CBD) study area, the travel time was not effected and the reduction in stops was 8%. When compared to Linked Vehicle Actuated (LVA) control, SCATS showed some benefits and some degradations in the recorded performance measures on the arterial and in the CBD areas. The comparison of SCATS and TRANSYT optimized fixed times concluded that SCATS can improve travel time and number of stops from 3% to 18%. The actual improvement depends upon the type of road system (CBD network, arterial corridor, etc.) under study.

A similar comparative study carried out by the authors of the previous study evaluated a precursor to SCATS.⁽³⁷⁾ The paper documented a performance study of the Department of Motor Transport (DMT) signal system against optimized fixed time networks of isolated and coordinated signals. The study also analyzed bus priority signal preemption under different forms of control. Using travel time as its measure of effectiveness, the research study demonstrated that the DMT control strategy showed an improvement of 35% to 39% over optimized fixed time control during morning and evening peak hours. However, the DMT system increased the minor cross street delay. The bus priority system under DMT control showed an improvement of 11% to 26% in bus travel times over the optimized fixed time operation.

A comparative study of SCATS versus SCOOT was conducted by the Australian Road Research Board.⁽³⁸⁾ It detailed the similarities and differences in the data requirements, hardware, and operation of the two systems. Unfortunately, a direct field comparison of the operational differences between SCATS and SCOOT was not possible. Direct comparisons using simulated or actual data are very difficult, due to the different locations where traffic flow data is gathered. In SCATS, traffic information is collected at the approach stop lines. The required traffic flow information for SCOOT is collected upstream of the stop lines. The two systems also differ in their operating requirements for computer processing. The paper stated that SCATS is better in some applications because it has the capacity to estimate congestion better than SCOOT. By contrast, SCOOT can be more effective in certain heavy flow situations because it incorporates an automatic double-cycling mechanism which SCATS does not have.

The study indicated that the two systems are also similar in many respects. They both implement frequent but small changes in cycle time, phase splits and offset to accommodate rapid fluctuations in traffic demand. Past field trials have shown that during certain time periods, fixed time signal control can out perform both of these two systems.^(37,39) The study concluded by stating that neither system is perfect and that both systems could benefit from additional improvements.

Another comparison of SCATS to other forms of advanced signal control was completed prior to the installation of the Oakland County FAST-TRAC project.⁽⁴⁰⁾ The study was conducted to compare four different types of advanced traffic management systems; SCATS, SCOOT, UTCS, and OPAC. The comparison study was completed to select the type of real-time adaptive signal control that would be used in the County. The study did not incorporate field experiments to support the selection decision. Each system were compared on the merits of certain criteria that was of particular value to the Road Commission for Oakland County.

2.4.2 SCOOT

The amount of available published research on comparative studies involving SCOOT appeared to be greater than that of SCATS. This is the result of SCOOT's greater level of use in North America. A study was recently completed as part of the Metropolitan Toronto SCOOT demonstration project. The initial size of the Toronto SCOOT network was 75 signalized intersections. A report of preliminary findings was prepared and presented in 1994.⁽³⁹⁾ The report claimed that the Toronto SCOOT project resulted in a decrease of 6% to 11% in travel time along the study corridor during peak periods of traffic demand. The study also documented travel time improvements that measured as high as 34% on certain arterial roadways after major sporting events. The preliminary report showed that benefits were also apparent in vehicular and pedestrian safety. The study did acknowledge that under certain flow conditions in Toronto, some SCOOT controlled intersections could be out performed by fixed time control. The study did not, however, document the details of the experimental design, the analysis techniques, nor all of the data collection methods and performance measures.

Another recent SCOOT evaluation study in North America was completed in Oxnard, California.⁽¹⁰⁾ The Oxnard project involved the first installation of SCOOT in the United States. The report documented an observed improvement in total system delay and number of stops. Unfortunately, the study was only a cursory report of observed traffic conditions. The study conclusions were based on the SCOOT data collection statistics for recorded stops and delay. Therefore, the author stated that the amount of data collected for analysis did not allow the results to be scientifically corroborated.

Other studies of SCOOT have examined traffic operating conditions under off-peak traffic flow conditions. One assessed the change in certain performance measures during low flow conditions.⁽⁴¹⁾ The study used the number of stops that were experienced by vehicles traveling through both a corridor and grid network of SCOOT governed intersections. The study was conducted in suburban London, England and used data collected during off-peak

times. The study found that in the corridor study area, the number of stops was reduced by 17% compared to fixed time control. In the grid network the study found that SCOOT control also resulted in a 17% savings when compared to fixed time signal control. However, the study also showed that during very low flow periods (1:30am to 2:00am) SCOOT was out performed by vehicle actuated (VA) signal control. This was reasonable to expect since VA control can eliminate signal phases on the cross-street and SCOOT cannot.

2.5 Literature Review Conclusions

The review of past published literature into the various areas related to the study has demonstrated the interest in and importance of advanced traffic control systems, computer-aided traffic modeling, and comparative studies of the various forms of traffic signal control. A review of the literature has shown the important role that ATMS will play in more efficiently utilizing our transportation infrastructure. Today, real-time adaptive signal control systems like SCATS and SCOOT are available for mainstream use in the United States. As a result, studies which can assist current and future users of such systems to determine their expected benefits are extremely valuable.

Unfortunately, the existing published research literature has also indicated the need for further research into more detailed measures and newer methods to assess the changes which can be expected from adding SCATS control to a signalized network. Some of the past studies have conducted comparative studies using route travel time and the stop frequency field measurements and have shown the benefits of SCATS and SCOOT over optimized fixed timed systems. However, the study authors have used travel time or the number of stops as their only performance measures. While these performance indicators are very helpful, they cannot reveal all of the details of what is occurring in the system. They only present the “big picture.” The South Lyon evaluation study was proposed to overcome this existing lack of information.

The primary reason for the lack of detailed analysis has been the lack of sophisticated data collection and analysis methods and tools. Now, traffic flow databases can be compiled using automatic collection and storage techniques. Traffic flow data can be collected continuously; at any time and under any flow condition. This is possible because of systems like Autoscope sensing technology and complex and high-speed computer systems. As a result of commercially available computer simulation modeling and analysis tools like SOAP, NETSIM and THOREAU, traffic flow analyses can be completed quickly and inexpensively under repeatable and controlled conditions.

The South Lyon evaluation study will take advantage of these more sophisticated analysis tools to complete a comparative study of certain detailed aspects of real-time adaptive signal control. The research project will use some recent methods of data collection and computer simulation to model and test the effect of the change to SCATS signal control in South Lyon using intersection approach delay performance measures.

Chapter 3.

Research Objectives and Approach

It has been hypothesized that the use of advanced traffic management systems, like SCATS, will result in significant improvements to traffic flow performance within a controlled network. Prior studies^(4,10,11,39,41) have demonstrated that SCATS and SCOOT can reduce route travel times and intersection delay when compared to conventional fixed time systems. Other studies have shown how adaptive control systems can be used to improve the operation of transit bus systems or flow conditions during special event situations, like sporting events. However, the published research literature has also demonstrated a lack of significant in-depth research into some of the specific ways that these flow improvements are attained.

One of the primary reasons for the lack of information about certain flow performance details is that they are difficult to measure, calculate, and analyze. For example, intersection stop delay is one of the prime contributors to travel time changes during the day. It is also a useful measure of system performance because it can indicate the efficiency of signal phase splits and is used to rate the Level of Service of signalized intersection approaches in the

Highway Capacity Manual.⁽¹⁷⁾ Two comparative studies^(36,37) that were reviewed in the preceding chapter documented how the use of SCATS resulted in reduced travel time and number of stops at red lights. However, neither of these studies used stopped delay as a measure of effectiveness. The use of travel time and number of stops is valuable in assessing certain aspects of system performance. However, they do not provide a level of detail necessary to analyze certain aspects of urban traffic operations. The use of intersection delay statistics give details about signal efficiency and can better explain the changes which are brought about by SCATS signal control.

One of the past studies⁽³⁶⁾ attempted to use stopped delay as a measure of effectiveness, however, it was not possible because the recorded stopped times were found to be “unreliable.” Delay statistics are often difficult to field measure. Timing information for stops, starts, and turning movements must be collected for all vehicles on an approach. Reduction of the data is also complicated. Recently developed techniques like video image sensing and recording have made it possible to collect data in a more simplified fashion. Unfortunately, even with these advances, data reduction remains a long and tedious process.

For some time it has appeared that the most promising method to overcome some of the shortcomings of the past research was the use of simulation. Simulation programs like NETSIM and SOAP provide a very useful means to assess certain traffic parameters under highly controlled and repeatable experiments. To their disappointment, past researchers have also found these programs to be limited in their ability to simulate adaptive traffic signal control. The Federal Highway Administration has recently contracted to upgrade the NETSIM program to incorporate an adaptive signal control interface mechanism. Within this new system, traffic flow information can be relayed to an external program which can affect signal phase timing changes within the NETSIM simulation run. The process involves a continuous feedback loop between the movement of traffic and modification of signals.

Due to the proprietary nature of most adaptive signal control systems and the inherent difficulties involved in making modifications to the existing NETSIM code, the realization of a NETSIM based real-time control simulator remains in the developmental stage. Until this new system is perfected, the simulation of real-time adaptive traffic signals remains a cumbersome process. However, the simulation of real-time traffic signal control can be accomplished by using a series of incremental step models which modify signal cycle and phase splits on a cycle-by-cycle basis.

This study will take advantage of the incremental simulation process to model a network of real-time adaptive traffic signals. This research will advance the understanding of adaptive signal control by completing an evaluation of delay time characteristics within the South Lyon ATMS project area. The results of the study will provide new evidence to evaluate the claim that improvements to certain traffic delay parameters can be expected when SCATS is introduced to an area. The study will test the hypothesis that significant and measurable changes (improvements) to certain delay characteristics are likely after the implementation of SCATS. To attain this goal, several research objectives will be met.

3.1 Objectives

The prime objectives of the South Lyon ATMS evaluation project are to record, document, and analyze the changes which occurred to the traffic flow conditions within the South Lyon signalized road network as a result of the addition of the SCATS signal control management system. To accomplish this objective, this study will incorporate a detailed process of data collection, simulation model construction, and statistical analysis. Data collection will be carried out using various means, including field observation, and video image sensing. The analysis of the data will be completed with the assistance of the SOAP isolated signalized intersection simulation and analysis program. Several SOAP models will be constructed for each intersection during the “before” and “after” analysis periods to calculate certain measures of operational performance recorded during the separate analysis periods of the

study. After the performance measures for each period are calculated, a comparative analysis of the two intervals will be carried out using suitable statistical testing procedures. The analysis will indicate whether the measured change in operating conditions after the implementation of SCATS was statistically significant.

To determine the extent of the change in quantifiable terms and document the results, the study will address the specific questions shown below.

- 1) What is the difference in the total intersection delay time in the South Lyon road network for the existing non-adaptive, pretimed, signal scheme and the SCATS adaptive control mode? Is the measured difference in the total intersection delay time statistically significant or is it a result of random changes which occur within the traffic stream?
- 2) What is the difference in the average approach delay times at selected intersections within the South Lyon road network between the existing non-adaptive, pretimed, signal scheme and the SCATS adaptive control mode? Is the measured difference in intersection approach delay time statistically significant or is it as a result of random changes which occur within the traffic stream?

The research questions will establish the measures of performance to compare the two different signal control strategies during the “before” and “after” periods of the study. The improvement brought about by changes in traffic control can be assessed using many different measures (i.e., safety, delay, travel time, etc.). The two measures selected for this study were based on their relevance to the goal of reducing traffic delays in the community of South Lyon. Each is described in detail in the following sections.

3.1.1 Total Intersection Delay

The total delay at an intersection is defined as the difference in travel time experienced by a vehicle as it is affected and unaffected by the traffic control at an intersection. It includes

the “lost” time due to deceleration and stopped delay.⁽⁴²⁾ It is also the composite of other delay sources, including queue delay at over-saturated intersections and “unnecessary” stopped delay. Information acquired from a recently completed study of a SCATS implementation project in Troy, Michigan has shown that the unnecessary stopped delay could be of particular significance to the South Lyon study. Unnecessary stopped delay is defined as “the portion of the stopped delay which occurs when there is no vehicle entering an approach on the opposing legs of the intersection.”⁽⁴³⁾ During the SCATS implementation project in Troy, many intersections received exclusive left turn lane signal control where none had previously existed. As a result, left turns could be completed only under a protected left turn phase. Status reports performed after the change demonstrated the existence of added delay and user dissatisfaction at locations where permissive left turns were no longer allowed. There are two intersections with protected/permissive left turn phasing in South Lyon. It is expected that the total delay statistic will measure the unnecessary delay at these intersections.

Many different analysis techniques for the calculation of total intersection delay have been developed.⁽⁴⁴⁾ The most widely used employ mathematical models to calculate various aspects of total delay which are the result of vehicle arrival patterns. The comparison of total delay during the “before” and “after” periods of this study will be accomplished through the use of the SOAP simulation model.

3.1.2 Approach Delay

The research study will also assess the change to the specific portion of intersection delay known as approach delay. The approach delay is measured separately at each approach. It is defined as the length of time that vehicles approaching the intersection from a particular direction are delayed due to a red signal phase and/or a stopped queue in front of them which prohibits their travel through the intersection.⁽⁴⁴⁾ To express approach delay in more useful terms it is often converted to average stopped delay per vehicle on a given approach during a specified time interval. This is the measure by which the Highway Capacity Manual⁽¹⁷⁾

assigns a Level of Service rating to signal controlled intersections.

The average approach delay per vehicle can be measured in various ways, using various means. One method is to record the delay experienced by vehicles located at three positions within the stopped queue. Delay measurements are taken from the first vehicle arriving after the start of the red phase, the last vehicle to join the stopped queue, and that of a vehicle lying somewhere in the middle of the queue. The three delay times are averaged and assigned to each of the total number of vehicles in the queue. To study an hour long period this process of delay measurement and assignment would need to be completed for each approach during all signal cycles within the hour to determine the average delay during that time period. The average approach delay times during the “before” and “after” periods of this study, will be accomplished automatically using SOAP traffic simulation models.

3.2 Approach

The experimental approach used to determine the extent of the changes after the implementation of SCATS, will involve a modified “before/after” analysis. A typical “before/after” analysis technique requires the collection and study of like data elements during time periods both before and after a change is made to a system. The premise of this type of study states that when all other factors involved in the system are controlled for, any differences which are recorded are attributable solely to the changed variable.

For reasons that will be detailed later in this chapter, the research methodology of this study will require a modification of the traditional “before/after” design. The analysis of the “after” condition will take place prior to the analysis of the “before” condition. The “after” study will analyze traffic conditions in South Lyon after the implementation of SCATS traffic signal control. The “before” analysis will evaluate the same traffic conditions under optimized fixed time traffic control. The same measures of operational effectiveness; total intersection delay and average intersection approach delay will be used to assess both

”before” and ”after” periods.

As is often the case with many research methodologies, the “before/after” technique of analysis contains some inherent weaknesses. Some of the shortcomings of this technique stem from the lack of total control over the fixed factors involved in the experiment. The experimental assumption is that all factors remain constant and all recorded changes would be the result of the change to SCATS signal control. Unfortunately, traffic volumes, turning movements, and incident occurrences can vary significantly from hour to hour, day to day, and week to week. Therefore, it would be impossible to hold all of the factors constant in the field. To restrict the amount of variability in these elements during the separate periods of the analysis, computer simulation will be used. Simulation will allow controlled and repeatable experiments to be performed on the traffic stream. With the use of the SOAP intersection simulation and analysis program, it is also possible to calculate and present detailed information about the performance of a signal at an intersection. To accomplish the same level of detailed analysis in a field setting would be nearly impossible.

The research strategy will incorporate four primary steps of data collection, ”before” and ”after” simulation experimentation, and a comparative statistical analysis. Each of the four steps will build upon the results gained from its predecessor. The first step will involve the collection and sorting of all data elements required to construct and execute the comparative traffic simulation models. The second and third steps will include the assembly of the models to conduct the “after” and “before” analyses. The final step of the study framework will complete the statistical comparison of the “before” and “after” measures of effectiveness. Detailed descriptions of each of these steps is presented in the following sections.

3.2.1 Data Collection

The data collection phase of the study will involve the collection of both physical elements and traffic flow parameters of the South Lyon traffic network. The physical elements of the

system include features of the South Lyon road network such as the number of road segments, intersections, approach lanes and use configurations, as well as traffic control items such as posted speed limits. The original fixed time signal timing information will also be recorded during this time and subsequently verified against Road Commission signal log records. All of these data elements will be collected manually, primarily through visual inspection.

The collection of traffic volumes will not be completed in the field, rather they will be computed from SCATS data files. These files are created by the SCATS control software and are stored at the Road Commission for Oakland County traffic operations center in Troy, Michigan. Traffic flow information is collected at the intersections in South Lyon by the Autoscope video image detection system. The Autoscope detection architecture allows the presence of vehicles to be acknowledged at each approach to the SCATS intersections. Traffic information is collected primarily for the purpose of selecting an appropriate timing plan for the intersection. However, this information can also be stored for later analysis.

A typical SCATS data file contains several important pieces of data which can be used to analyze the operation of the signal and traffic conditions. It is made up of a stream of data records that include a cycle-by-cycle history of signal phase splits, cycle length, and approach degree of saturation. Using relatively simple computer programs, the files can be sorted and the pertinent traffic volume and signal timing information extracted for use.

The collection of traffic volume and signal timing data for the “after” analyses will not be conducted immediately after the change to SCATS signal control in South Lyon. The collection of the data will begin after an “acquaintance and adjustment” period has taken place. The adjustment period will be required for several reasons. Most important, it will allow drivers to adjust to the new signal phasing strategies. SCATS is not only real-time adaptive, it may also adjust, rearrange, or eliminate certain phases from the signal cycle. Thus, drivers who were familiar with the fixed time signal operation will be allowed to adjust

their driving habits to fit the new SCATS control plans. The adjustment period will also allow the Road Commission for Oakland County time to correct and “fine tune” the operation of the SCATS system.

3.2.2 The “After” Traffic Analysis

The second step of the experimental approach strategy will be to complete the “after” analysis study. The “after” analyses will be conducted using the stored signal and traffic data and physical features of the South Lyon collected in the first step. A SOAP simulation model of the traffic conditions for a one hour interval will be coded with this information. Separate models will be constructed for each of the six SCATS controlled intersections with the network.

Unfortunately, the SOAP modeling environment, nor any other currently commercially available traffic modeling software, allow modifications of traffic signal timings in response to traffic volume to be made during program execution.

To overcome this lack of sophistication, the “after” analyses will be conducted using a series of incremental SOAP simulation runs. Each SOAP model series will correspond to a time interval as it was recorded in South Lyon. Each increment in the series will represent a single signal cycle time “slice.” The SCATS implemented signal phase split plan, offset, and cycle length for each one cycle increment recorded in the data file will be used to code the model. The length of each time slice will depend on the length of signal cycle length which was selected by the SCATS control program. The output data from this sequence of simulation runs will be compiled to analyze the full one hour period.

The approach traffic volumes used in the “after” simulation models will be augmented by turning movement volumes as they occurred in the field. This is useful since the SCATS control structure implements signal timing plans based on a “saturation equalization” concept. Some of the intersections have phase splits that are modified based on the degree

of saturation for critical movements on the constituent approaches. Additionally, SCATS implements cycle length and phase splits changes based on the efficiency of the preceding cycle. If one particular movement was below saturation during a cycle, it will in theory, receive less green time during the next cycle.

The final phase of the “after” analysis will be to use the “after” traffic model output to calculate the various measures of effectiveness (MOE). These measures will include the total intersection delay, average intersection stopped delay, and the average travel time for selected routes within the network and will serve as the basis for comparison against the “before” simulation results.

3.2.3 The “Before” Traffic Analysis

Step three will encompass the “before” traffic analysis. The “before” simulation model will represent the traffic flow conditions in South Lyon prior to the implementation of the SCATS control system. Instead of using field traffic volume data collected in South Lyon under the fixed time signal settings, the “before” analysis will use the same traffic volumes as the “after” study. This arrangement will insure a direct comparison of conditions. The traffic signal timings will be modified from the “after” models. An optimized version of the RCOC fixed time signal phase split, cycle, and offset timing plans will be used to process the traffic demand. Separate “before” models for each intersection will be executed to calculate the signal MOE’s. However, each run will model a full one hour period instead of the multi-step approach used in the “after” analysis.

An optimized version of the original RCOC fixed timing plan will be used so that an objective comparison can be made between SCATS and fixed time control. The original Road Commission pretimed signal phase split, cycle, and offset timing plans were developed to efficiently accommodate peak and off-peak traffic demand using a system of historical traffic volume and flow monitoring. The original RCOC signal timing plans may not represent the time settings for the greatest reduction in delay for traffic volume recorded

during the study time periods. The fixed signal timings will be optimized using the SOAP phase split optimizer before being used to calculate the output MOE's. The use of these optimized timings will help to demonstrate the difference in delay conditions between SCATS and optimized fixed time control. Any improvement which is gained from SCATS will represent the result of its utility rather than the result of a comparison to a poorly timed fixed time system.

Separate simulation models representing each of the six SCATS controlled intersections will be constructed and executed during the "before" analyses. In contrast to the segmented "after" models, each of the "before" simulation models will be executed as a single continuous model. The one hour approach traffic volumes will be the same as "after" study and turning movement percentages will use the same distribution as the "after" analysis. Since the signals timing plans are fixed they will not be influenced by the level of traffic. The sole difference between the two analyses will be the traffic signal timings.

The final phase of the "before " analysis will be to determine the SOAP "before" traffic model output measures of effectiveness. As in the "after" analysis, the measures will include the total intersection delay, average intersection stopped delay, and the average travel time for selected routes within the network. After these figures are calculated they will be compared in the final phase of the study.

3.2.4 Comparison of Results and Conclusions

The final step of the project will be to compare and document the observed differences in the measures of effectiveness between the "before" and "after" periods. The comparison will be performed using statistical testing procedures which have been developed specifically for evaluating the results of experiments identical to that which has been proposed in this study.

The primary statistical testing procedure that will be used to compare the "before" and "after" simulation output data will be the t-test. The t-test incorporates a procedure which is

ideal for making paired comparisons of two data sets, especially “before/after” studies. A comparison of the mean total delay, stopped delay, and average travel time in the “before” period will be made against the mean total delay, stopped delay, and average travel time in the “after” period. The t-test allows a statistical determination of the degree of difference between the two study times to be calculated. It will also allow the significance of the difference to be determined to a specified level of confidence.

The t-test will be used to evaluate the hypothesis of the study; that SCATS control will result in a significant change to the average values of the performance measures in the South Lyon system. The test procedure will be based on the mean and standard deviation of the delay and travel times determined for the “before” and “after” analyses. The t-testing method makes it possible to determine if the change is attributable to SCATS or if it is due to random variations in operating conditions of the traffic.^(45,46)

Chapter 4.

South Lyon Traffic Analysis

The analysis of traffic flow conditions before and after the implementation of SCATS traffic signal control was conducted using mathematical and computerized modeling and analysis techniques. Currently, there are several computer based analysis packages which can be used for the evaluation of traffic signal performance. The levels of input and output data complexity found in these packages vary significantly. One commercially available traffic signal analysis tool is the Arterial Analysis Package (AAP). The AAP incorporates several different computer modeling and analysis programs that can evaluate different aspects of signalized traffic flow. The intent of the AAP system is to coordinate the use of these component programs to permit the simulation, analysis, and comparative evaluation of different signal timing strategies for a network of traffic signals. One of the constituent programs is TRANSYT-7F. TRANSYT-7F is used for the analysis of arterial traffic flow. It assists in the selection and evaluation of traffic signal offsets and cycle lengths. Another component of the AAP is the Signal Operations Analysis Package (SOAP). SOAP focuses on individual intersections. It allows automated comparisons and evaluations of various

intersection signal timing strategies.

Currently, neither the AAP, NETSIM, nor any other existing traffic modeling system permit a detailed analysis of real time adaptive traffic control systems like SCATS. To overcome the current lack of analysis tools, a new technique was developed to model the “before” and “after” delay conditions of the South Lyon traffic network. This new technique uses a combination of the SOAP signalized intersection traffic analysis package, existing mathematical models, and a new computational computer program developed specifically for the processing SCATS output data files.

The goal of this methodology was to use it to construct a set of traffic analysis models capable of simulating the intersection approach delay conditions of the South Lyon system before and after the implementation of SCATS. While the SOAP program could not be used directly for this purpose, the new analysis procedure was developed based on the SOAP delay computational methodology. A number of steps were required to create and make use of this analysis procedure. The following sections of this chapter describe the process and assumptions that were used to create the various models and present the results.

