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## **Improved Traffic Signal Coordination Strategies for Actuated Control**

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16. Abstract  This report documents research conducted to develop better strategies to use with traffic actuated control in coordinated signal systems. Recommendations are presented on more efficient strategies for coordination using actuated control. Representative arterial traffic control problems were modeled into a statistical testbed using TRAF-NETSIM. A set of scenarios covering a range of arterial geometry, traffic volumes and traffic actuated control settings were tested and evaluated. PASSER II-90 was used to develop base signal timing plans.  Chapter One describes the various objectives that were intended to be achieved by this research. It also discusses signal coordination strategies for actuated control. Chapter Two presents the background information and various traffic engineering simulation models available for use in this study.  Chapters Three and Four explain the study methodology adopted for this research and the results obtained for the various study scenarios, respectively. Chapter Five presents the conclusions and recommendations of the research.		
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**IMPROVED TRAFFIC SIGNAL COORDINATION STRATEGIES FOR  
ACTUATED CONTROL**

**Project 65110 - Final Report**

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## EXECUTIVE SUMMARY

Traffic actuated signals have been efficiently used in controlling isolated intersections because they respond to random traffic fluctuations using loop detectors on all approaches. Application to coordinated arterial operations is a more complex task and documented insights into the operational performance of various arterial signal timing strategies is limited and not readily available.

The purpose of this study was to develop a better understanding of the performance of various traffic models providing arterial coordination using actuated control and determine better ways to use the added flexibility of actuated control in a coordinated system, and recommend more efficient strategies for coordination using actuated control. Representative traffic control problems were modeled into a statistical testbed using TRAF-NETSIM. A series of scenarios covering a range of arterial geometry, traffic volumes, and traffic actuated control settings were tested and evaluated.

The results indicate that green splits have to be more perfectly timed in pretimed operation for optimal performance at higher volume levels. At low volumes, any reasonable signal timing strategy works well as long as the detectors work and traffic signals are coordinated. NETSIM simulation results for pretimed control demonstrate that PASSER II-90's green splits are optimal and any significant improvement to the arterial is only possible by employing traffic actuated control. It was observed that actuated system performance remained the same when the arterial's coordinated pretimed phase was reduced from its optimum pretimed value using existing actuated control technology. This finding suggests that a more optimal allocation of arterial green times is possible. Development of an advanced signal controller to implement the recommended control strategy is proposed.

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## ABSTRACT

Traffic actuated signals have been efficiently used in controlling isolated intersections because they respond to random traffic fluctuations using loop detectors on all approaches. Application to coordinated arterial operations is a more complex task and insights into the operational performance of various arterial signal timing strategies is limited.

The purpose of this study was to develop a better understanding of the performance of various traffic models providing arterial coordination using actuated control and determine better ways to use the added flexibility of the actuated control in a coordinated system, and recommend more efficient strategies for coordination using actuated control. Representative traffic control problems were modeled into a statistical testbed using TRAF-NETSIM. A series of scenarios covering a range of arterial geometry, traffic volumes, and traffic actuated control settings were tested.

The results indicate that green splits have to be more perfectly tuned in pretimed operation for optimal performance at higher volume levels. At low volumes, any reasonable signal timing strategy works well as long as the detectors work and traffic signals are coordinated. NETSIM simulation results for pretimed control demonstrate that PASSER II-90's green splits are optimal and any significant improvement to the arterial is only possible by employing traffic actuated control. It was observed that actuated system performance remained the same when the arterial's coordinated pretimed phase was reduced from its optimum pretimed value using existing actuated control technology. This finding suggests that a more optimal allocation of arterial green times is possible. Development of an advanced signal controller to implement the recommended control strategy is proposed.

## CHAPTER I

### INTRODUCTION

Increasing traffic volumes continue to place heavy demands on many already overburdened city streets; therefore, effective means for handling this problem are needed. Coordinated signals along an arterial street system often provide a good solution for this growing problem. The control objective is to efficiently operate these systems such that delays, stops and fuel consumption are minimized. Three types of signal control systems are used by traffic engineers; namely, pretimed, semi-actuated, and fully actuated. The performance of these systems depends on effective detector-controller combinations, respective operational requirements, and control strategies. Signal coordination along an arterial is a complex procedure because of the close interaction between the various parameters involved in the process of coordination.