4.1 Data Collection

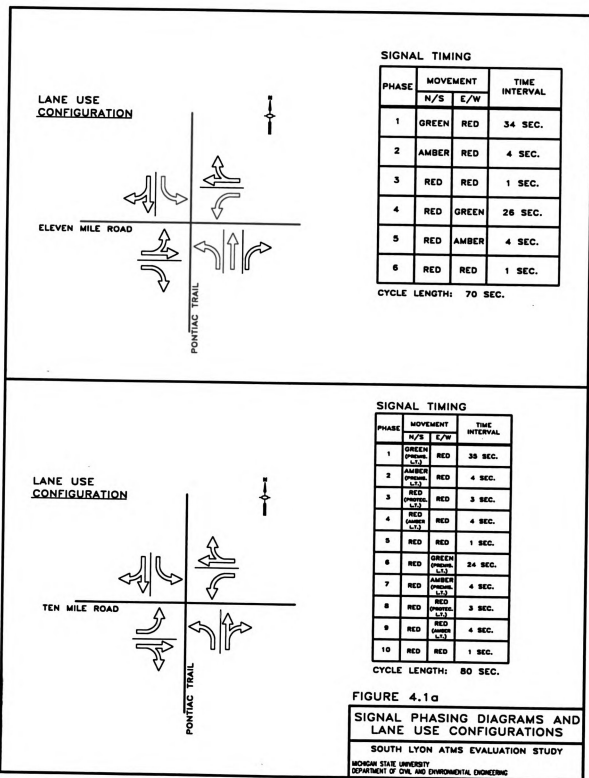
The first phase of the model development involved the collection and reduction of all elements necessary to describe the conditions at the South Lyon intersections. The SOAP program and its constituent equations are fairly detailed in their analysis of traffic conditions resulting from various signal timing strategies. By contrast, the input data requirements are not nearly as detailed. As a result, the data required to code and execute the models were relatively easily obtained. The acquisition of additional data to compare the model results to actual traffic conditional was also required.

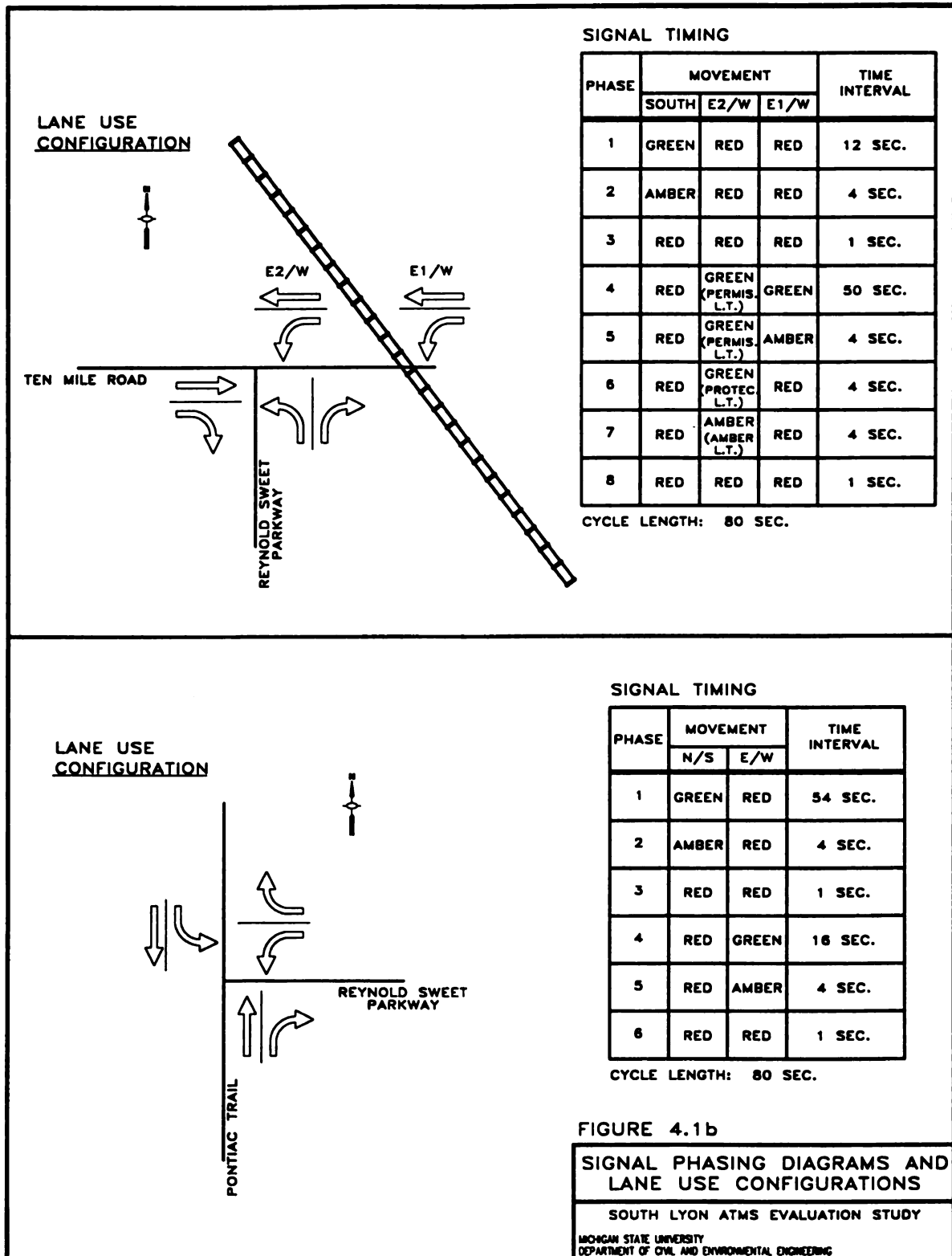
The collection of data fell into three primary categories. The first category included the SCATS traffic signal timing and the traffic volume information. These data were collected remotely and stored automatically by the FAST-TRAC SCATS system. The second category of data were collected by more traditional methods of direct observation. This data included elements such as intersection approach geometries and the fixed time signal plans. The last set of data collected for use in this study were collected as part of related SCATS evaluation studies in South Lyon. This information was used primarily for the comparison and verification of the model output data.

4.1.1 "Before" Data

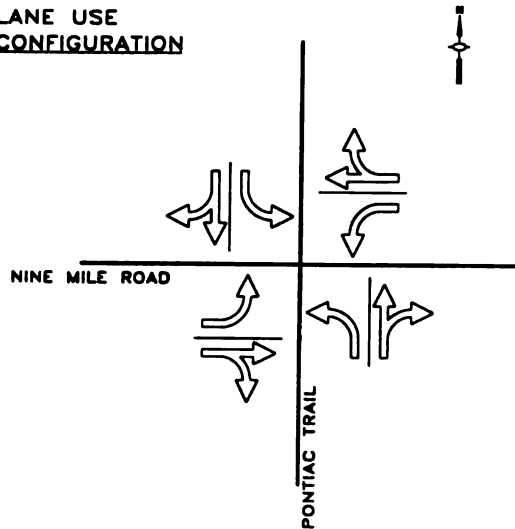
The collection of the "before" traffic volume and traffic signal timing data took place during the spring, summer and fall of 1995; prior to the implementation of the SCATS signal control and Autoscope video imaging system. The fixed time signal timing data was collected during a field visit on April 22, 1995 and verified against Road Commission for Oakland County signal log records. There were six signalized intersections within the South Lyon street network. They are the intersections of: Pontiac Trail with Nine Mile Road, Reynold Sweet Parkway, McHattie Street, Ten Mile Road, and Eleven Mile Road. The only signalized intersection not in the Pontiac Trail corridor was the Ten Mile Road/Reynold Sweet Parkway intersection, located approximately 1,000 feet east of Pontiac Trail. As part of the FAST-TRAC project, the control of all six of these intersections were converted to SCATS control. A street map showing the locations of each of the study intersection was presented earlier in Figure 1.2

The "before" signal cycle lengths, phase patterns, and intersection approach lane geometry are illustrated in Figures 4.1a, 4.1b, and 4.1c. The cycle lengths at all intersections, except for the Pontiac Trail/Eleven Mile Road signal, were 80 seconds. At this location the traffic signal was set to a cycle length of 70 seconds. Thus, there was no coordinated progression on Pontiac Trail between Ten Mile and Eleven Mile Roads. All signals operated under a six phase operation except for the signals at the Ten Mile Road intersections with Pontiac Trail





**LANE USE
CONFIGURATION**

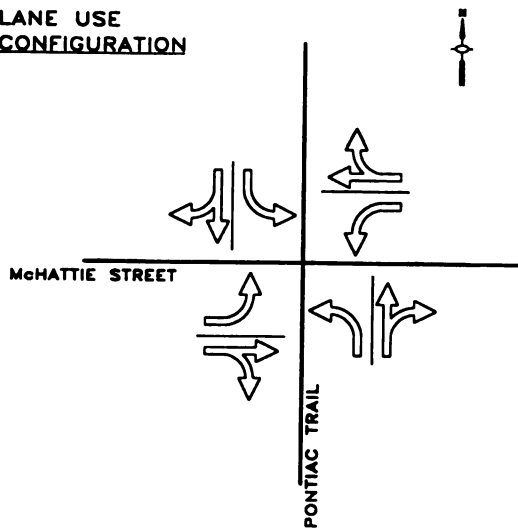


SIGNAL TIMING

PHASE	MOVEMENT		TIME INTERVAL
	N/S	E/W	
1	GREEN	RED	48 SEC.
2	AMBER	RED	4 SEC.
3	RED	RED	1 SEC.
4	RED	GREEN	22 SEC.
5	RED	AMBER	4 SEC.
6	RED	RED	1 SEC.

CYCLE LENGTH: 80 SEC.

**LANE USE
CONFIGURATION**



SIGNAL TIMING

PHASE	MOVEMENT		TIME INTERVAL
	N/S	E/W	
1	GREEN	RED	44 SEC.
2	AMBER	RED	4 SEC.
3	RED	RED	1 SEC.
4	RED	GREEN	26 SEC.
5	RED	AMBER	4 SEC.
6	RED	RED	1 SEC.

CYCLE LENGTH: 80 SEC.

FIGURE 4.1c

**SIGNAL PHASING DIAGRAMS AND
LANE USE CONFIGURATIONS**

SOUTH LYON ATMS EVALUATION STUDY

MICHIGAN STATE UNIVERSITY
DEPARTMENT OF CIVIL AND ENVIRONMENTAL ENGINEERING

and Reynold Sweet Parkway. At these two intersections the signal timing configurations allowed for separate left turn phases on each of the approach legs. The road geometry of the link segments and intersection approaches was measured at the same time as the traffic signal timings. All of the approaches to the study intersections featured an exclusive left turn lane. With the exception of the south approach to the Pontiac Trail/Eleven Mile Road intersection, all approaches to the study intersections also featured shared through/right turn lanes. None of these approach geometries were altered during or between the "before" and "after" phases of the study. Originally, there was no exclusive left turn phasing at the Pontiac Trail intersection at Nine and Eleven Mile Roads. After the completion of the FAST-TRAC project the north and southbound left turn movements at each of these locations were given permissive/protected left turn phasing.

Most of the road segments, or links, between the intersections featured two lane cross sections. The exceptions to the two lane cross section were segments of Pontiac Trail and Reynold Sweet Parkway. A continuous center lane for left turns exists on Pontiac Trail between Ten Mile Road and Reynold Sweet Parkway. The common center left turn lane also extended north of Ten Mile Road for 500 feet. A continuous center lane for left turns existed on Pontiac Trail for a distance of approximately one half mile north of Nine Mile Road. The center turn lane also extended south of Nine Mile Road for a distance of approximately 700 feet. At the intersection approaches, the standard two-lane cross sections increase to more than two lanes. Wider approaches are able to accommodate exclusive and shared through/turn lanes.

A schematic diagram of the Reynold Sweet Parkway and Ten Mile Road intersection is shown in Figure 4.1b. The position of the railroad track at this location required the construction of a "double signal" at the westbound approach to the intersection. Westbound traffic is controlled by a multi-phase signal allowing a pre-emptive red for train crossings or permissive/protective left turn when no trains are expected.

The posted speed limits varied in the South Lyon network. In the central business district vicinity of the Ten Mile Road/Pontiac Trail intersection, speeds were restricted to 25 miles per hour. Posted speed limits on Pontiac Trail are 35 miles per hour immediately outside the core commercial district and 45 miles per hour in the vicinity of Nine and Eleven Mile Roads. The posted speed limit on Reynold Sweet Parkway was 35 miles per hour.

4.1.2 "After" Data

The collection of the "after" traffic volume and signal timing information took place during the week of May 6th through May 10th, 1996. The "after" data elements of the system were composed primarily of the traffic volume and traffic signal timing features of the system. Both of these key statistics were collected automatically by the SCATS data processing system. In addition to adaptive signal control, the SCATS system has the capability to collect and store a number of important details relating to the flow of traffic and control of signals at the intersection.

Each of the signals controlled by SCATS incorporates a system of video imaging cameras which are positioned to record the presence of vehicles for critical movements at the stop line locations. A "critical movement" is a left turn, right turn, or through movement which is allotted green time during the signal cycle. At a minimum, through movements must be recorded to allot green time to the approaches. At locations where a separate left turn phasing is used, Autoscope cameras are added to record the left turn traffic volumes. No right turn traffic volume information is collected in South Lyon. The right turn and through traffic both use the through lane and are unopposed by conflicting traffic movements.

A typical SCATS output file contains a wealth of information. A segment of the Ten Mile Road/Pontiac Trail intersection SCATS output data file is shown in Figure 4.2. The SCATS output file consists of a stream of cycle-by-cycle information containing key performance statistics for each critical movement on the constituent approaches. The first line of each record shows basic information such as the date, time, region, and location of the

**Figure 4.2 Sample Segment of SCATS Output File
Pontiac Trail/Ten Mile Road Intersection**

```

8-MAY-96 06:59 WLAKE SS 1 PL1.3 PV 4.3 CL 80+0 RL 86' SA 12 DS119
INT SA/LK PH PT! DS VO VK! DS VO VK! DS VO VK! DS VO VK!ADS
35 S 7 ' 2 42! 41 8 8! - -! - -! -! 35
35 S 8 ' 1 42! 39 6 9! - -! - -! -! 31
35 S 9* 4 10! 0 0 0! - -! - -! -! 0
35 S 10* 3 10! 0 0 0! - -! - -! -! 0
35 S 11 ' 5 18! 72 5 7! - -! - -! -! 46
35 S 12 ' 6 18>119 9 10! 42 3 3! - -! - ->102
35 S 13* 7 11! 0 0 0! - -! - -! -! 0
35 S 14* 8 11! 54 2 3! - -! - -! -! 34
8-MAY-96 07:01 WLAKE SS 1 PL4.3 PV 4.3 CL 80+0 RL 86' SA 12 DS115
INT SA/LK PH PT! DS VO VK! DS VO VK! DS VO VK! DS VO VK!ADS
35 S 7 ' 2 41! 38 7 8! - -! - -! -! 37
35 S 8 ' 1 41! 37 7 8! - -! - -! -! 32
35 S 9* 4 10! 0 0 0! - -! - -! -! 0
35 S 10* 3 10! 0 0 0! - -! - -! -! 0
35 S 11 ' 5 18! 69 2 6! - -! - -! -! 60
35 S 12 ' 6 18>115 7 10! 36 3 3! - -! - ->110
35 S 13* 7 12! 0 0 0! - -! - -! -! 0
35 S 14* 8 12! 52 3 3! - -! - -! -! 41
8-MAY-96 07:02 WLAKE SS 1 PL4.3 PV 4.3 CL 80+0 RL 80' SA 12 DS 51
INT SA/LK PH PT! DS VO VK! DS VO VK! DS VO VK! DS VO VK!ADS
35 S 7 ' 2 39! 22 4 4! - -! - -! -! 31
35 S 8 ' 1 39! 43 8 9! - -! - -! -! 40
35 S 9* 4 10! 0 0 0! - -! - -! -! 0
35 S 10* 3 10! 0 0 0! - -! - -! -! 0
35 S 11 ' 5 27! 14 2 2! - -! - -! -! 45
35 S 12 ' 6 27! 51 6 6! 0 0 0! - -! - -! 87
35 S 13* 7 10! 0 0 0! - -! - -! -! 0
35 S 14* 8 10! 0 0 0! - -! - -! -! 29
8-MAY-96 07:03 WLAKE SS 1 PL4.3 PV 4.3 CL 80+0 RL 82' SA 8 DS 87
INT SA/LK PH PT! DS VO VK! DS VO VK! DS VO VK! DS VO VK!ADS
35 S 7 ' 2 23! 51 4 6! - -! - -! -! 39
35 S 8 ' 1 23! 87 9 11! - -! - -! -! 61
35 S 9* 4 11! 0 0 0! - -! - -! -! 0
35 S 10* 3 11! 0 0 0! - -! - -! -! 0
35 S 11 ' 5 27! 48 3 7! - -! - -! -! 41
35 S 12 ' 6 27! 57 7 7! 0 0 0! - -! - -! 68
35 S 13* 7 10! 0 0 0! - -! - -! -! 0
35 S 14* 8 10! 0 0 0! - -! - -! -! 11

```

intersection. It also contains signal control information like the current mode of operation, tactical or strategic, the primary split plan and cycle length, the controlling strategic approach, and the intersection degree of saturation. The third through tenth lines reveal the important statistics for each of the eight strategic approaches. Strategic approach one and three represent the through and left turn movements for northbound Pontiac Trail. The through and left turn information for south, east, and westbound approaches are shown as lines 2 and 4, 5 and 7, and 6 and 8, respectively.

The first column showing "35" is the code number for the Pontiac Trail /Ten Mile Road intersection. The second column, beginning with the letter "S," indicates the strategic approach number and vehicle group. The next column, under the heading "PT," indicates the length of the green phase dedicated to each movement. The following column, under "DS," indicates the degree of saturation for the critical approach during that cycle. The next column, under the heading "VO, " shows the actual volume of traffic which was recorded at the approach location by the Autoscope sensor. The next column in the group, designated with the heading "VK" indicates the number of vehicles estimated by the SCATS control program when the algorithm selected the appropriate green phase length. The final column for each of the critical movement lines indicates the average degree of saturation for the movement. The average is calculated from the degrees of saturation recorded for the current and previous two signal cycles. This process is then repeated for each successive signal cycle.

Since all six of the signalized intersections were converted to SCATS control, all of the necessary traffic volume information was collected remotely, using the SCATS/Autoscope data processing system. Unfortunately, not all of the intersections were equipped to collect all of the data that was required for analysis in this study. The SCATS configuration at the intersections of Pontiac Trail at McHattie Street and Reynold Sweet Parkway did not allow for the collection of left turn movement data. The traffic volumes collected by the SCATS system at these locations are limited solely to the through movements. Using this

information signal timings are interpreted by SCATS in the local controller. The coordination of the cycle length and offset between adjacent intersections is computed at the Troy traffic operations center. The lack of recorded traffic signal output files for these two intersections made the delay parameter assessment impossible in this study. Delay parameters were calculated only at the four intersections of Pontiac Trail and Nine Mile Road, Pontiac Trail and Ten Mile Road, Pontiac Trail and Eleven Mile Road, and Reynold Sweet Parkway and Ten Mile Road.

4.1.3 Related Data

Interest in the performance of the FAST-TRAC system has resulted in the completion of a number of concurrent studies. As a result, many different types of traffic data have been collected by the Road Commission for Oakland County and other research teams conducting performance evaluation studies in South Lyon. One particular study⁽⁴⁷⁾ involved the collection and analysis of empirically recorded approach traffic volume and delay data. This information was particularly useful in this study.

The collection of this intersection approach directional turning movement and delay data took place prior to the activation of SCATS in December, 1995 and later after the activation of SCATS in May, 1996. The data were collected with the use of video cameras positioned to record the arrival characteristics of oncoming traffic. Specific approach movements at the intersections of Nine Mile and Eleven Mile Roads with Pontiac Trail were video taped on Wednesday, December 6th, Thursday, December 7th, and Friday, December 8th 1995. The delay data was recorded during the hours of noon to five o'clock p.m. Taping during the usual peak hour of 5:00 p.m. to 6:00 p.m. was not possible due to the low visibility conditions after 5:00 p.m.

Two cameras were positioned at the southeast corner of the Nine Mile Road/Pontiac Trail intersection. The cameras were aimed to record oncoming traffic on the north and west approaches to the intersection. Two different cameras were positioned on the southwest

corner of the Eleven Mile Road/Pontiac Trail intersection. These cameras were aimed to record oncoming traffic on the north and east approaches to the intersection. Data reduction took place when the video tapes were reviewed using a television, video cassette recorder, and stop watch. Although time consuming, this method of data collection and reduction resulted in accurate and detailed time measurements of individual vehicles. Tapes could be played, rewound, and replayed to record the arrival and delay time characteristics for simultaneously arriving vehicles. To accomplish the same results in a field setting would have required up to eight people per approach. Summarized results showing the “before” and “after” volume, delay, and signal information is presented in Table 4.1.

4.2 Development of the Traffic Analysis Models

The original intent of this study was to use the SOAP traffic signal analysis software to directly model the “after” delay conditions in South Lyon on an incremental, cycle-by-cycle, basis. Unfortunately, certain aspects of the SOAP program make the use of this approach impossible. To complete an affective comparison, a new computerized methodology was developed. After further data analysis it was determined that this system would also have to be used to analyze the “before” conditions. This section details the methodology of the SOAP delay calculation procedure as well as highlighting some of the limitations that prohibited the use of the SOAP program for the completion of this study. The development of the new analysis methodology will also be described in this chapter.

4.2.1 The SOAP Program and Its Limitations

SOAP was developed for the analysis of traffic signal design alternatives at four-legged intersections with or without protected left turning phase intervals in the signal sequence, including fixed time, semi-actuated, and fully actuated control. One of the benefits of the SOAP program is that it allows the operating characteristics of an individual intersection to be expressed in terms of specific measures of effectiveness (MOE). SOAP MOEs include

Table 4.1. Field Recorded Traffic Data

South Lyon SCATS Delay Evaluation Study													
Pontiac Trail and Nine Mile Road	Average Volume (veh/hr)		Average Cycle Length (sec)		Average Green Time (sec)		Average Delay (sec/veh)		Average Time in Queue (sec/veh)		Total Delay (veh-hr)		
	"before"	"after"	"before"	"after"	"before"	"after"	"before"	"after"	"before"	"after"			
Southbound Through	508	592	80	85	48	50	13.13	12.78	28.22	25.37	1.85	2.11	
Southbound Left Turn	41	52	80	85	-na-	8	17.37	21.07	29.00	29.62	-na-	-na-	
Eastbound Left Turn	140	140	80	85	22	19	36.12	40.61	37.43	54.54	1.40	2.14	
	Average Intersection Delay (sec/veh)										18.10	17.93	
Pontiac Trail and Eleven Mile Road													
	Southbound Through	460	490	90/70	82	40/34	46	14.84	11.32	24.19	21.40	1.89	1.54
	Southbound Left Turn	35	35	-na-	85	-na-	6	17.72	13.45	23.68	18.92	-na-	-na-
	Eastbound Left Turn	125	130	90	86	40	28	31.33	44.32	39.97	56.29	-na-	-na-
	Average Intersection Delay (sec/veh)										20.37	18.62	

Source: Michigan State University, Department of Civil and Environmental Engineering

various vehicle approach delays, number of stopped vehicles, fuel consumption, queue lengths, and other flow characteristics.⁽²²⁾ A further benefit to the system is that it allows these MOE to be calculated for relatively short time intervals. Its design allows a user the ability to analyze up to 48 separate time increments in a single program execution. Thus, it was originally hoped that a series of forty five 80 second time increments could be used to evaluate one hour of delay at intersection with an 80 second signal cycle length.

Unfortunately, it was discovered that this approach would not be possible with SOAP. The initial plan was to use SOAP to model the “before” South Lyon intersections based on the RCOG fixed traffic signal timings and the traffic volumes recorded in the SCATS output files. The “after” conditions would be modeled on a cycle-by-cycle basis using the same traffic volumes and modifying the signal timings after each signal cycle. The minimum allowable SOAP analysis time interval is five minutes. SCATS control makes modifications to the traffic signal phasing plan every signal cycle. As a result, some of the cycle length settings for intersections in South Lyon were as short as 50 seconds.

It was also recognized that the SOAP approach delay calculation procedure uses a deterministic modeling approach that would be very useful in this study. The deterministic approach lends itself to a situation like a fixed time/SCATS comparison because it has the ability to make a delay calculations for any length analysis period. The SOAP computational strategy calculates the critical movement delay for a specified time period of signal operation. The amount of delay is a function of the conditions which exist during the analysis interval, independent of the time period length. For example, SOAP calculates identical average delays for a volume of 50 vehicles arriving during a five minute interval and 600 vehicles arriving during an hour long interval. The SOAP procedure does not differentiate between the two as long as the traffic proportions, signal timing, saturation flow, vehicle headway, and lost time were the same. The total intersection delay is calculated by using the sum of the average incremental delays throughout the full analysis period. While this delay calculation methodology is quite useful, it is not as comprehensive as some of the more

sophisticated traffic simulation systems. Some of these shortcomings are addressed later in this chapter.

The delay calculation procedure that is used by SOAP employs a modified version of the Webster and TRANSYT-7F delay calculation algorithms. The Webster algorithm was developed during the 1950's and 1960's for calculating delay at signalized intersections.⁽⁴⁸⁾ The Webster equation, shown below, contains three separate delay terms.

$$d_i = [C(1-\lambda)^2/2(1-\lambda x)] + [x^2/2q(1-x)] - [0.65(C/q^2)^{1/3} * x^{2+5\lambda}]$$

where,

d_i = average delay per vehicle on the particular approach of the intersection (sec/veh)

C = cycle time (seconds)

λ = proportion of the cycle that is effectively green for the phase under consideration (i.e., g/C)

q = flow (vehicles per hour)

s = saturation flow (vehicles per second of green)

x = degree of saturation (i.e., $x = q/\lambda s$)

The equation calculates the average delay per vehicle on an intersection approach, heretofore classified as “approach delay.” It includes both stopped delay as well as lost time due to accelerating from a stop and decelerating from the free flow travel speed. Each of the three terms in the Webster equation represent the contribution of a different delay component apparent at signalized intersections. The first term represents the average delay for an approach assuming uniform arrivals at a fixed-time signal controlled intersection. It was derived from deterministic queuing theory equations. The second delay term is added to the first to account for random arrivals. The third term is subtracted from the first two and can vary from zero (in the case of purely random arrivals) to the value of the second term (in the case of purely uniform arrivals). The third term was empirically derived from simulation and field measurement.⁽⁴⁸⁾

To calculate approach delay, SOAP has made a modification to the original Webster equation. The change involves the elimination and replacement of the second and third terms of the algorithm. The replacement term comes from an algorithm developed in England in the late 1970's by Robertson for use in the TRANSYT signal design and analysis program.⁽⁴⁹⁾ Robertson retained Webster's first term for uniform vehicle arrivals but replaced the last two terms with a single term to give more accurate predictions of approach delay during higher degrees of saturation. The Robertson equation is in the form:

$$D_2 + D_3 = [(B_n/B_d)^2 + x^2/B_d]^{1/2} - B_n/B_d$$

where,

$$B_n = 2(1 - x) + xz$$

$$B_d = 4z - z^2$$

$$z = (2x/v) * (60/T)$$

v = approach volume (veh/hr)

T = period length (min)

The Robertson modification to the Webster equation was incorporated to more accurately assess delay for traffic volumes which approach or exceed the design capacity of the intersection. The Webster equation, by itself, is useful when analyzing approaches with a degree of saturation between approximately 15 and 97 percent. When the degree of saturation exceeds 97 percent, the Webster equation produces delay values which are negative and do not become positive until a degree of saturation in excess of 130 percent is attained. To illustrate this concept the following example is presented. When the volume of a particular approach with a saturation flow of 1,600 vehicles per hour is increased from 1,300 to 1,400 vehicles per hour, the average delay predicted by the TRANSYT model increases from 20.6 to 27.3 seconds per vehicle. The same average delay value calculated with the unmodified Webster equation shows an increase from 23.9 to 74.5 seconds per vehicle.⁽²²⁾

The SOAP delay calculation procedure for left turn traffic involved a more complicated version of the through movement calculation methodology. The left turn delay calculation strategy expands the basic through movement calculation procedure by employing a delay prediction based on a calculated left turn capacity. The SOAP methodology assumes the left turn capacity for a permissive/protected left turn phase during the signal cycle is the result of three separate capacity and delay calculations. The first regime determines the delay resulting from the protected phase of the signal plan. The capacity and delay for this interval are relatively simple to calculate. The delay can be calculated using the basic Webster/TRANSYT equation where the input parameters are those assumed or recorded for the left turn movement. The second delay regime comes from the number of left turns which can be completed during the permissive phase. This delay is calculated by first determining the portion of permissive left turn green time in which there is no through traffic opposing the left turn movement. This is found by subtracting the actual opposing through volume from its theoretical saturation flow volume. The "unsaturated" or remaining green time can be used to accommodate left turns unopposed by through traffic. The third regime of left turn clearance capacity is determined from the number of turns that can complete the left turn maneuver during the "all red" clearance interval. In the SOAP documentation these clearance interval left turners are referred to as "sneakers." In South Lyon, it was assumed that one sneaker vehicle would be able to complete a left turn during the clearance interval.

The calculation of left turn delay in South Lyon was completed only for permissive/protected left turn conditions. No "permissive only" left turn delay could be analyzed since the SCATS data collection and analysis architecture collects left turn volume and phasing statistics only for protected left turn movements.

After understanding the internal procedure of the SOAP program's delay calculation methodology, it became possible to duplicate the procedure and incorporate additional features for use in this study. The new procedure would also incorporate a mechanism to shorten the allowable analysis window from the SOAP imposed minimum of five minutes,

to a time interval of 50 seconds. Thus, it would be possible to calculate average approach vehicle delays and total intersection delays for the intersections in South Lyon directly from the SCATS output file data.

4.2.2 “After” Delay Calculation Model

Recognizing the merits of this type of deterministic delay calculation procedure, a computer program incorporating a similar approach was developed to calculate the delay of critical movements within the South Lyon under SCATS control. The program used the SOAP calculation methodology as well as a data extraction system to read traffic and signal timing information from a SCATS output data file. To analyze the “after” traffic conditions, the program used the Autoscope recorded volumes and SCATS signal phase timings to calculate average approach delay for each signal cycle. Total delay was calculated using the product of hourly vehicular volume and average approach delay. The same program configuration was used to complete the “before” analysis. Instead of using the SCATS signal timings, an optimized fixed time signal plan, in which the signal timings did not vary from cycle to cycle was used.

The analysis models were divided into two separate groups. The first set of models were developed to analyze the “after” conditions of South Lyon. The “after” analysis was completed prior to the “before” analysis because of the manner in which the traffic volume and traffic signal data were collected. The “before” models also required the completion of a SOAP signal timing optimization analysis to determine the most effective signal phase split arrangement to accommodate the hourly traffic volumes. The same analysis technique and cyclical traffic volume data were used for both the “before” and “after” periods. The sole variant between the two groups was the traffic signal timing.

Four separate computer programs, one for each of the four intersections analyzed in South Lyon, were coded using the Fortran programming language. Each intersection required a separate program to accommodate various SCATS output data file formats. Each

intersection had a different number and order of the critical approaches within each data set. The intersection of Ten Mile Road and Pontiac Trail incorporated eight critical approaches. Each of the four intersection approach legs included a single shared through/right turn lane and a single exclusive left turn lane. The intersections of Nine and Eleven Mile Roads with Pontiac Trail included through lane information only for two of the four approach legs. Separate left turn data were recorded for the north and southbound approaches at both intersections. The Ten Mile Road/Reynold Sweet Parkway intersection data set included through and left turn data for the westbound approach, through data for the eastbound approach, and a single unopposed left turn approach volume and signal data on the northbound approach. The data collection configuration at the Ten Mile Road/Reynold Sweet Parkway location was different from the other three because it has only three approach directions.

An output listing of the program source code for the program written to analyze the intersection of Pontiac Trail and Ten Mile Road is included in Appendix A of this report. The program is composed of three separate components of data retrieval, delay calculation, and delay output information. The program was designed to read the SCATS output data file and extract the traffic volume detected and the green time dedicated to each of the eight critical intersection approach movements. This information was used to “feed” the modified Webster/TRANSYT delay equation. The average approach delay was calculated separately for each movement during each cycle. The hourly average of this delay as well as the total of all delay for the intersection experienced during the full hour were calculated and written to an output file. A sample segment of this output file has been included as Appendix B of this report. As shown in the sample output, the program structure allowed the data to be extracted, delay to be calculated, and statistics to be written continuously until the end of the SCATS file was encountered. While the length of the output file was the same for each intersection, the number of SCATS data records that were extracted and used in the calculation process to determine the delay times under SCATS controlled conditions varied from approximately 30,000 to over 45,000 records.

Three input parameters used in the “after” models were not taken directly from the SCATS output data files. These were the vehicle start-up lost time, headway, and critical movement saturation flows. Each of these parameters is critical to determining the delay at signalized intersections. The headway and saturation flow rates determine the capacity that a particular lane group has to service the traffic demand. A traffic demand in excess of the capacity of the approach will experience greater delay. The lost time value reflects the amount of time that a green signal phase can not service the approach traffic demand. The lost time parameter is also critical because its effects are felt during each signal phase. A few seconds of lost time for a four phase signal with a one minute cycle can result in over nine hours of wasted green time every day. The values for lost time, headway, and saturation flow for each of the intersection approach locations were collected from Road Commission for Oakland County Traffic Operations Center records.

SCATS data files were recorded for the South Lyon intersections during a one week time period starting at midnight Monday May 5, 1996 and ending at midnight Saturday May 10, 1996. From the recorded data it was possible to analyze twenty separate periods for each critical intersection approach movement as part of this study. As a result the total size of the comparison sample data set included 480 records for the “before” condition and 480 records for the “after” condition.

The analysis program calculated the average approach delay and total intersection delay for each hour of the day. To analyze a varying sample of traffic conditions, four separate daily analysis periods were selected. The first was the hour between 12:00am and 1:00am. This hour represents one of the low traffic demand periods of the day. Often, several traffic signal cycles would occur before a single vehicle was detected on a particular approach. Under these conditions it was thought that SCATS would function at its best. Only the minimum green time would be allocated to the low volume movements. Correspondingly, it was expected that delays for the remaining approaches would also be minimized.

Two peak traffic demand periods, 7:00am to 8:00am and 5:00pm to 6:00pm, were also analyzed. These intervals were selected for the opposite reason. The comparison of SCATS to fixed time signal control would help to illustrate the differences in operation during high demand periods in which SCATS could implement a longer cycle length and better allocate green time to the high demand movements in an effort to minimize delay. The final analysis period was the hour from 12:00pm to 1:00pm. During this hour the demand was between the high demand volume of the morning and evening peak hours, and the midnight low level volume.

4.2.3 “Before” Delay Calculation Model

The second phase of the South Lyon traffic analysis involved the completion of the “before” portion of the “before/after” study. The “before” delay analysis incorporated a two step approach. Rather than using the actual RCOC signal timings for South Lyon, a set of “optimized” fixed time settings were used to determine the “before” delay conditions. The decision to use optimized fixed time was made to assess the benefit of real time adaptive signal control against a well timed fixed system. A comparison against the original timing plans may have showed a benefit based on a poorly timed fixed system. Therefore, the benefit would be from improving a bad condition instead of comparing two different, though equally good, systems.

The SOAP program was also used to determine an “optimized” fixed timing plan to compare the adaptive and fixed control strategies. The explicit SOAP optimization strategy attempts to minimize delay by using a cycle length, green split, and dial assignment optimization process. All of these parameters can be calculated automatically by the program. SOAP also allows an implicit optimization method. The implicit method requires some judgement on the part of the user with regard to the use of permissive versus protected left turn control, actuated control, and phase sequence selection. All of the implicit optimization methods and some of the explicit ones were based on some of the SCATS minimum parameters to assure a fair comparison.

The SOAP optimization process works by attempting to minimize the total intersection delay for the time period under analysis. Earlier it was shown that SCATS minimizes the delay by equalizing the degree of saturation for each of the constituent intersection approaches. By contrast, SOAP attempts to reduce stops and delay on a “global” scale. This philosophy is best illustrated by a major street/minor cross street intersection situation. In this situation the major street volumes are significantly higher than the minor street traffic. SOAP would minimize the intersection delay by allocating a proportionately higher percentage of green time to the major street approaches. However, the benefit realized by the heavier movement delay reductions would be gained at the expense of the minor street traffic. In extreme cases the minor street approach traffic could experience average delay greatly in excess of those experienced by the major street approaches. The total delay is minimized because the inordinately average high delays are experienced by a relatively low number of vehicles.

As noted in the SOAP manual⁽²²⁾ this method results in an unfair allocation of green time, especially in situations where one of the minor street approach volumes is relatively high. However, this method can result in substantial savings in vehicle emissions and operating costs because the total amount of stops and delay at the intersection is minimized.

The optimization procedure used to determine the “before” fixed time signal plan did not take full advantage of the SOAP optimization process. The signal cycle lengths used for the fixed plans were the same as the SCATS average in each of the four analysis periods. The similar cycle lengths were used to account for the need for coordinated progression between the signals. SOAP analyzes each intersection in isolation. In reality SCATS could have been limited in its selection of a more suitable cycle length by the need to maintain coordination with adjacent signals. Minimum green time restrictions were also placed on the SOAP system. In several instances SOAP attempted to allocate very low green times to minor street movements. However, these green times would not allow adequate time for pedestrian clearance and could result in safety problems with drivers attempting turning movements into a traffic stream with inadequate gaps.

Two other restrictions were placed on the SOAP selection process. The same permissive/protected left turn phasing was maintained between both of the test groups. Once again, this decision was based on real-world safety considerations in which protected left turn phasing would be warranted by the lack of acceptable left turn gaps. The final restriction was the forced use of the same phase sequence pattern. It was felt that this would result in a more balanced comparison without significantly effecting the signal performance parameters.

Separate optimization trials were completed for each time period at each of the four intersections. These signal timings were based on the average traffic volume recorded during the week of data collection. The fixed time plan did not vary from day to day. The traffic volumes and delay calculation procedure used during the “before” analysis periods did not change. The program was modified so that the timing plan was fixed throughout the analysis while the same SCATS traffic volumes were read for each cycle. It is recognized that a direct one to one correspondence may not have existed during each fixed signal phase and the volumes from each SCATS phase period. However, it was felt that the total number of SCATS signal cycles would be approximately equal to the number of fixed time signal phases for each separate analysis hour. The signal timing plans used to analyze each of the various analysis periods are shown in Tables 4.2a through 4.2d.

4.3 Model Limitations

Like all traffic models, the modeling technique used to calculate delay conditions in South Lyon had some inherent weaknesses. These weakness were the result of two primary sources. The first came from the SOAP program and delay calculation procedures. The

Table 4.2a Green Phase Split in Optimized Fixed Time Operation

South Lyon SCATS Delay Evaluation Study Intersection of Pontiac Trail and Ten Mile Road - Optimized Signal Timings									
Approach Movement	12:00 am - 1:00 pm		7:00 am - 8:00 am		12:00 pm - 1:00 pm		5:00 pm - 6:00 pm		Percentage of the Cycle
	Time (sec)	Percentage of the Cycle	Time (sec)	Percentage of the Cycle	Time (sec)	Percentage of the Cycle	Time (sec)	Percentage of the Cycle	
Northbound Through	35	63.6%	52	61.5%	45	52.9%	42	46.9%	
Northbound Left Turn	4	7.3%	7	8.3%	7	8.2%	7	7.8%	
Southbound Through	35	63.6%	52	61.5%	45	52.9%	42	46.9%	
Southbound Left Turn	4	7.3%	7	8.3%	7	8.2%	7	7.8%	
Westbound Through	11	20.0%	17	20.1%	24	28.2%	32	35.8%	
Westbound Left Turn	4	7.3%	7	8.3%	7	8.2%	7	7.8%	
Eastbound Through	11	20.0%	17	20.1%	24	28.2%	32	35.8%	
Eastbound Left Turn	4	7.3%	7	8.3%	7	8.2%	7	7.8%	
All-Red Clearance Intervals	2	3.6%	3	3.6%	2	2.4%	3	3.4%	
Total Cycle Length (sec)	55		85		85		90		

note: Phase split optimization was completed using the Signal Optimization and Analysis Package (SOAP)

Table 4.2b Green Phase Split in Optimized Fixed Time Operation

South Lyon SCATS Delay Evaluation Study Intersection of Pontiac Trail and Nine Mile Road - Optimized Signal Timings									
Approach Movement	12:00 am - 1:00 pm		7:00 am - 8:00 am		12:00 pm - 1:00 pm		5:00 pm - 6:00 pm		Percentage of the Cycle
	Time (sec)	Percentage of the Cycle	Time (sec)	Percentage of the Cycle	Time (sec)	Percentage of the Cycle	Time (sec)	Percentage of the Cycle	
Northbound Through	34	68.7%	38	68.6%	37	67.5%	61	67.8%	
Northbound Left Turn	5	10.1%	5	5.9%	5	5.9%	5	5.6%	
Southbound Through	34	68.7%	38	68.6%	37	67.5%	61	67.8%	
Southbound Left Turn	5	10.1%	5	5.9%	5	5.9%	5	5.6%	
Westbound Through	9	18.2%	20	23.7%	21	24.9%	23	25.6%	
Eastbound Through	9	18.2%	20	23.7%	21	24.9%	23	25.6%	
All-Red Clearance Intervals	3	6.1%	3	3.6%	3	3.6%	2	2.2%	
Total Cycle Length (sec)	50		85		85		90		

note: Phase split optimization was completed using the Signal Optimization and Analysis Package (SOAP)

Table 4.2c Green Phase Split in Optimized Fixed Time Operation

South Lyon SCATS Delay Evaluation Study Intersection of Pontiac Trail and Eleven Mile Road - Optimized Signal Timings									
Approach Movement	12:00 am - 1:00 am		7:00 am - 8:00 am		12:00 pm - 1:00 pm		5:00 pm - 6:00 pm		
	Green Phase Allocation		Green Phase Allocation		Green Phase Allocation		Green Phase Allocation		
	Time (sec)	Percentage of the Cycle	Time (sec)	Percentage of the Cycle	Time (sec)	Percentage of the Cycle	Time (sec)	Percentage of the Cycle	
Northbound Through	38	69.7%	60	70.6%	62	77.5%	65	76.5%	
Northbound Left Turn	6	11.0%	5	5.9%	5	6.3%	7	8.2%	
Southbound Through	38	69.7%	60	70.6%	62	77.5%	65	76.5%	
Southbound Left Turn	6	11.0%	5	5.9%	5	6.3%	7	8.2%	
Westbound Through	9	16.5%	19	22.4%	12	15.0%	12	14.1%	
Eastbound Through	9	16.5%	19	22.4%	12	15.0%	12	14.1%	
"All-Red" Clearance Intervals	3	5.5%	2	2.4%	2	2.5%	2	2.4%	
Total Cycle Length (sec)	55		85		80		85		

note: Phase split optimization was completed using the Signal Optimization and Analysis Package (SOAP)

Table 4.2d Green Phase Split in Optimized Fixed Time Operation

South Lyon SCATS Delay Evaluation Study Intersection of Reynold Sweet Parkway and Ten Mile Road - Optimized Signal Timings									
Approach Movement	12:00 am - 1:00 am		7:00 am - 8:00 am		12:00 pm - 1:00 pm		5:00 pm - 6:00 pm		
	Green Phase Allocation		Green Phase Allocation		Green Phase Allocation		Green Phase Allocation		
	Time (sec)	Percentage of the Cycle	Time (sec)	Percentage of the Cycle	Time (sec)	Percentage of the Cycle	Time (sec)	Percentage of the Cycle	
Westbound Through	43	78.2%	54	72.0%	52	74.3%	53	70.7%	
Westbound Left Turn	4	7.3%	5	6.7%	5	7.1%	5	6.7%	
Eastbound Through	43	78.2%	54	72.0%	52	74.3%	53	70.7%	
Northbound Left Turn	6	10.9%	14	18.7%	11	15.7%	15	20.0%	
"All-Red" Clearance Intervals	2	3.6%	2	2.7%	2	2.9%	2	2.7%	
Total Cycle Length (sec)	55		75		70		75		

note: Phase split optimization was completed using the Signal Optimization and Analysis Package (SOAP)

second main area of limitation came from the architecture of the SCATS system. The SCATS/Autoscope architecture is designed to collect and process the data required to most efficiently implement signal timings. Unfortunately, the data necessary for the operation of the system is not perfectly designed for the completion of comprehensive and detailed delay studies.

The SOAP analysis package was developed specifically for the analysis of isolated intersections. It also allows the calculation of a number of signalized intersection measures of performance. The program is limited, however, in some aspects which were important to this study. The most important limitation of the SOAP environment is that it lacks a mechanism to adjust the approach traffic arrival distribution. SOAP considers distribution of vehicle arrivals to be uniform with respect to any cycle. No attempt is made to model coordinated progression and the arrival of vehicles is assumed not to be influenced by upstream signals. As a result a direct assessment of the benefits of coordinated progression that SCATS can demonstrate was not possible in this study.

Another limitation of the SOAP program was the lack of ability to assess the conditions on a stochastic basis. Unlike analysis packages like NETSIM, SOAP does not differentiate between drivers and their various driving habits. Differences in these parameters would primarily impact the start-up lost time and vehicle headway. While the impact of variability of these parameters was not accounted for in this study, the large sample size helped to minimize the effect of variation on the average values.

Another feature that is available in systems like NETSIM are detailed descriptions of geometric features and their relationship to traffic operations. For example, the methodology used for this analysis assumed that there were no "over saturated" left turn or right turn lanes. This condition would result in through lane blockages and increased delays due to traffic unable to move. The analysis methodology employed in this study assumed an infinite length of turn lanes and no potential for "spill-back" queues from downstream intersections

or through lane blockages. In reality, there were a limited number of occurrences of through lane blockages on the east and westbound approaches to the intersection of Pontiac Trail and Ten Mile Road.

The operational configuration of the Autoscope/SCATS system in South Lyon also presented some limitations in this study. Most notable was the lack of the ability to calculate of delay for all movements at the intersections. The system was configured to detect vehicles and modify signal timings for only the critical approach movements. Left turning traffic was detected only in locations where an exclusive left turn phase was present. In all cases the right turning was combined with the through traffic movement. Therefore, no delay parameters were calculated exclusively for right turning traffic at any of the intersections. However, the impact of the lack of this data was not critical since the right turn traffic shared the through traffic lane with the through traffic. Therefore, the SOAP delay calculation procedure remained useful for all of these locations. The only exclusive right turn lane in the South Lyon system was located on the northbound approach of Reynold Sweet Parkway to Ten Mile Road. No delay data was calculated for this movement.

While the utility of using the SCATS output data files was obvious, the use of these files also presented other limitations in the study. The original plan was to assess the delay conditions at all six of the South Lyon SCATS controlled intersections. Due to the data collection configuration of the system the intersections of Pontiac Trail at Reynold Sweet Parkway and McHattie Street could not be analyzed. The SCATS data input requirements at these two intersection was such that the approach through volumes were all that were necessary to control the timing of the signals. The cycle lengths at these two locations is coordinated at the RCOC Traffic Operations Management Center. The phase splits, however, are controlled locally at the intersection signal controller. No volume or timing data is transmitted or stored at the control center. As a result, there were no data files to analyze in this study.

An additional factor which limited the model somewhat did not become apparent until after the first attempts at delay modeling were completed. It was found that the Webster/TRANSYT delay equation within the model predicted inordinately high delay values for approach traffic levels in excess of the saturation flow. This phenomenon occurred despite the SOAP correction of adding the Robertson model terms to the Webster formula to limit such conditions. While over saturated conditions occurred infrequently in South Lyon, this condition did present a problem at several locations. The most noticeable events were observed during the low volume conditions when vehicles on the minor street approaches were delayed in excess of one signal cycle although the approach volumes could not have resulted in a loaded cycle. To correct this problem the maximum value for the degree of saturation in the delay calculation equation was limited to 100%. This limitation resulted in predictions of delay which were more realistic compared to the field observed values.

4.4 Delay Model Output Data

After all of the programs were debugged and fully operational they were executed to produce the output statistics required to compare the delay conditions in South Lyon with and without SCATS signal control. A sample segment of data output produced by the model is illustrated in Figure 4.3. The comparative MOE for average approach delay and total intersection delay are presented in Tables 4.3a through 4.6f. The first set of tables, 4.3a through 4.3f, are for the intersection of Pontiac Trail and Ten Mile Road. Tables 4.4a through 4.4f, 4.5a through 4.5f, 4.6a through 4.6f, illustrate the same statistics for the intersection Pontiac Trail and Nine Mile Road, Pontiac Trail and Eleven Mile Road, and Ten Mile Road and Reynold Sweet Parkway, respectively.