Coordination is a term used to describe a process in which two or more intersections are synchronized so that vehicles can pass through each intersection without stopping. There has been an increased use of actuated control in arterial signal systems due to the variations in traffic demand throughout the day. However, there is still a lack of concrete methods for analyzing and optimizing actuated control systems. Considerable attention has been given to the problem of timing coordinated actuated signals. The development of optimized timing plans for coordinated actuated systems remains quite complicated, mainly because all of the state-of-the-art signal timing programs (e.g., TRANSYT-7F, PASSER II-90, MAXBAND) have been designed for the analysis and optimization of pretimed signal systems. Programs developed exclusively for actuated control have yet to be developed.

The control parameters (offsets, splits) that are optimized with the existing programs do not correspond to actuated control settings (yield point, permissive periods, force-offs, etc.). On the other hand, traffic simulators, such as TRAF-NETSIM and TEXAS Model, can analyze the performance of actuated coordinated systems, but are not capable of optimizing the signal settings.

Actuated traffic signals are designed to respond to random traffic variations through the placement of traffic detectors on one or more intersection approaches (1). With appropriate detector-controller configurations, actuated control can be used to provide flexible signal control to effectively handle traffic fluctuations. By carefully implementing proper actuated designs, control systems can efficiently adjust phase green times at signalized intersections for effective arterial coordination.

### **Problem Statement**

Pretimed coordination often performs well under high volume conditions and predictable oversaturation. However, the capability to provide control flexibility and optimum performance under low volumes is restricted. In pretimed coordination, the cross street phases last as long as the green times calculated by various computer programs for pretimed control and not as long as required for the existing demand. There is a lot of wasted green time on cross streets especially under low volumes as the green times are allocated based on pretimed control strategies. The calculation of phase sequence also assumes that the cross street phases will last as long as the green splits for pretimed control (2). The net operational result, when using pretimed strategies for actuated control, is that arterial platoons often get their green light too "early" and then travel along the street and hit another red light. Pretimed control can disrupt the smooth platoon flow along the arterial under variable demand conditions.

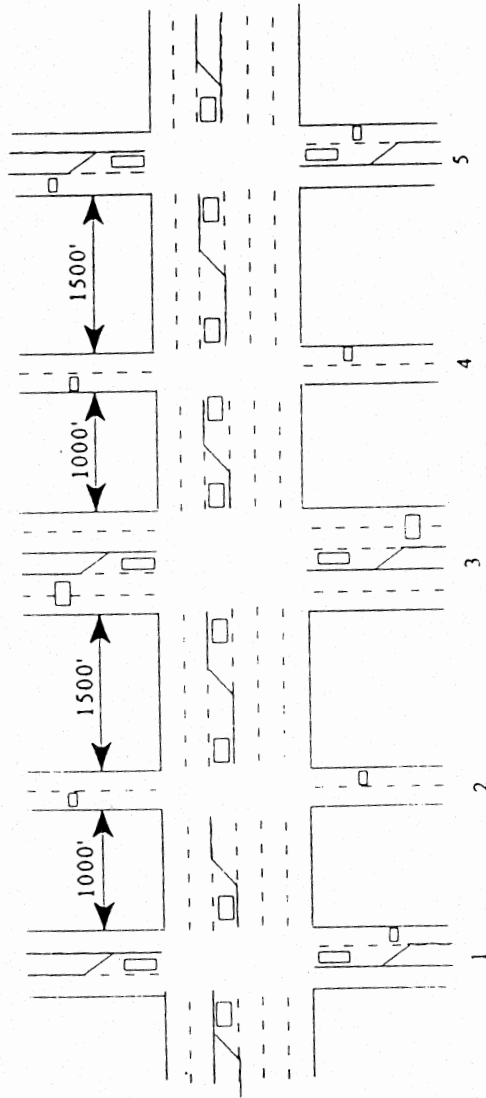
It is difficult to combine actuated control and signal coordination easily and provide satisfactory performance. The effects of the highly probabilistic behavior of actuated systems make the investigation of the issues extremely difficult. There is still a lack of concrete strategies for optimally operating an arterial system using actuated control. There remains a much desired need to develop efficient and reliable traffic signal timing algorithms based on actuated control concepts.