The tables are structured to illustrate the hourly volume and delay statistics for each of the critical approach movements. The tables are further divided into four sets of columns, one for each of the analysis intervals. Below each of the hourly approach delay values is the total

**Figure 4.3 Sample Segment of Delay Model Output
Pontiac Trail/Ten Mile Road Intersection**

Period begins at 7:00

Movement #1 hrly vol. =447.000 ave. delay = 43.215

Movement #2 hrly vol. =401.000 ave. delay = 38.613

Movement #3 hrly vol. = 17.000 ave. delay = 24.958

Movement #4 hrly vol. = 16.000 ave. delay = 37.307

Movement #5 hrly vol. =194.000 ave. delay = 31.360

Movement #6 hrly vol. =336.000 ave. delay = 52.589

Movement #7 hrly vol. = 50.000 ave. delay = 34.943

Movement #8 hrly vol. = 67.000 ave. delay = 30.712

Intersection total delay= 17.606 veh-hrs

ave. cycle length = 85.810sec

Period begins at 8:00

Movement #1 hrly vol. =353.000 ave. delay = 29.904

Movement #2 hrly vol. =324.000 ave. delay = 32.991

Movement #3 hrly vol. = 16.000 ave. delay = 30.338

Movement #4 hrly vol. = 42.000 ave. delay = 23.932

Movement #5 hrly vol. =193.000 ave. delay = 37.659

Movement #6 hrly vol. =265.000 ave. delay = 34.587

Movement #7 hrly vol. = 22.000 ave. delay = 25.188

Movement #8 hrly vol. = 22.000 ave. delay = 26.563

Intersection total delay= 11.197 veh-hrs

ave. cycle length = 80.955sec

Period begins at 9:00

Movement #1 hrly vol. =369.000 ave. delay = 29.272

Movement #2 hrly vol. =389.000 ave. delay = 32.122

Movement #3 hrly vol. = 17.000 ave. delay = 65.652

Movement #4 hrly vol. = 14.000 ave. delay = 23.884

Movement #5 hrly vol. =186.000 ave. delay = 29.813

Movement #6 hrly vol. =228.000 ave. delay = 31.621

Movement #7 hrly vol. = 23.000 ave. delay = 24.237

Movement #8 hrly vol. = 27.000 ave. delay = 25.658

Intersection total delay= 10.765 veh-hrs

ave. cycle length = 80.733sec

intersection delay statistics for both the fixed time and SCATS adjusted signal control delay groups. Under the total intersection delay, the average cycle length for the analysis interval is also shown.

The first five tables for each location, designated “a” through “e,” illustrate the delay statistics for the days of Monday through Friday. The final table for each location, labeled “f,” shows the weekly average for all of the volume, delay, and cycle length statistics for the week. In the following chapter these statistics will be more closely analyzed and compared in an effort to assess their significance and relevance to one another.

Table 4.3a Delay Model Output

South Lyon SCATS Delay Evaluation Study Intersection of Pontiac Trail and Ten Mile Road												
Monday, May 6, 1996												
Approach Movement	12:00 am - 1:00 am			7:00 am - 8:00 am			12:00 pm - 1:00 pm			5:00 pm - 6:00 pm		
	Traffic Volume (veh)	Approach Delay (sec)	SCATS Control	Traffic Volume (veh)	Approach Delay (sec)	SCATS Control	Traffic Volume (veh)	Approach Delay (sec)	SCATS Control	Traffic Volume (veh)	Approach Delay (sec)	SCATS Control
		"Optimized"	Plan		"Optimized"	Plan		"Optimized"	Plan		"Optimized"	Plan
Northbound Through	62	5.7	9.1	447	30.8	43.2	400	17.0	29.6	463	33.7	45.3
Northbound Left Turn	4	4.5	7.8	17	22.7	25.0	21	46.8	53.2	44	39.0	37.9
Southbound Through	67	3.6	7.7	401	22.7	38.6	441	19.6	37.3	589	38.7	78.9
Southbound Left Turn	9	4.8	8.7	16	68.9	37.3	34	24.4	30.3	90	41.0	45.3
Westbound Through	13	30.3	26.7	194	27.8	31.4	250	38.0	33.3	445	62.3	75.5
Westbound Left Turn	2	18.1	17.0	50	67.6	34.9	18	30.3	23.5	37	44.5	43.1
Eastbound Through	10	26.8	30.0	336	39.0	52.6	187	31.4	28.3	218	32.4	33.2
Eastbound Left Turn	0	0.0	0.0	67	48.9	30.7	28	73.6	34.6	65	55.4	45.2
Intersection Delay (veh-hr)		0.42	0.51		13.75	17.61		9.78	12.63		26.56	32.88
Average Cycle Length (sec)		55.0	53.0		85.0	85.8		85.0	81.0		90.0	89.6

Table 4.3b Delay Model Output

South Lyon SCATS Delay Evaluation Study Intersection of Pontiac Trail and Ten Mile Road												
Tuesday, May 7, 1996												
Approach Movement	12:00 am - 1:00 am			7:00 am - 8:00 am			12:00 pm - 1:00 pm			5:00 pm - 6:00 pm		
	Traffic Volume (veh)	Approach Delay (sec) "Optimized"	SCATS Control	Traffic Volume (veh)	Approach Delay (sec) "Optimized"	SCATS Control	Traffic Volume (veh)	Approach Delay (sec) "Optimized"	SCATS Control	Traffic Volume (veh)	Approach Delay (sec) "Optimized"	SCATS Control
Northbound Through	158	5.7	13.6	456	33.8	48.8	376	16.2	30.7	501	48.9	58.8
Northbound Left Turn	4	3.4	7.8	26	28.8	29.3	36	25.6	30.4	34	68.2	39.3
Southbound Through	194	6.1	19.0	407	20.6	39.1	449	17.0	34.2	560	50.5	65.1
Southbound Left Turn	4	5.2	11.6	2	26.7	31.5	29	22.9	28.3	78	73.2	61.2
Westbound Through	60	32.9	21.8	196	27.3	33.5	231	43.4	39.5	431	56.7	75.9
Westbound Left Turn	4	18.1	13.2	34	79.5	37.6	30	31.9	25.0	45	30.9	43.3
Eastbound Through	35	33.1	23.8	338	44.5	51.8	202	30.8	27.8	203	27.3	32.8
Eastbound Left Turn	10	21.3	11.4	52	44.1	37.2	34	39.6	28.2	76	56.9	41.2
Intersection Delay (veh-hr)		1.53	2.29		13.86	18.42		9.40	12.06		26.81	32.36
Average Cycle Length (sec)		55.0	53.5		85.0	86.7		85.0	80.0		90.0	89.7

note: through traffic movements include right turn traffic

Table 4.3c Delay Model Output

South Lyon SCATS Delay Evaluation Study Intersection of Pontiac Trail and Ten Mile Road												
Approach Movement	12:00 am - 1:00 am			7:00 am - 8:00 am			12:00 pm - 1:00 pm			5:00 pm - 6:00 pm		
	Traffic Volume	Approach Delay (sec)	SCATS "Optimized"	Traffic Volume	Approach Delay (sec)	SCATS "Optimized"	Traffic Volume	Approach Delay (sec)	SCATS "Optimized"	Traffic Volume	Approach Delay (sec)	SCATS "Optimized"
	Plan	Control	Plan	Control	Plan	Control	Plan	Control	Plan	Control	Plan	Control
Northbound Through	135	5.7	9.7	449	33.7	43.0	414	17.0	30.3	511	42.5	47.0
Northbound Left Turn	0	0.0	0.0	18	55.1	31.0	14	28.8	35.5	37	59.4	42.4
Southbound Through	146	6.4	16.3	400	25.3	37.9	431	17.7	36.2	597	59.7	66.5
Southbound Left Turn	6	4.2	6.9	21	58.5	34.5	23	25.3	28.8	94	54.1	40.3
Westbound Through	103	49.4	31.4	156	25.5	31.2	225	42.7	38.5	377	46.4	76.1
Westbound Left Turn	6	18.1	18.1	43	47.4	36.2	21	31.8	23.5	44	23.8	25.2
Eastbound Through	29	18.4	23.3	307	34.3	60.2	178	30.7	28.0	191	26.3	29.7
Eastbound Left Turn	2	28.7	39.6	77	43.6	36.9	25	46.6	27.8	70	55.3	49.0
Intersection Delay (veh-hr)		2.20	2.23		13.16	17.64		9.04	12.26		25.58	30.01
Average Cycle Length (sec)		55.0	57.7		85.0	86.0		85.0	81.5		90.0	90.2

note: through traffic movements include right turn traffic

Table 4.3d Delay Model Output

South Lyon SCATS Delay Evaluation Study Intersection of Pontiac Trail and Ten Mile Road												
Approach Movement	12:00 am - 1:00 am			7:00 am - 8:00 am			12:00 pm - 1:00 pm			5:00 pm - 6:00 pm		
	Traffic Volume (veh)	Approach Delay (sec)	SCATS "Optimized" Plan	Traffic Volume (veh)	Approach Delay (sec)	SCATS "Optimized" Plan	Traffic Volume (veh)	Approach Delay (sec)	SCATS "Optimized" Plan	Traffic Volume (veh)	Approach Delay (sec)	SCATS "Optimized" Plan
Northbound Through	239	6.2	8.9	439	32.7	47.4	403	16.7	31.6	479	29.9	54.9
Northbound Left Turn	2	7.0	13.0	22	27.3	27.2	20	25.8	30.0	37	41.4	38.6
Southbound Through	163	5.8	10.6	387	22.1	39.9	468	18.7	37.1	565	55.6	71.9
Southbound Left Turn	20	6.4	10.5	17	88.9	33.0	39	25.0	31.0	115	49.8	55.9
Westbound Through	117	49.7	36.5	164	27.0	33.6	259	45.7	50.0	467	66.7	77.0
Westbound Left Turn	6	18.1	9.8	31	32.9	32.5	39	32.3	25.6	38	25.9	26.1
Eastbound Through	47	37.8	30.2	343	38.5	48.4	196	31.6	29.0	208	30.1	31.2
Eastbound Left Turn	3	19.9	11.4	39	25.1	23.0	32	51.3	28.3	75	61.7	44.4
Intersection Delay (veh-hr)		2.86	2.75		12.40	17.06		10.53	13.92		26.67	33.76
Average Cycle Length (sec)		55.0	55.3		85.0	84.5		85.0	81.3		90.0	89.9

note: through traffic movements include right turn traffic

Table 4.3e Delay Model Output

South Lyon SCATS Delay Evaluation Study Intersection of Pontiac Trail and Ten Mile Road													
Friday, May 10, 1996	Approach Movement	12:00 am - 1:00 am			7:00 am - 8:00 am			12:00 pm - 1:00 pm			5:00 pm - 6:00 pm		
		Traffic Volume (veh)	Approach Delay (sec)		Traffic Volume (veh)	Approach Delay (sec)		Traffic Volume (veh)	Approach Delay (sec)		Traffic Volume (veh)	Approach Delay (sec)	
			"Optimized" Plan	SCATS Control		"Optimized" Plan	SCATS Control		"Optimized" Plan	SCATS Control		"Optimized" Plan	SCATS Control
	Northbound Through	237	5.9	12.9	484	35.1	47.2	411	16.7	32.6	487	37.5	46.0
	Northbound Left Turn	2	7.0	14.9	17	27.0	26.0	29	26.9	31.4	65	45.4	38.1
	Southbound Through	188	6.0	9.4	391	21.8	38.8	488	20.3	44.2	579	56.7	73.7
	Southbound Left Turn	15	7.4	12.4	25	75.0	35.2	28	23.7	27.4	77	43.0	35.3
	Westbound Through	97	41.2	28.4	176	25.6	37.3	266	48.6	40.9	432	55.4	79.0
	Westbound Left Turn	2	18.1	9.4	28	37.1	49.8	36	32.0	25.1	40	29.6	28.2
	Eastbound Through	33	31.0	23.8	330	35.7	49.8	191	30.7	27.9	230	31.6	35.5
	Eastbound Left Turn	14	18.1	14.8	63	32.0	28.7	33	38.9	27.5	115	73.0	56.8
	Intersection Delay (veh-hr)		2.21	2.44		13.11	18.17		10.97	15.18		27.26	33.39
	Average Cycle Length (sec)		55.0	55.5		85.0	85.0		85.0	81.5		90.0	90.1

note: through traffic movements include right turn traffic

Table 4.3f Delay Model Output

South Lyon SCATS Delay Evaluation Study Intersection of Pontiac Trail and Ten Mile Road												
Week of 5/6/96 through 5/10/96 - Daily Average												
Approach Movement	12:00 am - 1:00 am			7:00 am - 8:00 am			12:00 pm - 1:00 pm			5:00 pm - 6:00 pm		
	Traffic Volume (veh)	Approach Delay (sec)		Traffic Volume (veh)	Approach Delay (sec)		Traffic Volume (veh)	Approach Delay (sec)		Traffic Volume (veh)	Approach Delay (sec)	
		"Optimized" Plan	SCATS Control		"Optimized" Plan	SCATS Control		"Optimized" Plan	SCATS Control		"Optimized" Plan	SCATS Control
Northbound Through	170	5.8	10.8	455	33.2	45.9	401	16.7	31.0	488	38.5	50.4
Northbound Left Turn	2	4.4	8.7	20	32.2	27.7	24	30.8	36.1	43	50.7	39.3
Southbound Through	152	5.6	12.6	397	22.5	38.9	455	18.7	37.8	578	56.2	71.2
Southbound Left Turn	11	5.6	10.0	16	63.6	34.3	31	24.3	29.2	91	52.2	47.6
Westbound Through	78	40.7	29.0	177	26.6	33.4	246	43.7	40.4	430	57.5	76.7
Westbound Left Turn	4	18.1	13.5	37	52.9	38.2	29	31.7	24.5	41	30.9	33.2
Eastbound Through	31	31.4	26.2	331	38.4	52.6	191	31.0	28.2	210	29.5	32.5
Eastbound Left Turn	6	17.6	15.4	60	38.7	31.3	30	50.0	29.3	80	60.5	46.9
Intersection Delay (veh-hr)		1.84	2.04		13.26	17.78		9.94	13.21		26.58	32.48
Average Cycle Length (sec)		55.0	55.0		85.0	85.6		85.0	81.1		90.0	89.9

note: through traffic movements include right turn traffic

Table 4.4a Delay Model Output

South Lyon SCATS Delay Evaluation Study Intersection of Pontiac Trail and Nine Mile Road Monday, May 6, 1996												
Approach Movement	12:00 am - 1:00 am			7:00 am - 8:00 am			12:00 pm - 1:00 pm			5:00 pm - 6:00 pm		
	Traffic Volume (veh)	Approach Delay (sec)		Traffic Volume (veh)	Approach Delay (sec)		Traffic Volume (veh)	Approach Delay (sec)		Traffic Volume (veh)	Approach Delay (sec)	
		"Optimized" Plan	SCATS Control		"Optimized" Plan	SCATS Control		"Optimized" Plan	SCATS Control		"Optimized" Plan	SCATS Control
Northbound Through	77	3.9	1.2	346	7.9	37.2	455	9.2	11.6	856	23.4	46.7
Northbound Left Turn	2	3.4	4.4	32	33.9	38.0	10	19.0	18.6	42	44.0	36.6
Southbound Through	53	3.9	1.1	727	17.9	37.2	567	11.5	20.4	651	12.2	28.6
Southbound Left Turn	0	0.0	0.0	4	9.1	12.2	8	16.8	18.0	20	40.2	35.5
Eastbound Through	0	0.0	0.0	51	32.5	28.4	48	30.7	27.6	64	28.1	30.3
Westbound Through	6	27.4	27.0	256	75.4	47.9	172	38.7	36.9	222	43.9	43.0
Intersection Delay (veh-hr)		0.19	0.09		10.52	12.91		5.33	6.91		11.70	20.11
Average Cycle Length (sec)		50.0	52.0		85.0	85.2		80.0	81.3		90.0	90.2

note: through traffic movements include right turn traffic

Table 4.4b Delay Model Output

South Lyon SCATS Delay Evaluation Study Intersection of Pontiac Trail and Nine Mile Road												
Tuesday, May 7, 1996												
Approach Movement	12:00 am - 1:00 am			7:00 am - 8:00 am			12:00 pm - 1:00 pm			5:00 pm - 6:00 pm		
	Traffic Volume (veh)	Approach Delay (sec) "Optimized"	SCATS Control	Traffic Volume (veh)	Approach Delay (sec) "Optimized"	SCATS Control	Traffic Volume (veh)	Approach Delay (sec) "Optimized"	SCATS Control	Traffic Volume (veh)	Approach Delay (sec) "Optimized"	SCATS Control
	Plan			Plan			Plan			Plan		
Northbound Through	167	4.1	2.9	335	7.6	11.7	461	9.6	14.4	870	24.5	48.9
Northbound Left Turn	5	4.4	5.1	19	69.8	43.2	13	59.8	24.5	27	24.9	28.7
Southbound Through	163	4.1	2.5	754	21.7	41.2	540	12.2	16.2	654	10.0	25.6
Southbound Left Turn	0	0.0	0.0	10	12.8	13.6	15	13.8	12.5	20	83.8	40.2
Eastbound Through	2	27.4	25.6	27	30.3	27.1	45	29.8	27.1	50	28.0	29.1
Westbound Through	14	47.2	31.5	263	75.3	61.6	183	40.2	39.5	259	56.4	50.6
Intersection Delay (veh-hr)		0.58	0.39		11.38	14.68		5.75	6.76		12.84	20.96
Average Cycle Length (sec)		50.0	51.5		85.0	86.5		80.0	79.9		90.0	90.5

note: through traffic movements include right turn traffic

Table 4.4c Delay Model Output

South Lyon SCATS Delay Evaluation Study Intersection of Pontiac Trail and Nine Mile Road Wednesday, May 8, 1996												
Approach Movement	12:00 am - 1:00 am			7:00 am - 8:00 am			12:00 pm - 1:00 pm			5:00 pm - 6:00 pm		
	Traffic Volume (veh)	Approach Delay (sec)		Traffic Volume (veh)	Approach Delay (sec)		Traffic Volume (veh)	Approach Delay (sec)		Traffic Volume (veh)	Approach Delay (sec)	
		"Optimized"	SCATS Control		"Optimized"	SCATS Control		"Optimized"	SCATS Control		"Optimized"	SCATS Control
Northbound Through	151	4.2	1.6	356	8.3	11.9	466	9.3	13.9	877	23.2	56.9
Northbound Left Turn	12	2.7	1.8	22	100.9	36.6	11	17.6	17.5	50	36.1	31.7
Southbound Through	159	3.9	2.0	727	24.4	36.5	554	10.5	19.2	667	12.5	36.9
Southbound Left Turn	2	1.8	1.9	6	13.3	11.5	12	17.0	18.2	23	85.3	39.8
Eastbound Through	11	40.0	31.9	44	30.8	26.9	44	29.3	27.2	60	27.9	27.5
Westbound Through	12	50.5	36.0	256	77.0	56.9	196	55.4	35.1	330	70.7	46.2
Intersection Delay (veh-hr)		0.65	0.38		12.24	13.14		6.30	7.11		16.02	26.11
Average Cycle Length (sec)		50.0	51.4		85.0	86.4		80.0	81.9		90.0	90.7

note: through traffic movements include right turn traffic

Table 4.4d Delay Model Output

South Lyon SCATS Delay Evaluation Study Intersection of Pontiac Trail and Nine Mile Road															
Thursday, May 9, 1996															
Approach Movement	12:00 am - 1:00 am				7:00 am - 8:00 am				12:00 pm - 1:00 pm				5:00 pm - 6:00 pm		
	Traffic Volume (veh)	Approach Delay (sec)		Traffic Volume (veh)	Approach Delay (sec)		Traffic Volume (veh)	Approach Delay (sec)		Traffic Volume (veh)	Approach Delay (sec)		Traffic Volume (veh)	Approach Delay (sec)	
		"Optimized"	SCATS Control		"Optimized"	SCATS Control		"Optimized"	SCATS Control		"Optimized"	SCATS Control		"Optimized"	SCATS Control
Northbound Through	173	4.1	1.9	327	7.3	11.1	464	9.7	15.0	872	27.0	45.3			
Northbound Left Turn	6	2.8	2.5	17	10.7	11.3	5	18.0	15.6	25	25.3	29.0			
Southbound Through	209	4.1	2.2	756	22.1	36.7	507	12.0	20.6	661	10.1	22.2			
Southbound Left Turn	0	0.0	0.0	29	128.6	50.4	2	10.2	12.6	16	119.7	35.3			
Eastbound Through	6	27.4	25.2	41	30.7	26.4	36	29.6	28.3	63	28.1	31.0			
Westbound Through	15	55.1	35.3	251	71.7	55.5	170	47.5	43.7	250	51.2	49.0			
Intersection Delay (veh-hr)		0.71	0.41		11.73	13.36		5.73	7.57		13.15	19.36			
Average Cycle Length (sec)		50.0	51.9		85.0	84.5		80.0	79.3		90.0	89.4			

note: through traffic movements include right turn traffic

Table 4.4e Delay Model Output

South Lyon SCATS Delay Evaluation Study Intersection of Pontiac Trail and Nine Mile Road Friday, May 10, 1996												
Approach Movement	12:00 am - 1:00 am			7:00 am - 8:00 am			12:00 pm - 1:00 pm			5:00 pm - 6:00 pm		
	Traffic Volume (veh)	Approach Delay (sec)		Traffic Volume (veh)	Approach Delay (sec)		Traffic Volume (veh)	Approach Delay (sec)		Traffic Volume (veh)	Approach Delay (sec)	
		"Optimized"	SCATS Control		"Optimized"	SCATS Control		"Optimized"	SCATS Control		"Optimized"	SCATS Control
Northbound Through	172	4.0	2.1	361	9.2	18.6	508	9.9	13.1	903	28.0	54.6
Northbound Left Turn	11	2.9	2.9	47	72.6	47.4	30	22.0	18.3	36	39.9	30.6
Southbound Through	206	4.2	2.7	765	19.9	42.1	565	10.6	14.6	639	12.4	28.2
Southbound Left Turn	0	0.0	0.0	6	11.2	10.8	6	18.6	16.6	22	99.2	37.0
Eastbound Through	4	27.4	28.0	44	30.5	28.9	56	30.0	32.3	81	28.4	29.8
Westbound Through	12	50.5	29.2	247	76.2	46.4	169	38.7	37.7	233	42.9	36.5
Intersection Delay (veh-hr)		0.64	0.39		11.71	14.99		5.55	6.59		13.63	22.26
Average Cycle Length (sec)		50.0	51.9		85.0	85.1		80.0	81.7		90.0	90.3

note: through traffic movements include right turn traffic

Table 4.4f Delay Model Output

South Lyon SCATS Delay Evaluation Study Intersection of Pontiac Trail and Nine Mile Road												
Week of 5/6/96 through 5/10/96 - Daily Average												
Approach Movement	12:00 am - 1:00 am			7:00 am - 8:00 am			12:00 pm - 1:00 pm			5:00 pm - 6:00 pm		
	Traffic Volume (veh)	Approach Delay (sec)		Traffic Volume (veh)	Approach Delay (sec)		Traffic Volume (veh)	Approach Delay (sec)		Traffic Volume (veh)	Approach Delay (sec)	
		"Optimized"	SCATS Control		"Optimized"	SCATS Control		"Optimized"	SCATS Control		"Optimized"	SCATS Control
Northbound Through	148	4.1	1.9	345	8.1	18.1	471	9.5	13.6	876	25.2	50.5
Northbound Left Turn	7	3.2	3.3	27	57.6	35.3	14	27.3	18.9	36	34.0	31.3
Southbound Through	158	4.0	2.1	746	21.2	38.7	547	11.4	18.2	654	11.4	28.3
Southbound Left Turn	0	0.4	0.4	11	35.0	19.7	9	15.3	15.6	20	85.6	37.6
Eastbound Through	5	24.4	22.1	41	31.0	27.5	46	29.9	28.5	64	28.1	29.5
Westbound Through	12	46.1	31.8	255	75.1	53.7	178	44.1	38.6	259	53.0	45.1
Intersection Delay (veh-hr)		0.55	0.33		11.52	13.82		5.73	6.99		13.47	21.76
Average Cycle Length (sec)		50.0	51.7		85.0	85.5		80.0	80.8		90.0	90.2

note: through traffic movements include right turn traffic

Table 4.5a Delay Model Output

South Lyon SCATS Delay Evaluation Study Intersection of Pontiac Trail and Eleven Mile Road Monday, May 6, 1996																
Approach Movement	12:00 am - 1:00 am				7:00 am - 8:00 am				12:00 pm - 1:00 pm				5:00 pm - 6:00 pm			
	Traffic Volume (veh)	Approach Delay (sec)		Traffic Volume (veh)	Approach Delay (sec)		Traffic Volume (veh)	Approach Delay (sec)		Traffic Volume (veh)	Approach Delay (sec)		Traffic Volume (veh)	Approach Delay (sec)		
		"Optimized"	Plan		"Optimized"	Plan		"Optimized"	Plan		"Optimized"	Plan		"Optimized"	Plan	
Northbound Through	48	3.5	5.9	339	6.5	9.4	317	4.1	7.4	422	5.6	9.0				
Northbound Left Turn	2	1.6	1.7	50	10.8	10.9	0	0.0	0.0	15	19.5	21.7				
Southbound Through	23	3.4	5.8	299	6.4	8.5	320	5.8	7.1	476	6.0	11.9				
Southbound Left Turn	2	3.1	3.2	2	17.7	13.3	14	5.8	6.3	17	12.1	13.5				
Eastbound Through	3	51.2	41.2	149	62.1	52.9	79	69.2	39.7	101	85.5	60.7				
Westbound Through	0	0.0	0.0	12	31.7	31.5	12	38.4	32.0	10	41.2	34.2				
Intersection Delay (veh-hr)		0.14	0.15		3.98	4.04		2.39	2.89		4.09	4.57				
Average Cycle Length (sec)		55	53.0		85.0	84.1		80.0	80.5		85.0	82.4				

note: through traffic movements include right turn traffic

Table 4.5b Delay Model Output

South Lyon SCATS Delay Evaluation Study Intersection of Pontiac Trail and Eleven Mile Road																
Tuesday, May 7, 1996																
Approach Movement	12:00 am - 1:00 am				7:00 am - 8:00 am				12:00 pm - 1:00 pm				5:00 pm - 6:00 pm			
	Traffic Volume (veh)	Approach Delay (sec)		Traffic Volume (veh)	Approach Delay (sec)		Traffic Volume (veh)	Approach Delay (sec)		Traffic Volume (veh)	Approach Delay (sec)		Traffic Volume (veh)	Approach Delay (sec)		
		"Optimized"	Control		"Optimized"	Control		"Optimized"	Control		"Optimized"	Control		"Optimized"	Control	
Northbound Through	123	3.6	6.2	322	6.7	10.8	309	3.9	6.4	482	9.7	12.6				
Northbound Left Turn	2	1.7	1.9	57	10.4	11.3	0	0.0	0.0	6	14.3	14.1				
Southbound Through	88	3.5	6.0	290	6.3	4.2	333	6.9	6.9	403	8.9	11.6				
Southbound Left Turn	4	2.4	2.4	2	9.8	7.3	7	7.4	7.2	7	10.9	13.8				
Eastbound Through	11	44.4	30.7	163	71.1	52.6	59	62.8	37.3	84	91.3	49.8				
Westbound Through	2	30.6	26.8	4	30.7	24.8	19	43.4	35.6	8	41.2	31.3				
Intersection Delay (veh-hr)		0.37	0.47		4.53	4.30		2.00	2.00		4.57	4.27				
Average Cycle Length (sec)		55	53.8		85.0	84.7		80.0	79.8		85.0	81.9				

note: through traffic movements include right turn traffic

Table 4.5c Delay Model Output

South Lyon SCATS Delay Evaluation Study Intersection of Pontiac Trail and Eleven Mile Road Wednesday, May 8, 1996												
Approach Movement	12:00 am - 1:00 am			7:00 am - 8:00 am			12:00 pm - 1:00 pm			5:00 pm - 6:00 pm		
	Traffic Volume (veh)	Approach Delay (sec) "Optimized"	SCATS Control	Traffic Volume (veh)	Approach Delay (sec) "Optimized"	SCATS Control	Traffic Volume (veh)	Approach Delay (sec) "Optimized"	SCATS Control	Traffic Volume (veh)	Approach Delay (sec) "Optimized"	SCATS Control
	Plan			Plan			Plan			Plan		
Northbound Through	140	3.6	6.2	306	6.4	9.7	316	4.1	6.7	458	5.8	8.6
Northbound Left Turn	0	0.0	0.0	45	10.1	11.8	2	5.1	5.3	4	7.0	7.9
Southbound Through	77	3.7	6.6	268	6.2	9.3	285	3.9	6.4	438	7.7	8.3
Southbound Left Turn	0	0.0	0.0	6	8.6	6.2	0	0.0	0.0	7	19.0	19.0
Eastbound Through	4	30.6	25.3	152	68.3	49.3	58	64.7	39.2	100	81.7	60.9
Westbound Through	2	30.6	25.0	15	31.1	29.3	10	38.4	34.0	4	41.2	36.4
Intersection Delay (veh-hr)		0.27	0.43		4.17	3.88		1.82	1.82		4.03	3.88
Average Cycle Length (sec)		55	52.9		85.0	82.9		80.0	80.1		85.0	84.5

note: through traffic movements include right turn traffic

Table 4.5d Delay Model Output

South Lyon SCATS Delay Evaluation Study Intersection of Pontiac Trail and Eleven Mile Road Thursday, May 9, 1996												
Approach Movement	12:00 am - 1:00 am			7:00 am - 8:00 am			12:00 pm - 1:00 pm			5:00 pm - 6:00 pm		
	Traffic Volume (veh)	Approach Delay (sec)		Traffic Volume (veh)	Approach Delay (sec)		Traffic Volume (veh)	Approach Delay (sec)		Traffic Volume (veh)	Approach Delay (sec)	
		"Optimized"	SCATS Control		"Optimized"	SCATS Control		"Optimized"	SCATS Control		"Optimized"	SCATS Control
Northbound Through	161	3.6	6.2	339	7.0	10.8	328	4.0	7.3	446	6.0	7.9
Northbound Left Turn	5	2.7	3.1	37	8.8	10.4	2	1.6	2.4	3	4.3	4.2
Southbound Through	120	3.5	6.1	271	6.2	8.4	334	4.6	8.3	413	5.4	8.9
Southbound Left Turn	13	2.7	2.8	0	0.0	0.0	4	9.9	8.9	5	7.9	8.4
Eastbound Through	4	27.3	28.1	179	66.3	57.8	65	73.7	38.2	65	78.3	56.3
Westbound Through	8	30.6	26.1	15	31.1	32.9	9	41.9	34.0	14	41.2	36.3
Intersection Delay (veh-hr)		0.39	0.58		4.65	4.77		2.24	2.22		2.95	3.18
Average Cycle Length (sec)		55	53.2		85.0	81.5		80.0	80.2		85.0	81.7

note: through traffic movements include right turn traffic

Table 4.5e Delay Model Output

South Lyon SCATS Delay Evaluation Study Intersection of Pontiac Trail and Eleven Mile Road Friday, May 10, 1996												
Approach Movement	12:00 am - 1:00 am			7:00 am - 8:00 am			12:00 pm - 1:00 pm			5:00 pm - 6:00 pm		
	Traffic Volume (veh)	Approach Delay (sec)		Traffic Volume (veh)	Approach Delay (sec)		Traffic Volume (veh)	Approach Delay (sec)		Traffic Volume (veh)	Approach Delay (sec)	
		"Optimized"	SCATS Control		"Optimized"	SCATS Control		"Optimized"	SCATS Control		"Optimized"	SCATS Control
Northbound Through	180	3.9	7.1	313	6.6	10.0	376	4.2	7.2	477	8.7	9.2
Northbound Left Turn	2	1.7	1.9	75	8.9	10.5	4	11.2	6.8	6	13.7	14.4
Southbound Through	106	3.4	5.9	260	6.2	8.9	352	4.2	10.8	508	6.3	9.8
Southbound Left Turn	0	0.0	0.0	6	14.0	11.6	14	8.1	8.8	17	14.8	15.6
Eastbound Through	2	30.6	25.0	178	73.9	60.8	75	78.9	46.3	79	104.0	63.4
Westbound Through	2	30.6	26.2	11	31.2	31.9	16	38.4	33.3	12	77.2	69.4
Intersection Delay (veh-hr)		0.33	0.56		4.98	4.86		2.71	2.57		4.66	4.32
Average Cycle Length (sec)		55	53.3		85.0	82.4		80.0	81.6		85.0	82.8

note: through traffic movements include right turn traffic

Table 4.5f Delay Model Output

South Lyon SCATS Delay Evaluation Study Intersection of Pontiac Trail and Eleven Mile Road												
Week of 5/6/96 through 5/10/96 - Daily Average												
Approach Movement	12:00 am - 1:00 am			7:00 am - 8:00 am			12:00 pm - 1:00 pm			5:00 pm - 6:00 pm		
	Traffic Volume (veh)	Approach Delay (sec)		Traffic Volume (veh)	Approach Delay (sec)		Traffic Volume (veh)	Approach Delay (sec)		Traffic Volume (veh)	Approach Delay (sec)	
		"Optimized"	SCATS Control		"Optimized"	SCATS Control		"Optimized"	SCATS Control		"Optimized"	SCATS Control
Northbound Through	130	3.6	6.3	324	6.6	10.1	329	4.1	7.0	457	7.2	9.5
Northbound Left Turn	2	1.5	1.7	53	9.8	11.0	2	3.6	2.9	7	11.8	12.5
Southbound Through	83	3.5	6.1	278	6.3	8.9	325	4.2	7.9	448	6.9	10.1
Southbound Left Turn	4	1.6	1.7	3	10.0	7.7	8	6.2	6.2	11	12.9	14.1
Eastbound Through	5	36.8	30.1	164	68.3	54.7	67	69.9	40.1	86	88.2	58.2
Westbound Through	3	24.5	20.8	11	31.2	30.1	13	40.1	33.8	10	48.4	41.5
Intersection Delay (veh-hr)		0.30	0.44		4.46	4.37		2.23	2.30		4.06	4.04
Average Cycle Length (sec)		55.0	53.2		85.0	83.1		80.0	80.4		85.0	82.7

note: through traffic movements include right turn traffic

Table 4.6a Delay Model Output

South Lyon SCA TS Delay Evaluation Study Intersection of Reynold Sweet Parkway and Ten Mile Road												
Monday, May 6, 1996												
Approach Movement	12:00 am - 1:00 am			7:00 am - 8:00 am			12:00 pm - 1:00 pm			5:00 pm - 6:00 pm		
	Traffic Volume (veh)	Approach Delay (sec) "Optimized"	SCATS Control	Traffic Volume (veh)	Approach Delay (sec) "Optimized"	SCATS Control	Traffic Volume (veh)	Approach Delay (sec) "Optimized"	SCATS Control	Traffic Volume (veh)	Approach Delay (sec) "Optimized"	SCATS Control
Westbound Through	39	2.0	0.2	258	4.8	0.8	273	4.2	0.6	550	13.2	1.7
Westbound Left Turn	0	0.0	0.0	41	15.9	11.0	41	6.5	3.3	60	10.8	5.6
Eastbound Through	29	2.0	0.2	439	6.4	5.3	259	4.2	3.0	303	5.5	4.3
Northbound Left Turn	0	0.0	0.0	2	30.3	52.4	4	32.8	53.4	10	43.4	49.7
Intersection Delay (veh-hr)		0.04	0.00		1.32	0.86		0.72	0.36		2.78	0.85
Average Cycle Length (sec)		50	51.4		75.0	75.8		70.0	73.5		75.0	76.8

note: through traffic movements include right turn traffic

Table 4.6b Delay Model Output

South Lyon SCA TS Delay Evaluation Study Intersection of Reynold Sweet Parkway and Ten Mile Road												
Tuesday, May 7, 1996												
Approach Movement	12:00 am - 1:00 am			7:00 am - 8:00 am			12:00 pm - 1:00 pm			5:00 pm - 6:00 pm		
	Traffic Volume (veh)	Approach Delay (sec)	SCATS Control	Traffic Volume (veh)	Approach Delay (sec)	SCATS Control	Traffic Volume (veh)	Approach Delay (sec)	SCATS Control	Traffic Volume (veh)	Approach Delay (sec)	SCATS Control
Westbound Through	29	2.1	0.2	258	5.0	0.9	269	4.1	0.6	519	8.7	1.4
Westbound Left Turn	0	0.0	0.0	30	12.8	7.0	57	7.0	4.2	77	10.7	5.6
Eastbound Through	36	2.1	0.2	423	6.7	4.0	246	4.1	3.2	289	5.1	4.0
Northbound Left Turn	0	0.0	0.0	4	30.3	61.2	6	32.8	46.8	12	77.8	45.9
Intersection Delay (veh-hr)		0.15	0.00		1.28	0.65		0.75	0.41		2.15	0.80
Average Cycle Length (sec)		50	51.8		75.0	75.7		70.0	71.3		75.0	75.4

note: through traffic movements include right turn traffic

Table 4.6c Delay Model Output

South Lyon SCATS Delay Evaluation Study												
Intersection of Reynold Sweet Parkway and Ten Mile Road												
Wednesday, May 8, 1996												
Approach Movement	12:00 am - 1:00 am			7:00 am - 8:00 am			12:00 pm - 1:00 pm			5:00 pm - 6:00 pm		
	Traffic Volume (veh)	Approach Delay (sec)	SCATS Control	Traffic Volume (veh)	Approach Delay (sec)	SCATS Control	Traffic Volume (veh)	Approach Delay (sec)	SCATS Control	Traffic Volume (veh)	Approach Delay (sec)	SCATS Control
Westbound Through	30	2.0	0.2	265	6.2	0.8	273	4.4	1.0	483	7.1	3.6
Westbound Left Turn	0	0.0	0.0	73	18.1	19.0	39	8.7	6.2	65	11.4	7.4
Eastbound Through	23	2.0	0.2	414	8.9	7.5	266	4.4	4.0	318	5.4	5.0
Northbound Left Turn	0	0.0	0.0	5	31.2	51.3	17	58.8	52.3	6	43.5	55.7
Intersection Delay (veh-hr)		0.03	0.00		1.68	1.38		1.03	0.69		1.77	1.19
Average Cycle Length (sec)		50	51.9		75.0	77.0		70.0	69.5		75.0	75.1

note: through traffic movements include right turn traffic

Table 4.6d Delay Model Output

South Lyon SCATS Delay Evaluation Study Intersection of Reynold Sweet Parkway and Ten Mile Road												
Thursday, May 9, 1996												
Approach Movement	12:00 am - 1:00 am			7:00 am - 8:00 am			12:00 pm - 1:00 pm			5:00 pm - 6:00 pm		
	Traffic Volume (veh)	Approach Delay (sec)	SCATS Control	Traffic Volume (veh)	Approach Delay (sec)	SCATS Control	Traffic Volume (veh)	Approach Delay (sec)	SCATS Control	Traffic Volume (veh)	Approach Delay (sec)	SCATS Control
Westbound Through	24	2.0	0.0	256	5.4	0.7	324	4.5	1.0	616	6.4	1.9
Westbound Left Turn	0	0.0	0.2	40	9.8	4.9	43	8.0	4.6	60	12.0	7.1
Eastbound Through	20	2.0	0.2	372	6.9	5.7	297	4.2	4.2	349	5.7	4.8
Northbound Left Turn	0	0.0	0.0	6	30.3	40.0	12	32.8	31.8	9	66.3	59.9
Intersection Delay (veh-hr)		0.02	0.00		1.26	0.76		0.70	0.59		1.48	1.05
Average Cycle Length (sec)		50	51.6		75.0	72.2		70.0	65.2		75.0	76.6

note: through traffic movements include right turn traffic

Table 4.6e Delay Model Output

South Lyon SCATS Delay Evaluation Study Intersection of Reynold Sweet Parkway and Ten Mile Road												
Friday, May 10, 1996												
Approach Movement	12:00 am - 1:00 am			7:00 am - 8:00 am			12:00 pm - 1:00 pm			5:00 pm - 6:00 pm		
	Traffic Volume (veh)	Approach Delay (sec)	SCATS Control	Traffic Volume (veh)	Approach Delay (sec)	SCATS Control	Traffic Volume (veh)	Approach Delay (sec)	SCATS Control	Traffic Volume (veh)	Approach Delay (sec)	SCATS Control
		Optimized Plan			Optimized Plan			Optimized Plan			Optimized Plan	
Westbound Through	35	2.0	0.3	244	4.8	0.8	351	4.6	0.8	507	14.2	1.5
Westbound Left Turn	0	0.0	0.0	55	11.4	6.4	51	8.1	4.6	66	12.6	7.7
Eastbound Through	22	2.0	0.2	413	6.2	4.6	301	4.3	3.3	378	7.0	6.0
Northbound Left Turn	0	0.0	0.0	2	30.2	44.7	6	32.8	56.2	23	140.6	55.7
Intersection Delay (veh-hr)		0.03	0.00		1.23	0.70		0.98	0.51		3.86	1.34
Average Cycle Length (sec)		50	51.4		75.0	75.3		70.0	75.4		75.0	75.3

note: through traffic movements include right turn traffic

Table 4.6f Delay Model Output

South Lyon SCATS Delay Evaluation Study Intersection of Reynold Sweet Parkway and Ten Mile Road												
Week of 5/6/96 through 5/10/96 - Daily Average												
Approach Movement	12:00 am - 1:00 am			7:00 am - 8:00 am			12:00 pm - 1:00 pm			5:00 pm - 6:00 pm		
	Traffic Volume (veh)	Approach Delay (sec)	SCATS Control	Traffic Volume (veh)	Approach Delay (sec)	SCATS Control	Traffic Volume (veh)	Approach Delay (sec)	SCATS Control	Traffic Volume (veh)	Approach Delay (sec)	SCATS Control
Westbound Through	31	2.0	0.2	256	5.2	0.8	298	4.4	0.8	535	9.9	2.0
Westbound Left Turn	0	0.0	0.0	48	13.6	9.7	46	7.7	4.6	66	11.5	6.7
Eastbound Through	26	2.0	0.2	412	7.0	5.4	274	4.2	3.5	327	5.7	4.8
Northbound Left Turn	0	0.0	0.0	4	30.5	49.9	9	38.0	48.1	12	74.3	53.4
Intersection Delay (veh-hr)		0.05	0.00		1.35	0.87		0.84	0.51		2.41	1.05
Average Cycle Length (sec)		50.0	51.6		75.0	75.2		70.0	71.0		75.0	75.8

note: through traffic movements include right turn traffic

Chapter 5.

Comparison and Interpretation of Modeled Delay

In the preceding chapter, intersection approach delay was calculated for the four South Lyon intersections when they were under the control of both SCATS and fixed time traffic control. The delay for the critical approach movements was presented in Tables 4.3a through 4.6f. Each of these tables contained information for the four daily time intervals of 12:00am to 1:00am, 7:00am to 8:00am, 12:00pm to 1:00pm, and 5:00pm to 6:00pm. The goal of this chapter will be to analyze these data to assess the differences in delay resulting from the two control strategies. The significance of these differences will be determined by using various methods of comparison, including direct and indirect statistical tests. The comparisons will also assess the change in delay both within and between the various time and location data groups. It is expected that the analysis of these differences will allow interpretations to be made relative to the change of signal control in South Lyon. Taken together, these comparisons will also demonstrate how the control philosophy of SCATS impacted the delay parameters of intersections in South Lyon.

5.1 Total Intersection Delay

The analysis of intersection delay was accomplished through various comparisons of the total intersection delay in the two data sets. The definition of total intersection delay is the sum of the delay experienced by all vehicles at all approaches to an intersection. It is usually calculated from the product of the average vehicle delay and the total number of vehicles during a particular analysis interval. In this study, an average delay value was calculated for each approach movement during each signal cycle. The total delay came from the summation of these cycle-by-cycle delays recorded during the full analysis period. The use of total delay as a measure of effectiveness is helpful because it illustrates the overall impact of SCATS control on the operation of an intersection. The comparison of the total delay statistics also helps to illustrate some of the philosophical differences between fixed and adaptive signal control.

The underlying philosophy of SCATS is to balance the degree of saturation on all of the approach legs to the intersection. The goal is not necessarily to minimize total intersection delay. SCATS manages the signal cycle by strategically distributing green time to each of the approaches. This green time allocation does not, however, guarantee shorter delays to major and minor street traffic. The benefits of this strategy are numerous, including a more effective use of available green time, shorter minor street delays, and reduced driver frustration. The obvious drawback to this approach is the potential for increases in total intersection delay and decreases in signal efficiency on a system wide basis. Since SCATS does not minimize total delay, traffic delay may increase resulting in additional wasted fuel and increased exhaust emissions.

The fixed time phase split plans for each intersection and each analysis period were determined with the SOAP software package and were shown in Tables 4.3a through 4.6f. The SOAP optimization structure attempts to minimize total intersection delay by distributing a higher percentage of green time to the highest volume movements. The SOAP

delay minimization often comes at the cost of inordinately high delays to minor street movements. The underlying philosophy of SOAP is to inconvenience a relatively small number of drivers for the overall benefit of the whole intersection. The comparison of SCATS to an optimized fixed time system will ensure that if a performance improvement is documented, it will result from a comparison of two efficient systems rather than a good one to a bad one. In addition to analyzing the delay difference, the comparison of total delay in SCATS and an optimized fixed time operation will help to contrast the objective function of the two systems.

The comparison of total intersection delay used both a percentage comparison and specific statistical testing. The tests, detailed in the following paragraphs, resulted in many expected and unexpected outcomes. To assess the intersection delay differences on a system wide and hourly basis, a statistical comparison of total intersection delay was conducted. The delay data at the four intersections, for the four separate time intervals, during the five days of data recording, resulted in a sample size of 80 records for each “before” and “after” period. The two samples were contrasted using a paired comparison t-test. In a paired comparison the difference between the two separate samples is assessed. The computed means, variances, and standard deviations for total intersection delay in the entire South Lyon system as well as each separate time period are shown in Table 5.1.

The mean difference in total delay for the total population was +1.46 vehicle hours. The positive value indicates that mean total intersection delay parameter increased after the implementation of SCATS when compared to fixed time operation. A paired comparison t-test was conducted to determine the statistical significance of this result. First, a 95% confidence interval was calculated to determine the upper and lower bound of the statistical mean. Using the standard deviation of 2.67 vehicle hours, it was determined with 95% confidence that the average change in total delay was between +2.05 and +0.87 vehicle hours. To test the hypothesis that SCATS caused the observed change in delay, an inference test was also completed.

Table 5.1 Statistical Comparison of Total Delay

South Lyon SCATS Delay Evaluation Study					
Difference in Average Total Intersection Delay (veh-hr), May 6th - 10th, 1996					
	12:00 am - 1:00 am	7:00 am - 8:00 am	12:00 pm - 1:00 pm	5:00 pm - 6:00 pm	Overall
Mean	0.02	1.56	1.07	3.20	1.46
Variance	0.05	4.33	2.08	16.86	7.15
Standard Deviation	0.23	2.08	1.44	4.11	2.67
Sample Size	20	20	20	20	80
95% Confidence Interval					
Lower Bound	0.13	2.53	1.74	5.12	2.05
Upper Bound	-0.09	0.59	0.40	1.28	0.87
Hypothesis Test					
critical value of the t-distrib.	2.09	2.09	2.09	2.09	1.98
observed value of t	0.39	3.35	5.41	3.48	3.70
	DO NOT REJECT Ho @ 0.05	REJECT the Null Hypothesis @ 0.05	REJECT the Null Hypothesis @ 0.05	REJECT the Null Hypothesis @ 0.05	REJECT the Null Hypothesis @ 0.05

A statistical inference test uses the data to determine whether a change between two data groups is the result of an applied treatment (SCATS) or if is the result of random variation within the data. A rejection region at a 95% level of significance was used to test the “no change” null hypothesis. The critical value of the t-distribution and the t value for the observed delay data for the full data set are shown near the bottom of Table 5.1. A comparison of the t values shows that the value for the observed data (3.70) is greater than the critical t value (1.98). An observed t value which is greater than the critical value of the t distribution provides evidence that the observed difference in the two data sets is outside of the range of random data variation. Therefore, the null hypothesis of “no significant change” is not accepted and it can be concluded that the observed increase in total delay is statistically significant and is not merely the result of normal fluctuations in total intersection delay conditions during the week.

Additional paired comparison t-tests were conducted to analyze the hourly differences in total intersection delay. Values for the mean, variance, and standard deviation for each of these groups were calculated for each of the four analysis periods. Table 5.1 shows that after SCATS, the mean value of intersection delay increased during each of the analysis periods. To test the statistical significance of these findings 95% confidence intervals and hypothesis tests were conducted for each of the four analysis periods. The confidence intervals showed that during the 12:00am to 1:00am period the mean difference in total delay could reside within a range of performance improvement or degradation. The confidence interval for the mean difference in delay for the other three periods were all greater than zero, or within the region of delay increase. To test the statistical significance of these values inference tests were conducted for each.

As shown in each column at the bottom of Table 5.1 the hypothesis tests conducted for the morning, midday, and evening periods all showed that the observed difference between the two data sets to be outside of the range of random variation. Thus, like the conclusion for

the overall data set, it was possible to reject the “no change” null hypothesis for each. The conclusion that can be drawn from these tests is that there is evidence to support the claim that SCATS signal control increased the total intersection delay over that of fixed time during these intervals.

The inference test for the midnight period showed an inconclusive result for the effect of SCATS on the total intersection delay from 12:00pm to 1:00pm in South Lyon. The increase was 0.02 vehicle hours at all intersections, or an average increase of approximately 0.30 seconds per vehicle during this period. The primary reason for the inconclusive finding in analysis of total delay during this period was the combination of a very small delay change and a comparatively high degree of variability within the data set. The variation resulted in wide confidence interval and a low observed value of t at which the null hypothesis could not be rejected.