Studies conducted by Chang and Koothrappally (3) have indicated that coordinated actuated operation performs much better than pretimed coordinated strategies. Most recent research conducted on actuated operation has dealt with the prediction of traffic delays, level of service for signal systems, detector designs, and estimating average cycle lengths and green lengths, rather than for signal control. Actuated controllers have the capability to fall back to pretimed operations, as well as to handle variable demands under different operating conditions. Actuated operation can efficiently allocate the green splits based on the existing demand making coordination effective.

### **Research Objectives**

The main objectives of this research were two-fold. The first objective was to investigate the effects of phase green split variation on the performance of an arterial system. An illustration of an arterial is shown in Figure 1. The second objective was to develop strategies to improve the performance of the arterial using coordinated actuated concepts based on the above results. The strategies were verified for an arterial testbed over a wide range volume conditions and other control parameters. The following five tasks were performed in order to realize these research objectives.





**Figure 1 Schematic Diagram of a Five Intersection Arterial.**

1. A thorough literature review was conducted to fully understand actuated control concepts, their weaknesses and strengths. Efforts were directed to identify the different analytical procedures involved in analyzing and optimizing the arterial operations using actuated control.
2. An experimental testbed was developed for studying various traffic actuated signal control system strategies which was presumed to be representative of a typical arterial. Real world traffic control problems were modeled into a statistical testbed using the latest microscopic traffic simulation program available, currently TRAF-NETSIM.
3. Strategies were developed which can enhance arterial signal coordination using actuated control using the simulation results. Several sets of parametric values developed from analytic formulations, covering a wide range of general arterial geometry and traffic actuated control settings, were tested while formulating the strategies.
4. The performance of the strategies developed over a wide range of traffic volume conditions and other control parameters was verified.
5. The results obtained were verified for their statistical significance. Using these results, alternatives were proposed to improve arterial signal coordination using actuated control.

### **Scope**

The study had to be restricted to simulation analysis and did not have the luxury of field data. The available resources were judiciously utilized to attain utmost benefits from this research. The wide acceptance and use of PASSER II-90 for arterial signal timing in this country made it the first choice for all the analysis. Since it is of great importance for the traffic engineer to be aware of more effective strategies that could result in energy savings, considerable attention and time was devoted in

developing alternatives that improve arterial signal operations and potential energy savings. The development of an advanced signal controller has been envisioned. Further studies can be conducted applying this vision to improve arterial signal coordination using actuated control. The research reported herein will help the traffic engineer better analyze and understand the process of arterial coordination using actuated control.

### **Organization**

This research is organized into five chapters. The first chapter has presented the problem statement, research objectives, and scope of work addressed in this research. A general literature review provides the necessary background for this research in the second chapter. The study methodology followed to realize the research objectives is described in third chapter. The results and analyses of this research are documented in the fourth chapter with conclusions and recommendations forming the fifth and last chapter.

## CHAPTER II

### BACKGROUND

#### Introduction

This chapter provides the background and past research in the problem areas identified in this research. The different types of signal control strategies are first discussed. The control parameters crucial to arterial coordination using actuated control are also explained. The literature pertinent to this research is briefly explained in the following sections. Some of the existing models for predicting the phase green times at actuated intersections are discussed. Finally, traffic engineering models for dealing with these areas are briefly explained.

#### Isolated System Vs Coordinated System

The basic operational difference between an isolated system and a coordinated system is that consideration is given to the provision of disrupted traffic flow along the arterial in the case of a coordinated system. *Isolated signal control* is that form of signal control for a single intersection through which the flow of traffic is controlled without giving any consideration to the operation of adjacent signalized intersections (4). *Coordinated signal control* is that form of signal control for signalized intersections along an arterial street in which major consideration is given to the provision of progressive traffic flow along the arterial. In this case, as opposed to the isolated signal control, consideration is given to operating the signals as a system. *Coordination* can be defined as the establishment of a definite timing relationship between adjacent traffic signals (4).