The data were also analyzed using non-statistical methods to identify trends within and between the data sets. These analyses included comparisons of the percentage difference between the two data sets and the calculation of various weekly averages for the groups of the modeled delay output. A tabular comparison of average intersection delay statistics is shown in Table 5.2. The delay difference in the two systems is shown in terms of a percent change in the right column for each time period. This value represents the optimized delay minus the SCATS delay, divided by the optimized delay. Thus, a negative percent change value indicates a delay savings in the “after” SCATS period and a positive value represents a delay increase. The composite hourly difference for all locations are shown at the bottom of each column group. The daily average difference is shown at the far right side of the table. This table is particularly useful because it illustrates some of the general trends within and between the two sets of modeled delay data.

Table 5.2 Percentage Comparison of Total Intersection Delay

Intersection	South Lyon SCATS Delay Evaluation Study Comparison of Total Intersection Delay											
	12:00 am - 1:00 am			7:00 am - 8:00 am			12:00 pm - 1:00 pm			5:00 pm - 6:00 pm		
	Intersectin. Delay (veh-hr) "Optimized" Plan	SCATS Control	Percent Change	Intersectin. Delay (veh-hr) "Optimized" Plan	SCATS Control	Percent Change	Intersectin. Delay (veh-hr) "Optimized" Plan	SCATS Control	Percent Change	Intersectin. Delay (veh-hr) "Optimized" Plan	SCATS Control	Percent Change
Pontiac Trail/Nine Mile Road	0.55	0.33	-40.0%	11.52	13.82	20.0%	5.73	6.99	22.0%	13.47	21.76	61.5%
Pontiac Trail/Ten Mile Road	1.84	2.04	10.9%	13.26	17.78	34.1%	9.94	13.21	32.9%	26.58	32.48	22.2%
Pontiac Trail/Eleven Mile Road	0.30	0.44	46.7%	4.46	4.37	-2.0%	2.23	2.30	3.1%	4.06	4.04	-0.5%
Byrd Swt Pkwy/Ten Mile Rd.	0.05	0.00	-100.0%	1.35	0.87	-35.6%	0.84	0.51	-39.3%	2.41	1.05	-56.4%
Period Average	0.69	0.70	2.6%	7.65	9.21	20.4%	4.69	5.75	22.8%	11.63	14.83	27.5%
										6.16	7.62	23.7%

The percentage comparison of the data shows a trend toward increased total delay during periods of increased traffic demand. This trend is evident both in the time of day and location of comparison. The values of total delay difference shown at the bottom of Table 5.2 show an increase in total delay as the time interval moves to periods of increasing traffic demand. The delay difference in the midnight period is +2.6%. However, the delay difference in the morning, noon, and evening peak traffic periods increases to +20 to +27 percent. Overall, SCATS control showed a system-wide increase of 23.7% in the average value of total intersection delay. The last column of the table shows the overall average percentage change in total delay by location. In this column it can be seen that the greatest increase in total delay occurred at the highest volume intersections of Pontiac Trail and Nine Mile Road and Pontiac Trail and Ten Mile Road. The delay increase is considerably lower at the intersection of Pontiac Trail and Eleven Mile Road, an intersection with considerably lower volumes than the Nine and Ten Mile Road intersections with Pontiac Trail.

While the predominant trend is toward a total delay increase under SCATS, the percentage comparison table shows that total delay also decreased during several of the analysis periods and at several of the study locations. In total, intersection delay decreased during 7 of the 16 sample periods. Given the control strategy of SCATS, this reduction in total intersection delay is somewhat surprising, especially since the optimized signal timing plans were based on known volumes.

The most notable of the decreases occurred at the intersection of Ten Mile Road and Reynold Sweet Parkway. At this location total intersection delay decreased during all four of the analysis periods and showed an overall average decrease of 47.7%. Total intersection delay also decreased during the morning and evening peak periods at the intersection of Pontiac Trail and Eleven Mile Road, 2.0% and 0.5% respectively, and during the midnight period at Pontiac Trail and Ten Mile Road when total delay decreased by 40.0% after SCATS. When taken in combination with the areas of notable total delay increase, the areas delay reduction appear to illustrate a relationship between volume and total delay.

The comparison table shows that the locations and time intervals with the highest volume also exhibited the highest total delay increase percentage. Table 5.2 presents the intersections in descending order in terms of total intersection volume. The last column under the “Daily Average” heading shows a direct correlation to the decreasing difference in delay. The same correlation can be seen across the bottom of the table, although the correlation is not directly one to one as in the case of location.

A review of the daily output statistics shows a likely reason for the apparent connection between volume and total delay. Tables 4.3a through 4.6f presented the daily delay statistics for each location and analysis interval. These tables also illustrate a classic example of the difference between the effect of fixed and SCATS signal control. Under SCATS, the delays for the critical approach movements decrease in nearly every case, except for the highest volume approach movements in which the average delay per vehicle increased measurably. This is consistent with the objective function of SCATS which is to equalize the degree of saturation.

An example of this concept is illustrated in Table 4.4c, the delay comparison table for the intersection Pontiac Trail and Nine Mile Road on Wednesday, May 8th. In 4 out of the 6 approach movements the average vehicular delay decreased. The two exceptions to this trend are the north and southbound through movements of Pontiac Trail, not coincidentally the two heaviest volume movements. The northbound through movement experienced an average delay increase of 3.6 seconds per vehicle for 356 vehicles. The 727 vehicles in the southbound through movement experience an increase of 12.1 seconds per vehicle. While the additional delays experienced by these drivers would barely be noticed in a 30 minute commute, the cumulative effect of this delay totals approximately 2 hours and 48 minutes. This is the effect of SCATS. This point will become more evident in the approach delay analysis section of this chapter.

5.2 Approach Delay

The strategy used to conduct the analysis of approach delay was similar to that used for the analysis of total intersection delay. They both incorporated statistical and non-statistical procedures to analyze the differences between the various locations and time periods, as well as the internal differences within an individual location and time period. The primary difference between the two was the increase in the amount of data in the approach delay sample. Since the approach delay data set was larger, additional comparative analyses were required to assess the interrelationships between the various data sub-groups.

The first set of analyses were conducted to determine if, from a statistical standpoint, SCATS was able to lower approach delay. Other comparisons were completed using data averaging techniques. The following sections detail the methods used to conduct the analyses, the outcomes of the comparisons, and their interpretations and conclusions.

Paired t-tests were used to determine the difference between the fixed time and SCATS approach delay data sets. The difference in approach delay was calculated at each location, during each analysis period for the week of data collection, including all critical turning movements at the intersections. These resulted in a comparison sample set of 480 trials. Values for the mean, variance, and standard deviation for each data group were calculated for each of the four analysis periods. To test the statistical significance of these findings 95% confidence intervals and hypothesis tests were conducted for each of the four analysis periods. The results of the paired t-tests are shown in Table 5.3.

Overall, the mean decrease in approach delay for all turning movements was 1.59 seconds per vehicle. The 95% confidence interval for all approach delay observations was between -0.33 and -2.85 seconds per vehicle. From this confidence interval it appeared that the decrease in the modeled average approach delay was statistically significant. To test this theory, a hypothesis test was conducted using a t-test. A rejection region at a 95% level of significance was used to test the “no change” null hypothesis. The values for the critical

Table 5.3 Statistical Comparison of Approach Delay

South Lyon SCATS Delay Evaluation Study Difference in Average Approach Delay (sec/veh), May 6th - 10th, 1996					
	12:00 am - 1:00 am	7:00 am - 8:00 am	12:00 pm - 1:00 pm	5:00 pm - 6:00 pm	Overall
Mean	-1.34	-1.71	-0.90	-2.40	-1.59
Variance	32.85	284.35	120.09	344.51	195.75
Standard Deviation	5.73	16.86	10.96	18.56	13.99
Sample Size	120	120	120	120	480
95% Confidence Interval					
Lower Bound	-0.30	1.34	1.08	0.95	-0.33
Upper Bound	-2.38	-4.76	-2.88	-5.75	-2.85
Hypothesis Test					
critical value of the t-distrib.	-1.98	-1.98	-1.98	-1.98	-1.98
observed value of t	-2.56	-1.11	-0.90	-1.42	-2.49
	REJECT the Null Hypothesis @ 0.05	DO NOT REJECT Ho @ 0.05	DO NOT REJECT Ho @ 0.05	DO NOT REJECT Ho @ 0.05	REJECT the Null Hypothesis @ 0.05

value of the t distribution (-1.98) and observed value of t for the overall approach delay data set (-2.49) are shown in Table 5.3. The table shows that the calculated value of t for the observed data was significantly larger than the value of the test statistic taken from the t-distribution table. Based on these values the null hypothesis can be rejected and we can conclude the observed decrease in approach delay resulting from the implementation of SCATS in South Lyon is statistically significant.

To determine the difference in approach delay values for the four separate analysis periods four additional t-tests were conducted. The mean values for the difference in delay for each of the four analysis periods are also shown in Table 5.3. A set of 95% confidence intervals for the mean values were computed. The mean difference and confidence interval data give evidence that the difference in the delay was due to chance during three of the four data analysis periods. The midnight hour analysis period was the only time segment where both boundaries of the confidence interval were below zero. The average decrease in delay between the fixed and adaptive control modes from 12:00am to 1:00am was 1.34 seconds and the confidence interval range spanned from a decrease of 0.30 seconds to a decrease 2.38 seconds of delay per vehicle. The morning, noon, and evening periods all showed a confidence interval ranges that spanned mean values of average approach delay increases and decreases.

Hypothesis tests were completed to further analyze the differences in intersection approach delay. The hypothesis tests were consistent with the results of the confidence interval calculations. They showed that during three of the four analysis periods; morning, noon, and evening, the decreases in average intersection approach delay were not statistically significant. The calculated t statistic for the observed data were under the critical value of the t distribution. Therefore, the “no change” hypothesis could not be rejected nor was it possible to conclude that SCATS was successful at reducing the intersection approach delay during these periods. The only period which passed the hypothesis test was the hour from 12:00am to 1:00am in South Lyon. The calculated value of the t statistic for this hour (-2.56)

fell below the level of the critical value of the t distribution (-1.98). Thus, it was concluded the average approach delay decrease of 1.34 seconds per vehicle was not the result of chance variation within the data sample, rather it was likely related to the implementation of SCATS control.

As an additional measure of comparison, the percentage change in the weekly average approach delay statistics for each critical movement was also determined. Tables 5.4a, 5.4b, 5.4c, and 5.4d present the results of this comparison. Similar to the percentage change comparison of total delay, the delay difference was computed by subtracting the SCATS delay value from the fixed delay value and dividing that difference by the fixed delay. Overall, the tables show that the use of SCATS control resulted in a lower average approach delay at all four intersection locations. Once again, the greatest improvement occurred at the two lowest volume locations. The improvement was an average of 14.6% at the intersection of Pontiac Trail and Eleven Mile Road and 12.0% at the intersection of Ten Mile Road and Reynold Sweet Parkway. The average approach delay decrease at the Ten and Nine Mile Road intersections with Pontiac Trail were 2.5% and 6.3%, respectively.

The comparative results also illustrate the contrast in delay change which occurred between the low and high volume approach movements. Under SCATS control, low volume movements are less likely to experience prolonged delay compared to the heavy volume through movements. This condition is best illustrated once again by the morning peak hour approach delay differences at the intersection of Pontiac Trail and Nine Mile Road. Table 4.4f showed the average daily traffic volumes and modeled approach delay information for the week of May 6th through the 10th. During the hour between the 7:00am and 8:00am the total intersection delay were fairly similar for the optimized fixed time and SCATS control conditions. However, the individual critical approach movement delays that precipitated these similar total delay values were very different. This condition is illustrated in Table 5.4b.

Table 5.4a Percentage Comparison of Approach Delay

South Lyon SCATS Delay Evaluation Study Intersection of Pontiac Trail and Ten Mile Road												
Approach Movement	Week of 5/5/96 through 5/10/96 - Daily Average											
	12:00 am - 1:00 am			7:00 am - 8:00 am			12:00 pm - 1:00 pm			5:00 pm - 6:00 pm		
	Approach Delay (sec)	SCATS Control	Percent Change	Approach Delay (sec)	SCATS Control	Percent Change	Approach Delay (sec)	SCATS Control	Percent Change	Approach Delay (sec)	SCATS Control	Percent Change
Northbound Through	5.4	10.8	86.2%	33.2	45.9	38.3%	16.7	31.0	85.6%	50.7	39.3	22.5%
Northbound Left Turn	4.4	8.7	97.7%	22.5	38.9	72.6%	18.7	37.8	102.1%	56.2	71.2	26.7%
Southbound Through	5.6	10.0	78.6%	63.6	34.3	-46.1%	31.3	29.2	52.2	47.6	58.0	-8.8%
Southbound Left Turn	5.6	10.0	78.6%	63.6	34.3	-46.1%	31.7	24.5	-22.7%	52.4	39.3	-25.6%
Westbound Through	18.1	13.5	-25.4%	31.3	38.2	-27.8%	31.7	24.5	-22.7%	30.9	33.2	-7.4%
Westbound Left Turn	18.1	13.5	-25.4%	31.3	38.2	-27.8%	31.7	24.5	-22.7%	30.9	33.2	-7.4%
Eastbound Through	31.4	26.2	-16.6%	38.4	52.6	37.0%	31.0	28.2	-9.0%	29.5	32.5	-10.2%
Eastbound Left Turn	17.6	15.4	-12.5%	38.7	31.3	-19.1%	50.0	29.3	-41.4%	60.5	46.9	-22.5%
Period Average	16.2	15.8	-2.3%	44.8	37.8	-15.6%	30.9	32.1	3.9%	47.0	49.7	5.8%
										34.7	33.8	-2.5%

Table 5.4b Percentage Comparison of Approach Delay

South Lyon SCATS Delay Evaluation Study Intersection of Pontiac Trail and Nine Mile Road															
Week of 5/6/96 through 5/10/96 - Daily Average															
Approach Movement	12:00 am - 1:00 am			7:00 am - 8:00 am			12:00 pm - 1:00 pm			5:00 pm - 6:00 pm			Daily Average		
	Approach Delay (sec)	SCATS Optimized	Percent Change	Approach Delay (sec)	SCATS Optimized	Percent Change	Approach Delay (sec)	SCATS Optimized	Percent Change	Approach Delay (sec)	SCATS Optimized	Percent Change	Approach Delay (sec)	Percent Change	
Northbound Through	4.1	1.9	-53.7%	8.1	18.1	123.5%	9.5	13.6	43.2%	25.2	13.6	-46.0%	25.2	50.5	100.4%
Northbound Left Turn	3.2	3.3	3.1%	57.6	35.3	-38.7%	27.3	18.9	-30.8%	34.0	18.9	-44.4%	34.0	31.3	-7.9%
Southbound Through	4.0	2.1	-47.5%	21.2	38.7	82.5%	11.4	18.2	59.6%	11.4	18.2	59.6%	11.4	28.3	148.2%
Southbound Left Turn	0.4	0.4	0.0%	35.0	19.7	-43.7%	15.3	15.6	2.0%	15.3	15.6	2.0%	85.6	37.6	-56.1%
Eastbound Through	24.4	22.1	-9.4%	31.0	27.5	-11.3%	29.9	28.5	-4.7%	29.9	28.5	-4.7%	28.1	29.5	5.0%
Eastbound Left Turn	46.1	31.8	-31.0%	75.1	53.7	-28.5%	44.1	38.6	-12.5%	44.1	38.6	-12.5%	45.1	45.1	-14.9%
Period Average	13.7	10.3	-25.1%	38.0	32.2	-15.4%	22.9	22.2	-3.0%	26.7	22.2	-16.6%	39.6	37.1	-6.3%

Table 5.4c Percentage Comparison of Approach Delay

South Lyon SCATS Delay Evaluation Study Intersection of Pontiac Trail and Eleven Mile Road														
Week of 5/6/96 through 5/10/96 - Daily Average														
Approach Movement	12:00 am - 1:00 am			7:00 am - 8:00 am			12:00 pm - 1:00 pm			5:00 pm - 6:00 pm			Daily Average	
	Approach Delay (sec)		Percent Change	Approach Delay (sec)		Percent Change	Approach Delay (sec)		Percent Change	Approach Delay (sec)		Percent Change	Approach Delay (sec)	
	Optimized	SCATS Control		Optimized	SCATS Control		Optimized	SCATS Control		Optimized	SCATS Control		Optimized	SCATS Control
Northbound Through	3.6	6.1	41.7%	9.8	11.0	12.2%	3.6	2.9	20.7%	11.8	12.5	5.9%	6.7	7.0
Northbound Left Turn	1.5	1.7	13.3%	6.3	8.9	41.3%	4.2	7.9	88.1%	6.9	10.1	46.4%	5.2	8.3
Southbound Through	3.5	6.1	74.3%	10.0	7.7	-23.0%	6.2	6.2	0.0%	12.9	14.1	9.3%	7.7	7.4
Southbound Left Turn	1.6	1.7	6.3%	54.7	19.9%	69.9	40.1	42.6%	58.2	48.4	41.5	-14.3%	36.1	45.8
Eastbound Through	36.8	30.1	-18.2%	68.3	54.7	-19.9%	69.9	40.1	-42.6%	88.2	58.2	-34.0%	65.8	45.8
Eastbound Left Turn	24.5	20.8	-15.1%	31.2	26.1	-15.7%	40.1	33.8	-15.7%	48.4	41.5	-14.3%	36.1	31.6
Westbound Through	24.5	20.8	-15.1%	31.2	26.1	-15.7%	40.1	33.8	-15.7%	48.4	41.5	-14.3%	36.1	31.6
Period Average	11.9	11.1	-6.7%	22.0	20.4	-7.3%	21.4	16.3	-23.6%	29.2	24.3	-16.8%	21.1	18.0

Table 5.4d Percentage Comparison of Approach Delay

South Lyon SCATS Delay Evaluation Study														
Intersection of Reynolds Sweet Parkway and Ten Mile Road														
Week of 5/6/96 through 5/10/96 - Daily Average														
Approach Movement	12:00 am - 1:00 am			7:00 am - 8:00 am			12:00 pm - 1:00 pm			5:00 pm - 6:00 pm			Daily Average	
	Approach Delay (sec)		Percent Change	Approach Delay (sec)		Percent Change	Approach Delay (sec)		Percent Change	Approach Delay (sec)		Percent Change	Approach Delay (sec)	
	Optimized	SCATS Control		Optimized	SCATS Control		Optimized	SCATS Control		Optimized	SCATS Control		Optimized	SCATS Control
Westbound Through	2.0	0.0	-90.0%	5.2	0.8	-84.6%	4.4	0.8	-81.8%	9.9	2.0	-79.8%	5.4	1.0
Westbound Left Turn	0.0	0.0	0.0%	13.6	9.7	-28.7%	7.7	4.6	-40.3%	11.5	6.7	-41.7%	8.2	5.3
Eastbound Through	2.0	0.2	-90.0%	7.0	5.4	-22.9%	4.2	3.5	-16.7%	5.7	4.8	-15.8%	4.7	3.5
Northbound Left Turn	0.0	0.0	0.0%	40.5	49.9	63.6%	38.0	48.1	26.6%	74.3	53.4	-28.1%	35.7	37.9
Period Average	1.0	0.1	-90.0%	14.1	16.5	16.9%	13.6	14.3	5.0%	25.4	16.7	-34.0%	13.5	11.9
12.00%														

At the Pontiac Trail/Nine Mile Road intersection the primary through volume movements are northbound and southbound. Table 4.4f shows that the weekly average total of the east and westbound through volumes are a quarter of the averaged north-south through movement total. As such, the SOAP optimization strategy allocated a shorter green phase length to the east-west movements. Table 4.2b in chapter four showed that the fixed time model used a green phase length of 58 seconds for the north-south through movement and 20 seconds for the east-west through movements. This difference, approximately 35%, is roughly proportional to the difference in volume ratios. The resulting average delays were very different.

As shown in Table 5.4b, the approach delay under fixed time control ranged from a minimum average of 8.1 seconds for the northbound through movement to 75.1 seconds for the westbound through movement. The approach delay for the same movements under SCATS control were 18.1 seconds and 53.7 seconds. While a sizeable difference between the two delay was apparent under both control strategies, the difference in SCATS was only 53% as much as optimized fixed time operation. Table 5.4 shows that the average approach delay for the six critical approach movements averaged 67.0 seconds per vehicle in optimized fixed time mode and only 35.6 seconds per vehicle in SCATS mode. From this we see that the modeled approach delays in SCATS are more equally distributed.

The advantage to the optimized fixed strategy was that it resulted in a reduction to the level of overall intersection delay. However, the significance of the a more equalized distribution of delay is substantial. The delay for the morning northbound through movement at Nine Mile Road and Pontiac Trail approximately doubled in the adaptive control mode. While the increase sounds substantial, it was only an average 10 seconds per vehicle. During a morning commute trip of fifteen or twenty minutes, the additional 10 seconds of delay would be barely perceptible. By contrast the delay savings for the westbound through movement was almost 21 seconds per vehicle. While this savings appears small, a greater savings would be realized if the trip were to traverse a series of SCATS adaptive controlled intersections.

The same effect, with varying levels of success, can be seen at the other intersections within South Lyon.

Another less tangible advantage to the SCATS strategy for green time allocation is the possible reduction of driver frustration on minor cross streets. The study results showed some minor street approach delays in excess of one minute. Many of these delays were experienced in moderate flow situations. In an operational situation such delays would be unacceptable. Delay times in excess of multiple signal cycles could lead to both safety and operation complications. Safety concerns would be most apparent in left turn situations. Drivers waiting in lengthy queues would become more likely to accept dangerously small gap sizes in the opposing traffic stream. Such a condition could lead to angle and rear end collisions at an intersection. The equalization of degrees of saturation in SCATS could lessen the possibility of forced left turns because left turning traffic would not be allocated a short left turn phase.

5.3 Delay Data Comparison Conclusion

In this chapter the delay resulting from SCATS real-time adaptive control and fixed time traffic control in South Lyon were compared. The two types of delay that were analyzed were the total intersection delay and the average approach delay. While these two methods of delay measurement are similar in some respects, they are quite different in the manner in which they assess delay. It is because of these similarities and differences that an apparent contradiction exists in the experimental outcome.

The fundamental conclusion of the study was that approach delay decreased in South Lyon while total intersection delay increased. The overall increase in total delay after the implementation of SCATS was 1.46 vehicle hours. However, the overall decrease in approach delay under SCATS control was 1.59 seconds per vehicle. The conflict arises when it is recognized that total delay of an intersection is the sum of its constituent approach

delays. The experimental results showed that while total delay increased, the approach delay decreased. After careful analysis of the data it becomes apparent that this conflict is not unreasonable. It is logical based on the approach traffic volumes and the objective functions of the two control strategies.

The objective of SCATS is to balance the degree of saturation on the approach legs of an intersection. Its goal is not to minimize total intersection delay; although this often occurs. It is also possible to increase one while decreasing the other. The data showed this to have been the case in South Lyon. The data also showed that in many cases both total and approach delay reduced under SCATS control. During several time intervals at a small number of locations the increase in delay was substantial enough to raise the overall level of change in a negative direction.

Table 5.1 shows an overall increase in mean total intersection delay. However, it also illustrates that total delay decreased during the midnight and morning hours, although through inference testing these were shown not to be statistically significant. Table 5.2 shows that total intersection delay decreased during 7 of the 16 sample periods. The percentage comparison table also shows that on an averaged daily basis, total delay increased at 1 of the 4 study intersections.

The delay reduction results shown in both of these comparison tables were, however, heavily influenced by the poor performance of SCATS at the Pontiac Trail/Nine and Ten Mile Road intersections. At these locations total delay increased substantially when compared to fixed time operation. The primary reason for the significant increase in delay can be seen in Table 5.4b. At this intersection the heavy northbound and southbound Pontiac Trail through traffic experienced an substantial increase in approach delay under SCATS control. It is also apparent that the lower volume traffic movements on Nine Mile Road experienced an improvement in delay conditions. However, the actual number of vehicles on Nine Mile Road was very small in comparison to the Pontiac Trail volume. Therefore, the sum of the

delay and volume resulted in a significant decrease in overall performance for the intersection.

The apparent conflict of a total delay increase with an approach delay decrease is further clarified with an understanding of the comparison procedure. The approach delays were calculated based on the number of vehicles using the approach during the analysis period. No consideration was given to contrasting levels of demand at an intersection. For example, Table 4.4f shows that Nine Mile Road services 323 through vehicles while Pontiac Trail services 1,520 through vehicles during the same evening peak hour. In the comparative analyses no additional consideration was given to the Pontiac Trail approaches based on traffic demand. Approach delay values were compared on an equal terms rather than on a relative basis. In this way, the impact of SCATS on the approach delay could be measured and compared on a direct basis.

Chapter 6.

Summary and Conclusion

The purpose of this study was to document the change in traffic delay in the South Lyon, Michigan traffic network resulting from the installation of a SCATS traffic control system. One of the primary goals was to demonstrate how computer modeling and analysis techniques could be used to model and evaluate the effect of real-time adaptive traffic control. The other primary goal was to determine whether the introduction of SCATS control would result in a change to the traffic delay characteristics of the system. Both of these goals have been achieved. The study has also demonstrated some of the limitations in the existing delay models and the need for the development of more sophisticated modeling techniques to more effectively assess the merits of real-time adaptive traffic signal control.

6.1 Summary of the Research Study

The study involved a four step approach to evaluate the effect of real time adaptive control using traffic simulation models. First, a literature review was conducted to determine the existing level of knowledge in the field of adaptive signal control system modeling and

evaluation. The review of existing literature on subjects related to traffic modeling and the use of real time adaptive traffic signal control demonstrated that a substantial amount of work had been done to investigate the development of traffic models as well as the operational effect of adaptive traffic control. Past field studies showed that systems like SCATS and SCOOT demonstrated significantly improved performance over fixed time systems. The benefits were realized in traffic flow parameters like travel time, stopped delay, and the number of stops. These comparative evaluation studies were conducted using strictly empirical field observation and numeric data analysis. No computer models were available to evaluate these real-time adaptive traffic signal systems. This lack of effective tools demonstrates the need for the development of traffic modeling methods which could be used to more effectively evaluate existing and proposed traffic signal systems .

From the literature it appeared that the deficiency of traffic modeling methods and the shortage of experimental data comparing adaptive and fixed time control systems was due, in part, to a lack of appropriate tools to affect a two-way movement of computer data required for simulation of real-time adaptive control strategies. To overcome this deficiency this study used a approach that took advantage of output data from an operational SCATS system. From this data an analytical computer modeling routine capable of predicting delay parameters for specified operating conditions was developed.

The predictive delay model was developed using a combination of the Webster and TRANSYT delay equation to assess the delay conditions after SCATS was operational in South Lyon. The added dimension of this new model was its ability to read a SCATS output file and compute the resulting approach delay on a cycle-by-cycle basis. Separate models were coded to represent delay conditions at four South Lyon intersections during four different time periods of the day. The modeled delay output data was also compared to field data recorded in South Lyon after the activation of the SCATS control system. The comparison of modeled and field data showed that the “after” model represented a reasonably close match to the field conditions.

Next, a “before” model was constructed to simulate traffic flow conditions in South Lyon prior to the introduction of SCATS control. To make an assessment of the true benefit of the real time adaptive aspects of SCATS, the original South Lyon fixed time signal plans were adjusted to minimize intersection delay. Identical cycle-by-cycle traffic volumes were used for the analysis of both “before” and “after” conditions. The computer generated values of total intersection delay and approach delay were then used to make a comparison of delay under the two different control strategies.

Various statistical comparisons of the “before” and “after” data sets highlighted the changes which resulted from the implementation of SCATS in South Lyon. These comparisons showed that adaptive control resulted in an improvement to the performance measures under certain conditions. The comparison showed that the SCATS controlled signals resulted in a 1.56 second per vehicle decrease in the average value of approach delay for the 24 critical approaches in the South Lyon road network. The most significant improvement was shown to occur at the Ten Mile Road Reynold Sweet Parkway intersection. The comparative analysis also showed that SCATS was out performed by fixed time control in several instances. The comparison showed a 1.46 vehicle hour increase between the “before” and “after” values of total intersection delay. However, this difference was not statistically significant. The total intersection delay change was not statistically significant during all of the analysis time periods.

6.2 Conclusions

There are two main conclusions which can be drawn from this research study. First, it can be concluded that existing traffic delay models can be used to successfully model delay conditions at intersections controlled by real time adaptive traffic signals. Second, it was concluded that under certain demand conditions the implementation of SCATS control in South Lyon can result in improvements to traffic delay at the network intersections.

The level of success demonstrated in this study are encouraging. However, the next logical step is to extend this knowledge to other areas and to different systems. The application of this new traffic model or the realization of significant delay reductions compared to fixed time signal control may not always be possible. The following paragraphs address some of the factors which relate to these two issues. This section will also summarize some of the various benefits and costs associated with the FAST-TRAC system and SCATS in particular which have been learned during the completion of this study.

6.2.1 “Direct” Conclusions

The most obvious and direct conclusion which can be drawn from this study is that the use of SCATS resulted in an improvement to the modeled delay in South Lyon. However, the improvement was not universal. The amount of improvement varied and it was more apparent during some traffic volume situations than others. The location and the degree to which improvements were realized was also relative to the other time periods and intersection locations within the data set.

Three main conclusions were drawn from the various analyses conducted in the previous chapter. The first was that the average total intersection delay, on a system wide basis, was increased. This is not surprising since the objective of SCATS is to equalize saturation flows rather than to minimize total intersection delay. This increase, as indicated by the statistical tests, was not universal. The conclusion of an overall increase in total delay is somewhat misleading since one of the four intersections experienced a reduction in delay. However, the significant increase in delay at the Pontiac Trail/Nine Mile and Ten Mile Road intersections lowered the overall system performance.

The second primary conclusion was that SCATS more equally distributes average approach delays to the various approach movements. This is consistent with the SCATS control objective in which the approach degrees of saturation are equalized. The third and final primary conclusion was that SCATS appeared to be more effective at reducing delay during

low volume periods compared to high volume periods. This was disappointing because a reduction of delay during high volume periods is more critical to the overall efficiency of a traffic signal network and is considerably more difficult to obtain through adjustments in signal operation.

The primary questions of “if” and “by how much” SCATS improved delay in South Lyon have been addressed in this study. However, the question of whether or not similar outcomes could be expected in other networks is difficult to answer. The traffic volumes within the South Lyon road system are relatively low compared to those found in the other more congested suburbs in Oakland County. The results of the study indicate that SCATS improved total intersection delay most significantly during lower flow periods. Thus, in areas where the traffic volumes approach or operate above capacity, real time adjustment to signal timings may not necessarily enhance the operation of the network to measurable degrees. The delay experienced in these situations is not the result of poor signal timings, rather, it results from a lack of capacity provided by the approach geometry or the network road segments. Flow improvement and delay reduction could be more economically realized through the implementation of approach geometry and roadway capacity improvements.

The contribution of SCATS can not be discounted during all high demand periods. In high volume situations where heavy traffic volumes are moving primarily in one direction, a real time adaptive control system has some definite advantages. Among other features, systems like SCATS allow the implementation of coordinated progression on the major arterial street. The major street green phases are interrupted only when minor street traffic is present. This has been used in traffic networks in Australia and Toronto, Canada with measurable success.

The questions of applicability for the procedure developed in the study are not as difficult to answer. The procedure used to complete this study was developed specifically for use on SCATS output data files and the experiments and analysis conducted were completed after

the SCATS system was operational. The primary difficulty of employing this procedure at another location or another traffic control system is that the “after” data file containing both traffic volume and signal data must be available to conduct the study. Predictive simulations, in which a variety of traffic conditions are tested prior to field installations, are not possible with this approach. To conduct a predictive study, the SCATS control algorithms for determining phase splits, cycle length determination, and coordinated operation must be known. Due to the proprietary nature of the SCATS control software the algorithms can only be approximated and not used directly at this time.

The delay calculation models within the data processing routine are universal and can be applied to nearly any intersection or system of intersections. The Webster/TRANSYT model does contain some inherent weakness that could be improved through additional work. The most obvious limitation of the equation is that it does not allow for the adjustment of vehicle arrival patterns. The equation assumes that vehicle arrivals are always uniform. As a result it can be difficult to accurately assess the delay reduction benefit that SCATS can bring about through coordinated signal progression.

6.2.2 “Indirect” Conclusions

The general conclusion of “system improvement” afforded by real-time adaptive signal control systems must also be contrasted with the significant costs which are involved in the implementation, operation, and maintenance of such systems. Recent studies have shown that the implementation the FAST-TRAC system architecture in various locations within Oakland County has resulted in measurable benefits to the motorists driving within the SCATS networks. It has also brought the expenditure of over \$70 million in combined public and private resources into the road system of Oakland County. However, given the limited availability of public resources dedicated to transportation enhancement projects, the question of whether the benefits gained from the FAST-TRAC project are worth the price must also be addressed.

The cost of FACT-TRAC can not be measured solely in terms of the difference in installation cost between it and a fixed time system. Other more indirect and difficult to measure costs must also be evaluated. For example, the traffic safety aspects of the system should also be factored in the cost-benefit equation. Recent studies of the Troy FAST-TRAC system showed that the frequency and rate of traffic accidents increased after the implementation of SCATS, although the severity of injuries decreased.⁽⁵⁰⁾ The benefits derived from SCATS should also be compared to the cost for the engineering, design, operation, maintenance, research, and training required to keep the FAST-TRAC system operating.

The benefits and costs of FAST-TRAC systems can be debated. However, it is difficult to dispute the need to take advantage of advanced technologies to deal with the problems of urban congestion. Real-time adaptive signal control allows signal to respond to constantly changing conditions in a predetermined manner. Since urban traffic flow is a variable process, flow conditions can change quickly based on the occurrence of accidents, fluctuations in volume, and travel patterns. In the past, traffic engineers have been able to meet the challenges of arterial street mobility reasonably well with optimization tools which were available. In the future, it will be necessary to take advantage of advancements in the fields of traffic engineering, computer science, and electrical engineering to better utilize the existing transportation resources.

Projects such as the Oakland County FAST-TRAC program may be expensive and complicated. However, they are a necessary and integral part of the development of transportation engineering knowledge in the United States. The successes and failure or costs and benefits of this and future advanced traffic systems can and should be debated. However, there should be no debating the need for the development of new technologies and creative solutions to maintain and increase the state of traffic mobility.

6.3 Future Research Needs

This study has taken another step toward the use of more comprehensive and sophisticated simulation techniques to model adaptive signal control systems. While useful by itself, this study has also identified a number of needs and questions relating to the modeling of larger and more complex systems and the comparative assessment of alternative traffic control strategies; including real-time adaptive, actuated, and fixed time.

6.3.1 Advanced Simulation Systems

The most obvious area of need to forward the knowledge into the analysis of adaptive control systems is currently under development. The TRAF-NETSIM simulation system is the most widely used network simulation package. Unfortunately, it does not yet permit the simulation of adaptive control systems. The Federal Highway Administration has recently awarded contracts to incorporate a communication architecture into NETSIM that permits the simulation of adaptive traffic control. The goal of this research will be the creation of a modeling system capable of relaying traffic information to an external traffic control routine on a real time basis. The control routine could be modified to permit the use of any signal control algorithm, including SCATS. All currently available NETSIM output statistics and MOE information including delay, travel time, and stops could be collected for a proposed system. In contrast to the procedure used in this study, the proposed NETSIM system would also be able to model the effect of varying driver behavior, lane blockages, transit systems, on-street parking and pedestrian movements. Unfortunately, the operational version of this system remains years away.

The simulation of various types of traffic control is helpful in a number of respects. On the application level it allows traffic professionals the luxury of comparing and evaluating benefits and costs of alternative systems without the time and expense of field trials. In theoretical applications it can be used for the experimentation, testing, and refinement of existing and proposed control strategies. Future research studies could take advantage of the procedure detailed in this study to compare different strategies like SCATS, SCOOT, and

OPAC against fixed time. Such comparisons can be used to determine the merits of each and the ways in which one system may be better suited to accomplish certain delay reduction objectives than another.

6.3.2 Improved Methods of Analysis

The results of this study could also be used to make improvements to the existing SCATS control algorithms. The study showed that under SCATS the intersection delay parameters were increased up to 1.6 vehicle hours during certain time intervals when compared to fixed time. Further refinements of the cycle, phasing, and coordination selection algorithms, coupled with this testing procedure could be used to analyze methods to increase signal efficiency.

Another logical extension of using the real-time adaptive signal control modeling techniques is their incorporation into combined models of adaptive signal control with real-time incident detection and route guidance structures. Truly effective traffic responsive traffic systems need to include the ability to adapt to normal fluctuations in travel demand conditions as well as special event situations. Systems with the ability to detect an incident, then implement signal control changes and route guidance in response to the incident would be very useful. The use of advanced simulation modeling techniques accompanied by the incident producing capability of NETSIM or route guidance algorithms could be used to test proposed ITS systems prior to full scale field trials.

6.3.3 Cost/Benefit Assessments

Future research also needs to address the economic impacts of technically sophisticated systems like FAST-TRAC. FAST-TRAC has been shown to increase the efficiency of certain performance measures. Future research will need to include assessments of the economics of these benefits through comprehensive cost/benefit studies. This study and others have made steps in this direction. However, more factors need to be understood before the engineering community encourages large-scale and wide-spread implementation

of these systems.

One final area of future research concerning the use of adaptive signal control strategies would be to assess the safety impacts of their use. Information gained from empirical observation and law enforcement personnel during the completion of this study has shown that systems like SCATS require increased driver awareness. SCATS, as explained earlier, has the ability to shorten, lengthen, add, remove, and rearrange signal phases to better accommodate the traffic flow through a single or group of intersections. Drivers who are familiar with only fixed signal timings are required to go through a “learning curve” to acquaint themselves with the new strategy. Undoubtedly, this can lead to safety problems. Research to determine the length of time or amount of advanced warning and education that is required for drivers to become aware of the operation of these signals and their varying operation would also be important.

APPENDIX A

DELAY CALCULATION PROGRAM FOR THE

INTERSECTION OF PONTIAC TRAIL AND TEN MILE ROAD

```

C *****
C South Lyon SCATS Signal Delay Evaluation Project
C
C P. Brian Wolshon
C Department of Civil and Environmental Engineering
C Michigan State University Fall, 1996
C
C *****
C
C Pontiac Trail/Ten Mile Road Intersection
C RCOC Traffic Operations Center SCATS Output File
C May 6th - May 19th 1996
C SCATS Signal Timing Control
C *****
C
C Variable List:
C Gfaz = "green" phase for a particular movement per cycle (sec)
C vol = recorded traffic volume per cycle (veh)
C   C = signal cycle length (sec)
C   q = critical approach volume (veh)
C   h = discharge headway (sec)
C   s = saturation flow (veh/lane/hour of green time)
C   lam = proportion of green time available to a movement
C   g = effective green time
C   ltime = "lost" time -> 3.0 sec
C   X = degree of saturation -> q/lamda*s
C   V = hourly approach volume (veh/hr)

INTEGER hr,min,Gfaz(8),vol(8),fazitot,g(8),ltime,icount,hri
REAL q(8),h,s,X(8),D1(8),z(8),Bn(8),Bd(8),term(8),D2D3(8),delay(8)
REAL avelay(8),totdelay(8),avecyc,totvol(8),bigdelay(8),intdelay
REAL lam(8),term1(8),term2(8),V(8),aaa(8),bbb(8),C,totcyc
REAL Gsat(8),Gunsat(8),adjvol(8)
CHARACTER DUMMY*25
OPEN (1,FILE='pt10-aft.txt',STATUS='OLD')
OPEN (2,FILE='pt10-aft.out',STATUS='NEW')
intdelay=0
hri=100
totcyc=0
fazitot = 0
h = 2.2
s = 1600
ltime = 3

```

READ (1,101) hr, min

C Main Loop

DO 60 ii = 1,21000

C When the hour has been completed print out hourly volume,

C average movement delay and average cycle length for that hour.

C

IF (hr .GE. hri) THEN

WRITE (2,201) hri-1

DO 80 ia = 1,8

IF (totvol(ia) .NE. 0) THEN

avedelay(ia)=bigdelay(ia)/totvol(ia)

ELSE

avedelay(ia)=0

ENDIF

WRITE (2,202) ia,totvol(ia),avedelay(ia)

totintdelay = totintdelay + (totvol(ia) * avedelay(ia))

totvol(ia) = 0

bigdelay(ia) = 0

80 CONTINUE

avecyc=totcyc/(icount*8)

totcyc = 0

intdelay = totintdelay / 3600

WRITE (2,204) intdelay

WRITE (2,203) avecyc

intdelay=0

totintdelay = 0

icount=0

hri=hr+1

icount = icount + 1

READ (1,102) dummy

DO 11 ia = 1,8

READ (1,103) Gfaz(ia), vol(ia)

faztot = faztot + Gfaz(ia)

11 CONTINUE

C = faztot/2

If (C .eq. 0) then

Write (2,888)

C=120

endif

C Use the SCATS outfile data to determine delays with the use of
 C the first term of Webster's delay equation and the TRANSYT delay
 C model.

C First determine the critical hourly volume. Reducing the left turn
 C volume by 1 "sneaker" vehicle.

```
DO 21 ia = 1,8
  IF ((ia .EQ. 3) .OR. (ia .EQ. 4)) THEN
    adjvol(ia) = vol(ia) - 1
    IF (adjvol(ia) .LE. 0) THEN
      q(ia) = 0
    ELSE
      q(ia) = adjvol(ia)*(3600/C)
    ENDIF
  ELSEIF ((ia .EQ. 7) .OR. (ia .EQ. 8)) THEN
    adjvol(ia) = vol(ia) - 1
    IF (adjvol(ia) .LE. 0) THEN
      q(ia) = 0
    ELSE
      q(ia) = adjvol(ia)*(3600/C)
    ENDIF
  ELSE
    q(ia) = vol(ia)*(3600/C)
  ENDIF
```

C The volume of left turn traffic that can be accomodated during a
 C particular cycle is a function of the permissive period and the
 C protected period. Therefore, the effective green time for the
 C left turn phase must be computed from both time intervals.

C The Gsat variable is the time segment of the permissive left period
 C which is saturated by the opposing through traffic. The Gunsat
 C variable is the remaining time of permissive turn period in which
 C the left turning traffic is unopposed.

```
IF ((ia .EQ. 3) .OR. (ia .EQ. 7)) THEN
  Gsat(ia) = Gfaz(ia-1) * X(ia-1)
  Gunsat(ia) = Gfaz(ia-1) - Gsat(ia)
  IF (Gunsat(ia) .LE. 0) THEN
    g(ia) = GFaz(ia) - ltime
  ELSE
    g(ia) = Gfaz(ia) + Gunsat(ia) - ltime
  ENDIF
```

```

ELSEIF ((ia .EQ. 4) .OR. (ia .EQ. 8)) THEN
  Gsat(ia) = Gfaz(ia-3) * X(ia-3)
  Gunsat(ia) = Gfaz(ia-3) - Gsat(ia)
  IF (Gunsat(ia) .LE. 0) THEN
    g(ia) = GFaz(ia) -ltime
  ELSE
    g(ia)= Gfaz(ia)+Gunsat(ia)-ltime
  ENDIF
ELSE
  g(ia) = Gfaz(ia)-ltime
ENDIF
if (g(ia) .Eq. 0) then
  g(ia) = 7
  Write(2,999)
endif
lam(ia) = g(ia)/C
X(ia)=q(ia)/(lam(ia)*s)
21 CONTINUE

C   Calculate 1st term of the Webster delay model (D1) for each
C   critical movement.
DO 31 ia = 1,8
  D1(ia)=(C*(1-lam(ia))**2)/(2*(1-lam(ia)*X(ia)))

31 CONTINUE
C   Calculate 2nd and 3rd terms of the Webster delay model (D2 & D3)
C   using the coverted TRANSYT delay model single term for each
C   critical movement.
DO 41 ia = 1,8
  IF (q(ia) .GT. 0) THEN
    z(ia) = ((2*X(ia))/q(ia))*(60/C)
    Bn(ia) = (2*(1-X(ia)))+(X(ia)*z(ia))
    Bd(ia) = (4*z(ia))-z(ia)**2
    aaa(ia) = (Bn(ia)/Bd(ia))**2
    bbb(ia) = (X(ia)**2)/Bd(ia)
    term1(ia) = SQRT(aaa(ia)+bbb(ia))
    term2(ia) = (Bn(ia)/Bd(ia))
    term(ia) = term1(ia)-term2(ia)
    D2D3(ia) = (term(ia)*3600)/q(ia)
    delay(ia) = D1(ia)+D2D3(ia)
    totvol(ia) = totvol(ia) + vol(ia)
    totdelay(ia) = vol(ia) * delay(ia)
    bigdelay(ia)=bigdelay(ia)+totdelay(ia)
  
```

```

ELSE
    totvol(ia) = totvol(ia) + vol(ia)
    delay(ia) = 0
ENDIF
    totcyc = totcyc + C
    faztot = 0
41  CONTINUE

C  If the hour is not complete continue to process the statistics
C  on a cycle by cycle basis
C

ELSE
    hri=hr+1
    icount = icount + 1
    READ (1,102) dummy
    DO 10 ia = 1,8
        READ (1,103) Gfaz(ia), vol(ia)
        faztot = faztot + Gfaz(ia)
10  CONTINUE
    C = faztot/2
    If (C .eq. 0) then
        Write (2,888)
        C=120
    endif

C  Use the SCATS outfile data to determine delays with the use of
C  the first term of Webster's delay equation and the TRANSYT delay
C  model.
C
C  First determine the critical hourly volume. Reducing the left turn
C  volume by 1 "sneaker" vehicle.
DO 20 ia = 1,8
    IF ((ia .EQ. 3) .OR. (ia .EQ. 4)) THEN
        adjvol(ia) = vol(ia) - 1
        IF (adjvol(ia) .LE. 0) THEN
            q(ia) = 0
        ELSE
            q(ia) = adjvol(ia)*(3600/C)
        ENDIF
    
```

```

ELSEIF ((ia .EQ. 7) .OR. (ia .EQ. 8)) THEN
  adjvol(ia) = vol(ia) - 1
  IF (adjvol(ia) .LE. 0) THEN
    q(ia) = 0
  ELSE
    q(ia) = adjvol(ia)*(3600/C)
  ENDIF
ELSE
  q(ia) = vol(ia)*(3600/C)
ENDIF

```

C The volume of left turn traffic that can be accomodated during a
C particular cycle is a function of the permissive period and the
C protected period. Therefore, the effective green time for the
C left turn phase must be computed from both time intervals.