The basic approach to arterial street signal control considers that vehicles traveling along the arterial street are released in platoons from a signal and hence travel in platoons to the next signal. Thus, it becomes desirable to establish a time relationship between beginning of arterial green at one intersection and the beginning of the arterial green at the next intersection so that arterial traffic moves without stopping. It is also beneficial that static queues receive a green indication on their approach to a signalized intersection in advance of the arriving platoons from upstream on the arterial. This permits the continuous traffic flow along an arterial without stopping and aids in reducing the delay. Therefore, the control objective of a coordinated system is to keep the platoons flowing without disrupting the progressive movement of the vehicles along the arterial street.

Since the offset relationship must be obtained over time, it is necessary to utilize a common cycle or some multiple of a common cycle throughout the system (4). The phase splits may vary at each intersection, but the point of beginning of the major street green must have a constant time period.

### **Arterial Traffic Control Strategies**

In many traffic signal installations, the two most common types of intersection control are pretimed and vehicle actuated. In fact, some modern controllers can implement either type of control, depending on the level of traffic demand and the need to provide signal coordination (5). Pretimed coordinated control may be used during rush hour, high volume conditions and isolated actuated control in off-peak, lighter traffic.

## **Pretimed Control Strategy**

Pretimed control, also called as the *fixed time control* assigns the right-of-way at an intersection according to a predetermined time schedules. The sequence of right-of-way assignments and the length of the time interval for each signal indication in the cycle is fixed, based on historic traffic patterns (4). No recognition is given to the current traffic demand on the intersection approaches. This type of control is well suited to intersections with predictable traffic patterns, or frequent occurrence of saturated conditions.

Pretimed controllers have fixed green splits and are generally developed with optimization algorithms using various data obtained from extensive traffic counts. This kind of traffic control may be found acceptable for intersections, arterials and networks with very minor volume variations, where the benefits of actuation do not justify the cost. In general, pretimed systems can be operated efficiently using the timing plan obtained from signal optimization software. The control objectives of optimization under this operation are to maximize the opportunities for progressive flow of traffic along the arterial, to increase the bandwidth available and to provide priority to arterial movements. Typically, such systems operate quite well when the volumes are predictable and predominant in the through direction.

## **Traffic Actuated Control Strategy**

Traffic actuated control attempts to adjust green times continuously, and in some cases, the sequence of phasing (through skipping of phases with no traffic demand). These adjustments occur according with real-time measures of traffic demand obtained from vehicle detectors placed on one or more of the approaches to

the intersection. The full range of actuated control capabilities depends on the type of equipment employed and the operational requirements.

There are four types of traffic actuated control strategies that can be implemented. They are

1. Semi-Actuated Control;
2. Full-Actuated Control;
3. Volume-Density Control; and
4. Closed-Loop System Control.

These actuated control schemes vary in the amount of detectorization and in the establishment of criteria for phase termination (5).

### **Semi-Actuated Control**

Semi-actuated control have been widely used on arterials, because they provide flexible controls for minor street traffic to reduce delays and stops. When adjacent signals are coordinated, further operational improvement can be achieved by monitoring the progressive movement of traffic.

Semi-actuated operations are governed by complex interactions between the signal controls and the arriving vehicles (6). Typically, a semi-actuated signal consists of a non-actuated phase and several actuated phases. The non-actuated phase controls the major street through traffic, while actuated phases control other movements, including major street left turns and cross street traffic. The right-of-way is always given to the non-actuated phase as long as the actuated phases do not have traffic demand. Detectors are located only on the actuated-phase approaches. The primary timing variable for the non-actuated phase is minimum green. For the actuated phases, the primary timing variables include minimum green, extension interval and maximum

green (6). When pedestrian-related phases exist, the pedestrian Walk and Don't Walk intervals also become part of the timing variables.

In semi-actuated signal operation, the non-actuated phase is given the right-of-way as long as no vehicles actuate one of the detectors. If there are vehicles actuating during the minimum green of the non-actuated phase and such actuations result in a call for service, the green interval of the non-actuated phase would be terminated at the end of the minimum green (6). Otherwise the green interval would be extended automatically until the time a vehicle actuates one of the detectors. Under coordinated control, a background cycle length is imposed on each individual signal in order to achieve green bands for the progressive movements on the major street.