C The Gsat variable is the time segment of the permissive left period
C which is saturated by the opposing through traffic. The Gunsat
C variable is the remaining time of permissive turn period in which
C the left turning traffic is unopposed.

```

IF ((ia .EQ. 3) .OR. (ia .EQ. 7)) THEN
  Gsat(ia) = Gfaz(ia-1) * X(ia-1)
  Gunsat(ia) = Gfaz(ia-1) - Gsat(ia)
  IF (Gunsat(ia) .LE. 0) THEN
    g(ia) = GFaz(ia) -ltime
  ELSE
    g(ia)= Gfaz(ia)+Gunsat(ia)-ltime
  ENDIF
ELSEIF ((ia .EQ. 4) .OR. (ia .EQ. 8)) THEN
  Gsat(ia) = Gfaz(ia-3) * X(ia-3)
  Gunsat(ia) = Gfaz(ia-3) - Gsat(ia)
  IF (Gunsat(ia) .LE. 0) THEN
    g(ia) = GFaz(ia) -ltime
  ELSE
    g(ia)= Gfaz(ia)+Gunsat(ia)-ltime
  ENDIF
ELSE
  g(ia) = Gfaz(ia)-ltime
ENDIF
if (g(ia) .Eq. 0) then
  g(ia) = 7
  Write(2,999)
ENDIF

```

```

        lam(ia) = g(ia)/C
        X(ia)=q(ia)/(lam(ia)*s)
20  CONTINUE
C   Calculate 1st term of the Webster delay model (D1) for each
C   critical movement.
    DO 30 ia = 1,8
        D1(ia)=(C*(1-lam(ia))**2)/(2*(1-lam(ia)*X(ia)))
30  CONTINUE
C   Calculate 2nd and 3rd terms of the Webster delay model (D2 & D3)
C   using the converted TRANSYT delay model single term for each
C   critical movement.
    DO 40 ia = 1,8
        IF (q(ia) .GT. 0) THEN
            z(ia) = ((2*X(ia))/q(ia))*(60/C)
            Bn(ia) = (2*(1-X(ia)))+(X(ia)*z(ia))
            Bd(ia) = (4*z(ia))-z(ia)**2
            aaa(ia) = (Bn(ia)/Bd(ia))**2
            bbb(ia) = (X(ia)**2)/Bd(ia)
            term1(ia) = SQRT(aaa(ia)+bbb(ia))
            term2(ia) = (Bn(ia)/Bd(ia))
            term(ia) = term1(ia)-term2(ia)
            D2D3(ia) = (term(ia)*3600)/q(ia)
            delay(ia) = D1(ia)+D2D3(ia)
            totvol(ia) = totvol(ia) + vol(ia)
            totdelay(ia) = vol(ia)*delay(ia)
            bigdelay(ia)=bigdelay(ia)+totdelay(ia)
        ELSE
            totvol(ia) = totvol(ia) + vol(ia)
            delay(ia) = 0
        ENDIF
        totcyc = totcyc + C
        faztot = 0
40  CONTINUE
    ENDIF
    READ (1,101) hr, min
60  CONTINUE

```

```
101 FORMAT (14X,I3,1X,I2)
102 FORMAT (A25)
103 FORMAT (22X,I2,5X,I2)
201 FORMAT ('Period begins at ',I2,':00')
202 FORMAT ('Movement #',I1,' hrly vol. =',F7.3,' ave. delay =',F7.3)
203 FORMAT ('          ave. cycle length =', F7.3,'sec')
204 FORMAT ('Intersection total delay=', F7.3,' veh-hrs')
      CLOSE (1)
      CLOSE (2)
      STOP
      END
```

APPENDIX B

DELAY CALCULATION PROGRAM OUTPUT FOR THE

INTERSECTION OF PONTIAC TRAIL AND TEN MILE ROAD

Period begins at 0:00

Movement #1 hrly vol. = 62.000 ave. delay = 9.091
 Movement #2 hrly vol. = 67.000 ave. delay = 7.693
 Movement #3 hrly vol. = 4.000 ave. delay = 7.767
 Movement #4 hrly vol. = 9.000 ave. delay = 8.656
 Movement #5 hrly vol. = 13.000 ave. delay = 26.661
 Movement #6 hrly vol. = 10.000 ave. delay = 24.947
 Movement #7 hrly vol. = 2.000 ave. delay = 17.002
 Movement #8 hrly vol. = .000 ave. delay = .000
 Intersection total delay= .505 veh-hrs
 ave. cycle length = 52.970sec

Period begins at 1:00

Movement #1 hrly vol. = 20.000 ave. delay = 1.444
 Movement #2 hrly vol. = 41.000 ave. delay = 1.341
 Movement #3 hrly vol. = .000 ave. delay = .000
 Movement #4 hrly vol. = .000 ave. delay = .000
 Movement #5 hrly vol. = 2.000 ave. delay = 21.489
 Movement #6 hrly vol. = .000 ave. delay = .000
 Movement #7 hrly vol. = .000 ave. delay = .000
 Movement #8 hrly vol. = .000 ave. delay = .000
 Intersection total delay= .035 veh-hrs
 ave. cycle length = 50.118sec

Period begins at 2:00

Movement #1 hrly vol. = 28.000 ave. delay = 11.382
 Movement #2 hrly vol. = 10.000 ave. delay = .187
 Movement #3 hrly vol. = .000 ave. delay = .000
 Movement #4 hrly vol. = 2.000 ave. delay = 19.136
 Movement #5 hrly vol. = .000 ave. delay = .000
 Movement #6 hrly vol. = .000 ave. delay = .000
 Movement #7 hrly vol. = .000 ave. delay = .000
 Movement #8 hrly vol. = .000 ave. delay = .000
 Intersection total delay= .100 veh-hrs
 ave. cycle length = 50.985sec

Period begins at 3:00

Movement #1 hrly vol. = 18.000 ave. delay = 2.170
 Movement #2 hrly vol. = 22.000 ave. delay = 2.278
 Movement #3 hrly vol. = .000 ave. delay = .000
 Movement #4 hrly vol. = .000 ave. delay = .000
 Movement #5 hrly vol. = 2.000 ave. delay = 23.749
 Movement #6 hrly vol. = 4.000 ave. delay = 22.839
 Movement #7 hrly vol. = .000 ave. delay = .000
 Movement #8 hrly vol. = .000 ave. delay = .000
 Intersection total delay= .063 veh-hrs

ave. cycle length = 53.206sec

Period begins at 4:00

Movement #1 hrly vol. = 17.000 ave. delay = .166
 Movement #2 hrly vol. = 20.000 ave. delay = 2.312
 Movement #3 hrly vol. = .000 ave. delay = .000
 Movement #4 hrly vol. = .000 ave. delay = .000
 Movement #5 hrly vol. = 7.000 ave. delay = 23.921
 Movement #6 hrly vol. = 5.000 ave. delay = 25.968
 Movement #7 hrly vol. = .000 ave. delay = .000
 Movement #8 hrly vol. = .000 ave. delay = .000
 Intersection total delay= .096 veh-hrs

ave. cycle length = 53.597sec

Period begins at 5:00

Movement #1 hrly vol. =115.000 ave. delay = 15.315
 Movement #2 hrly vol. = 88.000 ave. delay = 12.940
 Movement #3 hrly vol. = .000 ave. delay = .000
 Movement #4 hrly vol. = .000 ave. delay = .000
 Movement #5 hrly vol. = 26.000 ave. delay = 27.359
 Movement #6 hrly vol. = 93.000 ave. delay = 25.413
 Movement #7 hrly vol. = 5.000 ave. delay = 15.010
 Movement #8 hrly vol. = 6.000 ave. delay = 15.554
 Intersection total delay= 1.706 veh-hrs

ave. cycle length = 62.186sec

Period begins at 6:00

Movement #1 hrly vol. =210.000 ave. delay = 20.428
 Movement #2 hrly vol. =183.000 ave. delay = 19.559
 Movement #3 hrly vol. = 6.000 ave. delay = 16.015
 Movement #4 hrly vol. = 2.000 ave. delay = 21.873
 Movement #5 hrly vol. = 62.000 ave. delay = 23.186
 Movement #6 hrly vol. =231.000 ave. delay = 33.126
 Movement #7 hrly vol. = 6.000 ave. delay = 21.226
 Movement #8 hrly vol. = 16.000 ave. delay = 16.828
 Intersection total delay= 4.860 veh-hrs

ave. cycle length = 79.889sec

Period begins at 7:00

Movement #1 hrly vol. =447.000 ave. delay = 43.215
 Movement #2 hrly vol. =401.000 ave. delay = 38.613
 Movement #3 hrly vol. = 17.000 ave. delay = 24.958
 Movement #4 hrly vol. = 16.000 ave. delay = 37.307
 Movement #5 hrly vol. =194.000 ave. delay = 31.360
 Movement #6 hrly vol. =336.000 ave. delay = 52.589
 Movement #7 hrly vol. = 50.000 ave. delay = 34.943
 Movement #8 hrly vol. = 67.000 ave. delay = 30.712

Intersection total delay= 17.606 veh-hrs

ave. cycle length = 85.810sec

Period begins at 8:00

Movement #1 hrly vol. =353.000 ave. delay = 29.904

Movement #2 hrly vol. =324.000 ave. delay = 32.991

Movement #3 hrly vol. = 16.000 ave. delay = 30.338

Movement #4 hrly vol. = 42.000 ave. delay = 23.932

Movement #5 hrly vol. =193.000 ave. delay = 37.659

Movement #6 hrly vol. =265.000 ave. delay = 34.587

Movement #7 hrly vol. = 22.000 ave. delay = 25.188

Movement #8 hrly vol. = 22.000 ave. delay = 26.563

Intersection total delay= 11.197 veh-hrs

ave. cycle length = 80.955sec

Period begins at 9:00

Movement #1 hrly vol. =369.000 ave. delay = 29.272

Movement #2 hrly vol. =389.000 ave. delay = 32.122

Movement #3 hrly vol. = 17.000 ave. delay = 65.652

Movement #4 hrly vol. = 14.000 ave. delay = 23.884

Movement #5 hrly vol. =186.000 ave. delay = 29.813

Movement #6 hrly vol. =228.000 ave. delay = 31.621

Movement #7 hrly vol. = 23.000 ave. delay = 24.237

Movement #8 hrly vol. = 27.000 ave. delay = 25.658

Intersection total delay= 10.765 veh-hrs

ave. cycle length = 80.733sec

Period begins at 10:00

Movement #1 hrly vol. =358.000 ave. delay = 28.185

Movement #2 hrly vol. =373.000 ave. delay = 26.923

Movement #3 hrly vol. = 25.000 ave. delay = 24.269

Movement #4 hrly vol. = 42.000 ave. delay = 31.461

Movement #5 hrly vol. =188.000 ave. delay = 27.691

Movement #6 hrly vol. =199.000 ave. delay = 30.695

Movement #7 hrly vol. = 21.000 ave. delay = 30.972

Movement #8 hrly vol. = 26.000 ave. delay = 20.148

Intersection total delay= 9.597 veh-hrs

ave. cycle length = 80.000sec

Period begins at 11:00

Movement #1 hrly vol. =419.000 ave. delay = 34.509

Movement #2 hrly vol. =433.000 ave. delay = 34.664

Movement #3 hrly vol. = 26.000 ave. delay = 29.684

Movement #4 hrly vol. = 34.000 ave. delay = 30.437

Movement #5 hrly vol. =218.000 ave. delay = 29.341

Movement #6 hrly vol. =200.000 ave. delay = 29.852

Movement #7 hrly vol. = 35.000 ave. delay = 22.239

Movement #8 hrly vol. = 22.000 ave. delay = 21.156

Intersection total delay= 12.468 veh-hrs

ave. cycle length = 80.044sec

Period begins at 12:00

Movement #1 hrly vol. =400.000 ave. delay = 29.585

Movement #2 hrly vol. =441.000 ave. delay = 37.316

Movement #3 hrly vol. = 21.000 ave. delay = 53.181

Movement #4 hrly vol. = 34.000 ave. delay = 30.289

Movement #5 hrly vol. =250.000 ave. delay = 33.341

Movement #6 hrly vol. =187.000 ave. delay = 28.290

Movement #7 hrly vol. = 18.000 ave. delay = 23.549

Movement #8 hrly vol. = 28.000 ave. delay = 34.599

Intersection total delay= 12.626 veh-hrs

ave. cycle length = 81.000sec

Period begins at 13:00

Movement #1 hrly vol. =372.000 ave. delay = 28.793

Movement #2 hrly vol. =495.000 ave. delay = 40.429

Movement #3 hrly vol. = 37.000 ave. delay = 29.607

Movement #4 hrly vol. = 22.000 ave. delay = 26.577

Movement #5 hrly vol. =246.000 ave. delay = 40.649

Movement #6 hrly vol. =192.000 ave. delay = 28.375

Movement #7 hrly vol. = 36.000 ave. delay = 23.206

Movement #8 hrly vol. = 38.000 ave. delay = 32.366

Intersection total delay= 13.866 veh-hrs

ave. cycle length = 80.200sec

Period begins at 14:00

Movement #1 hrly vol. =445.000 ave. delay = 47.543

Movement #2 hrly vol. =524.000 ave. delay = 54.310

Movement #3 hrly vol. = 30.000 ave. delay = 38.908

Movement #4 hrly vol. = 63.000 ave. delay = 37.799

Movement #5 hrly vol. =298.000 ave. delay = 62.220

Movement #6 hrly vol. =211.000 ave. delay = 36.153

Movement #7 hrly vol. = 35.000 ave. delay = 28.293

Movement #8 hrly vol. = 55.000 ave. delay = 55.973

Intersection total delay= 23.167 veh-hrs

ave. cycle length = 85.881sec

Period begins at 15:00

Movement #1 hrly vol. =477.000 ave. delay = 43.850

Movement #2 hrly vol. =518.000 ave. delay = 44.285

Movement #3 hrly vol. = 44.000 ave. delay = 35.484

Movement #4 hrly vol. = 53.000 ave. delay = 38.420

Movement #5 hrly vol. =360.000 ave. delay = 64.899

Movement #6 hrly vol. =212.000 ave. delay = 32.064

Movement #7 hrly vol. = 29.000 ave. delay = 27.762

Movement #8 hrly vol. = 73.000 ave. delay = 54.948

Intersection total delay= 22.897 veh-hrs

ave. cycle length = 89.050sec

Period begins at 16:00

Movement #1 hrly vol. =462.000 ave. delay = 46.145

Movement #2 hrly vol. =582.000 ave. delay = 68.489

Movement #3 hrly vol. = 37.000 ave. delay = 37.811

Movement #4 hrly vol. = 88.000 ave. delay = 40.612

Movement #5 hrly vol. =378.000 ave. delay = 69.939

Movement #6 hrly vol. =267.000 ave. delay = 42.614

Movement #7 hrly vol. = 56.000 ave. delay = 33.641

Movement #8 hrly vol. = 85.000 ave. delay = 55.856

Intersection total delay= 30.722 veh-hrs

ave. cycle length = 89.293sec

Period begins at 17:00

Movement #1 hrly vol. =463.000 ave. delay = 45.301

Movement #2 hrly vol. =589.000 ave. delay = 78.856

Movement #3 hrly vol. = 44.000 ave. delay = 37.980

Movement #4 hrly vol. = 90.000 ave. delay = 45.328

Movement #5 hrly vol. =445.000 ave. delay = 75.455

Movement #6 hrly vol. =218.000 ave. delay = 33.171

Movement #7 hrly vol. = 37.000 ave. delay = 43.064

Movement #8 hrly vol. = 65.000 ave. delay = 43.181

Intersection total delay= 32.883 veh-hrs

ave. cycle length = 89.625sec

Period begins at 18:00

Movement #1 hrly vol. =531.000 ave. delay = 53.251

Movement #2 hrly vol. =545.000 ave. delay = 58.467

Movement #3 hrly vol. = 34.000 ave. delay = 36.424

Movement #4 hrly vol. = 87.000 ave. delay = 53.181

Movement #5 hrly vol. =331.000 ave. delay = 56.870

Movement #6 hrly vol. =176.000 ave. delay = 29.846

Movement #7 hrly vol. = 32.000 ave. delay = 25.568

Movement #8 hrly vol. = 55.000 ave. delay = 57.128

Intersection total delay= 26.123 veh-hrs

ave. cycle length = 88.975sec

Period begins at 19:00

Movement #1 hrly vol. =421.000 ave. delay = 29.229

Movement #2 hrly vol. =482.000 ave. delay = 42.888

Movement #3 hrly vol. = 16.000 ave. delay = 28.417

Movement #4 hrly vol. = 35.000 ave. delay = 31.973

Movement #5 hrly vol. =270.000 ave. delay = 41.660

Movement #6 hrly vol. =164.000 ave. delay = 27.242

Movement #7 hrly vol. = 16.000 ave. delay = 19.648

Movement #8 hrly vol. = 37.000 ave. delay = 31.990

Intersection total delay= 14.379 veh-hrs

ave. cycle length = 82.068sec

Period begins at 20:00

Movement #1 hrly vol. =370.000 ave. delay = 28.586

Movement #2 hrly vol. =425.000 ave. delay = 32.464

Movement #3 hrly vol. = 18.000 ave. delay = 28.846

Movement #4 hrly vol. = 16.000 ave. delay = 34.437

Movement #5 hrly vol. =185.000 ave. delay = 28.492

Movement #6 hrly vol. =115.000 ave. delay = 25.698

Movement #7 hrly vol. = 17.000 ave. delay = 19.991

Movement #8 hrly vol. = 10.000 ave. delay = 25.838

Intersection total delay= 9.519 veh-hrs

ave. cycle length = 80.156sec

Period begins at 21:00

Movement #1 hrly vol. =322.000 ave. delay = 26.303

Movement #2 hrly vol. =316.000 ave. delay = 22.297

Movement #3 hrly vol. = 11.000 ave. delay = 20.424

Movement #4 hrly vol. = 7.000 ave. delay = 29.026

Movement #5 hrly vol. =198.000 ave. delay = 38.874

Movement #6 hrly vol. = 71.000 ave. delay = 23.412

Movement #7 hrly vol. = 16.000 ave. delay = 18.221

Movement #8 hrly vol. = 12.000 ave. delay = 23.243

Intersection total delay= 7.187 veh-hrs

ave. cycle length = 79.733sec

Period begins at 22:00

Movement #1 hrly vol. =186.000 ave. delay = 17.841

Movement #2 hrly vol. =158.000 ave. delay = 16.188

Movement #3 hrly vol. = 9.000 ave. delay = 13.807

Movement #4 hrly vol. = 8.000 ave. delay = 19.803

Movement #5 hrly vol. =100.000 ave. delay = 33.852

Movement #6 hrly vol. = 47.000 ave. delay = 26.175

Movement #7 hrly vol. = 15.000 ave. delay = 17.628

Movement #8 hrly vol. = 10.000 ave. delay = 18.234

Intersection total delay= 3.117 veh-hrs

ave. cycle length = 75.917sec

LIST OF REFERENCES

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- 1) Road Commission for Oakland County, "FAST-TRAC is on the Cutting Edge of Traffic Management Technology," Beverly Hills, Michigan, 1993.
- 2) Lowrie, P. R., "SCATS, Sydney Co-Ordinated Adaptive Traffic System, A Traffic Responsive Method of Controlling Urban Traffic," Roads and Traffic Authority Sydney, New South Wales, Australia, 1990.
- 3) Lowrie, P. R., "The Sydney Co-Ordinated Adaptive Traffic System - Principles, Methodology Algorithms," International Conference on Road Traffic Signaling, pp. 67-70, London, 1982.
- 4) Taylor, William C. and Thomas L. Maleck, "Interim Report on Intersection Delay," Department of Civil and Environmental Engineering, Michigan State University, 1994.
- 5) Carty, Patrick J., "Lessons Learned from the Oakland County IVHS Project," IVHS America International Conference, Washington, D.C., 1993.
- 6) Hunt, P.B., Robertson, D.I., Bretherton, R.D., R.I. Winton, "SCOOT - A Traffic Responsive Method of Coordinating Signals," Transport and Road Research Laboratory, Crownthorne, Berkshire, England, 1981.
- 7) Curtis, Owen, "Time-Based Coordination of Traffic Signals," Federal Highway Administration Report No. FHWA/PL/85/001, Washington, D.C., 1984.
- 8) Stillman, I.L. and H.M. Maynard, "Development of a Traffic Flow Sensing and Surveillance System," IEEE Automotive Conference, Detroit, Michigan, 1967.
- 9) Chirstensen, A. "Use of a Computer and Vehicle Loop Detectors To Measure Queues and Delays at Signalized Intersections," Highway Research Record, Number 211, Washington, D.C., 1967.
- 10) Genovese, Joseph A., "SCOOT in the USA," 1994 Compendium of Technical Papers, Institute of Transportation Engineers, Washington, D.C., 1994.
- 11) Simms, A.G. and K.W. Dobinson, "S.C.A.T. - The Sydney Co-Ordinated Adaptive Traffic System Philosophy and Benefits," International Symposium on Traffic Control Systems, Vol 2B, 1979.

- 12) Bielefeldt, Christian, "HERMES - High Efficiency Roads with Rerouting Methods and Traffic Signal Control," Compendium of Technical Papers, Institute of Transportation Engineers Annual Meeting, The Hague, Netherlands, 1993.
- 13) Bretherton, R.D., and G.T Bowen, "Incident Detection and Traffic Monitoring in Urban Areas," Proceedings of the DRIVE Conference, Brussels, Belgium, 1991.
- 14) Morello, E. and G. Sala, "Automatic Incident Detection in HERMES," Centro Studi sui Sistemi di Trasporto, Torino, Italy, 1991.
- 15) Fambro, Daniel B. and C.J. Messer, "Estimating Delay at Coordinated Signalized Intersections," Highway Capacity and Level of Service, Rotterdam, The Netherlands, 1991.
- 16) Gartner, Nathan H., "Impacts of Smart Signals on Intersection Capacity and Level of Service," Highway Capacity and Level of Service, Rotterdam, The Netherlands, 1991.
- 17) "Highway Capacity Manual," Special Report 209, Transportation Research Board, National Research Council, Washington, D.C., 1985
- 18) Bartle, Richard, M., Val Skoro, and D.L. Gerlough, "Starting Delay and Time Spacing of Vehicles Entering Signalized Intersections," Highway Research Record, 112, Washington, D.C., 1956
- 19) Kell, James H., "Analyzing Vehicular Delay at Intersections Through Simulation," Highway Research Board, Bulletin 356, Washington, D.C., 1962.
- 20) Kell, James H., "Results of Computer Simulation Studies as Related to Traffic Signal Operations," 33rd Annual Meeting of the Institute of Traffic Engineers, Toronto, Ontario, Canada, August, 1963.
- 21) Needham, R.G., "A Simulation Program of a Road Network Controlled by Traffic Responsive Signals," Road Research Laboratory, Crowthorne, England, 1970.
- 22) United States Department of Transportation, Federal Highway Administration, "Signal Operations Analysis Package User's Manual," Washington, D.C., 1979.
- 23) United States Department of Transportation, Federal Highway Administration, "TRAF-NETSIM User's Manual," Washington, D.C., 1995.

- 24) Van Aerde, Micheal, J. Voss, and G. McKinnon, "User's Guide to the Student Macintosh Version of the INTEGRATION Simulation Model," Department of Civil Engineering, Queens University, Kingston, Canada, 1991.
- 25) Van Aerde, Micheal and Sam Yagar, "Dynamic Integrated Freeway/Traffic Signal Networks: Problems and Solutions," Transportation Research Volume 22A, Number 6, 1988.
- 26) Hsin, Victor J.K. and Paul Wang, "Modeling Concepts for Intelligent Vehicle Highway Systems (IVHS) Applications," Proceedings of the 1992 Winter Simulation Conference, 1992.
- 27) Wang, Paul T. R. and William P. Niedringhaus, "Distributed/Parallel Traffic Simulation for IVHS Applications," Proceedings of the 1993 Winter Simulation Conference, Washington, D.C., 1993.
- 28) Codelli, David K., William P., et. al., "User's Manual for Traffic and Highway Object for Research Analysis, and Understanding (THOREAU) Volume II, Revision 1," The MITRE Corporation, McLean, Virginia, 1993.
- 29) Rathi, Ajay K. And Alberto Santiago, "Simulation and Intelligent Vehicle Highway Systems," U.S. Department of Energy Project Number DE-AC05-84OR21400, Washington, D.C., 1992.
- 30) Gruba, John L., Beaubien, Richard, F., "Combining Real Time, Adaptive Traffic Control and Machine Vision Detection for Advanced Traffic Management Systems," Compendium of Technical Papers, Institute of Transportation Engineers Annual Meeting, The Hague, Netherlands, 1993.
- 31) Beaubien, Richard F., "Advanced Traffic Management Systems for Arterial Streets, A European Perspective," Institute of Transportation Engineers International Conference, 1992.
- 32) Michalopoulos, Panos G. et. al., "Automatic Incident Detection Through Video Image Processing," *Traffic Engineering and Control*, February, 1993.
- 33) Rajendra, Kunwar and Robert E. Maki, "The IVHS Strategy in Michigan," IVHS America International Conference, Washington, D.C., 1993.
- 34) Sobolewski, Mike and James L. Wright, "Rural Applications of IVHS in Minnesota," IVHS America International Conference, Washington, D.C., 1993.

- 35) Wallace, Charles E. And Andrew K. Kilpatrick, "IVHS Applications for Rural Highways and Small Towns," IVHS America International Conference, Washington, D.C., 1993.
- 36) Luk, J.Y.K., A.G. Sims and P.R. Lowrie, "SCATS - Application and Field Comparison with a TRANSYT Optimized Fixed Time System," International Conference on Road Signaling, London, 1982.
- 37) Moore, S.E., A.G. Sims and P.R. Lowrie, "Three Traffic Signal Control Philosophies Applied to an Arterial Traffic System," Australian Road Research Board Proceedings, Volume 8, 1976.
- 38) Luk, J.Y.K., "Two Traffic-Responsive Area Traffic Control Methods: SCAT and SCOOT," Traffic Engineering and Control, 1984.
- 39) Kelman, W. Les, et. al., "The Metropolitan Toronto SCOOT Demonstration Project - A Preliminary Evaluation Report," Transportation Research Board, 73rd Annual Meeting, Washington, D.C., 1994
- 40) Grubba, John et. al., "Selecting Real-Time Adaptive Traffic Control for Oakland County, Michigan," Transportation Research Board, 72nd Annual Meeting, Washington, D.C., 1993.
- 41) Bretherton, R.D. and G.I. Rai, "The Use of SCOOT in Low Flow Conditions," Traffic Engineering and Control, December, 1982.
- 42) May, Adolf, "Traffic Flow Fundamentals," Prentice Hall, Englewood Cliffs, New Jersey, 1990.
- 43) Taylor, Micheal and W. Young, "Traffic Analysis, New Technology and Solutions," Hargreen Publishing Company, North Melbourne, Victoria, Australia, 1988.
- 44) McShane, William R. and Roger P. Roess, "Traffic Engineering," Prentice Hall, Englewood Cliffs, New Jersey, 1990.
- 45) Bhattacharyya, Gouri K. And Richard A. Johnson, "Statistical Concepts and Methods," John Wiley & Sons, New York, New York, 1977.
- 46) Mendenhall, William et. al., "Mathematical Statistics and Applications, Fourth Edition," PWS-KENT Publishing Company, Boston, Massachusetts, 1990.
- 47) Taylor, W.C. and Ahmed Abdel-Rachman, Working Paper, Michigan State University Department of Civil Engineering, East Lansing, Michigan 1996.

- 48) Webster, F.V. and B.M. Cobbe, "Traffic Signals," Road Research Laboratory Technical Paper No. 56, London, England, 1966.
- 49) Robertson, D.I. and P. Grower, "Use of TRANSYT Version 6," Transport and Road Research Laboratory Supplemental Report 255, Crowthorne, England, 1977.
- 50) Taylor, W.C., J. Wu and T. Hein, "Deployment of Intelligent Transportation Systems in Michigan - Impact on Traffic Accidents," Proceedings, World Congress on Intelligent Transportation Systems, Orlando, Florida, October, 1996, p.184

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