Semi-actuated control can be used at intersections where a major street with relatively uniform flow is crossed by a minor street having traffic with relatively low speeds and high volume fluctuations (1). The semi-actuated control can be applied to provide effective progression through green for better arterial coordination, thus efficiently combining the advantages of pretimed and actuated controllers.

### **Full-Actuated Control**

In full-actuated control, detectors are placed on all approaches to the intersections. Fully actuated controllers are often installed at intersections with relatively equal volume splits but varying or sporadic traffic distributions (7). Each phase has separate minimum green times to provide for queue dispersing time for standing vehicles. Full-actuated control allows phase skipping, when there is no demand on that particular phase. Phases can be kept on recall to give priority depending on the traffic demands on the other phases.



## **Volume-Density Control**

Volume-density control is a refined version of actuated control and is best utilized at isolated intersections of major high-speed roadways with considerable unpredictable fluctuations. This type of traffic control requires traffic information early enough to react in time to accommodate existing conditions. This means that detectors should be installed far in advance of the intersection (7).

Volume-density control is often designed for approaches with traffic speeds of 35 mph or greater. Detectors are placed on all the approaches to the intersection. Each phase has a certain minimum green interval and signal timing settings for the required number of actuations needed to increase the initial green to the maximum initial green.

## **Closed-Loop System Control**

Closed-loop systems are being installed in many cities of the United States using modern microcomputer technology. In these systems, the operation of individual intersections is controlled, in part, by a central computer. These systems provide an opportunity for the traffic engineer to remain in the office while monitoring the traffic signal operations of the controller and detectors running at remote intersection sites. The central computer is a data base management system. Due to rapid advancements in technology, several other modern real-time control systems are available today to the traffic engineer. Some examples of these systems are SCOOT, SCATS and ATSAC systems.

## **Important Design Variables for Traffic Actuated Control**

The traffic actuated system responds to random traffic demand fluctuations through controller settings and detector configuration combinations placed on one or more approaches to the signalized intersection. Proper traffic signal parameter settings are needed for effective actuated signal operations. If implemented properly, the actuated traffic signal system can efficiently adjust green splits and cycle lengths continuously. The primary timing variable for a non-actuated phase is minimum green. For the actuated phases, the primary timing variables include minimum green, extension interval and maximum green. When pedestrian related phases exist, the pedestrian Walk and Don't Walk intervals also become part of the timing variables. Apart from these timing variables, design considerations like type and length of detectors and setback of the detectors from the intersection are extremely important for traffic actuated control. Some of these actuated timing variables are explained below.

### *Minimum Green*

There is a minimum green time allocated to each phase of the intersection during every cycle. If a call is placed on any of the approaches to the intersection, then that phase is served for at least the minimum green time allocated to it. The phase gets extended beyond its minimum green in accordance with the existing demand on that phase, until it gaps out or reaches its maximum value. A phase is skipped and is not served its minimum green time if there is no demand on that phase.

### *Vehicle Extension*

Vehicle extension, also called *passage gap* or *vehicle interval*, is the amount of time a green interval is extended beyond its minimum green interval for each vehicle actuation for a traffic-actuated phase. Typically, a vehicle extension value of roughly 2.5 to 3.5 seconds is a good operational setting for many detector configurations. Under presence control, a vehicle can demand right-of-way and hold the green by staying in the detection area. After a vehicle departs from the detection area, the green is continued for a period equal to the specified vehicle extension. If no detector actuations take place during this vehicle extension, the green could be terminated. For a given vehicle extension interval, the chance of premature termination of a green duration increases as the length of the detection area is shortened (8). Premature termination of green duration is undesirable. To prevent it or to decrease the probability of its occurrence, long detectors can be used. Another alternative to prevent the problem is to use short loop detectors in conjunction with long extension intervals. There is still a much desired need to find out what combinations of detector length and vehicle extension intervals would result in high control efficiencies.

### *Maximum Green*

Maximum green is the longest period for which a green period will be displayed in the presence of a call on an opposing phase. Every phase in an actuated controller is assigned a maximum value that can be serviced against conflicting calls. A phase in an actuated controller will reach its maximum green period if there is a continuous demand on that phase and the headway between the vehicles is less than the specified vehicle extension period. Under coordination, maximum green is seldom reached due to the existence of a force off on all the actuated phases.

## **Coordinated Actuated Signal Controller Functions**

In a pretimed controller the cycle length is fixed and does not vary from cycle to cycle. Thus, if any point within the cycle is synchronized, the entire cycle must be synchronized as well. Therefore, to synchronize a pretimed controller, one needs to worry about the synchronization process and the cycle length selection of each controller. With an actuated controller, however, the establishment of the cycle length itself is a task of considerable complexity. This is because the cycle length of an actuated controller will normally vary from cycle to cycle depending on vehicle demand. A cycle length must then be artificially imposed on an actuated controller in coordinated operation. To accomplish this, there are certain external coordination functions used such as permissive periods, holds and force-offs. These functions force the controller to operate within the constraints of a background cycle while still allowing the controller to mostly operate in the actuated mode.

One of the more common configurations for a typical dual-ring controller is as follows:

### *Coordinated Phases*

Coordinated phases are phases 2 and 6 in accordance with the NEMA configuration. These phases are called by the Call to Non-Actuated input and are usually not extendible by vehicle demand. If pedestrian indications are provided on the coordinated phase, they are always called and will be held in Green/Walk until the yield point, at which time Flashing Don't Walk (Pedestrian Clearance) begins (assuming the presence of a conflicting call). If pedestrian features are not provided, the signal will advance directly to yellow at the yield point.

### *Yield Point*

Yield point is the earliest point in time at which the coordinated phase may end to give right-of-way to one or more of the opposing phases. It is the point in time, referenced to the system "zero" point, at which the non-actuated phase will yield to subsequent phases. This is referred to as the "offset" in some coordination units. The yield point becomes the new internal zero reference for the remainder of the design parameters.

### *Permissive Period*

A permissive period is a period in which the secondary phases, or the non-coordinated phases are allowed to be serviced following the coordinated phases. A permissive period is characterized by a start and end of the period and by the release of hold on the coordinated phases. Permissive periods are implemented to service the minor street traffic even after the onset of the yield point, as long as the subsequent phases are not affected.

### *Force-off*

A force-off is a fixed point in the background cycle length used to terminate the duration of the actuated phases, regardless of the demand on that phase, assuring a green window for the coordinated phases to provide for arterial progression. Either one actuated phase or a combination of two phases could be terminated using force-off points. A force-off is used to terminate an active actuated phase that is in a permissive period. The end of one force-off point is typically the beginning of another permissive period.

## **Literature Review**

Actuated traffic control has been used since the early 1930's. The operational performance of an isolated actuated controlled intersection or a set of coordinated actuated intersections largely depend on the traffic patterns and actuated controller parameters. A well designed actuated control plan that responds appropriately to traffic demand can significantly reduce delay and fuel consumption. Therefore, shortly after actuated signal control was introduced, researchers began to study the influence of traffic arrival and departure characteristics at a signalized intersection with traffic actuated control. Many researchers also focused on optimizing the controller settings, detector placement and the relationship between them. Although more advanced forms of adaptive traffic control strategies have been introduced recently, the original concepts of traffic actuated control still play a vital role today.

## **General Operating Considerations**

The use of long-loop for detection produces a vehicle call for the duration of time that the detector is occupied by the vehicle. This is in contrast to the way small-area detectors operate where the detector gives out a pulse of 0.1 seconds when the vehicle first hits the detector. This mode of operation is called the pulse mode or point detection. Long-loop detection operates in a detection mode called the presence mode, where the detector is active as long as the loop is occupied by the detector. The long-loop presence detector with full-actuated controllers operates in a mode known as lane-occupancy control or loop-occupancy control (LOC). LOC operation occurs when the controller is programmed for an initial green interval approaching zero. Vehicle extensions are set either to zero or to a very low value. Minimum green time or non-zero initial interval is not required as the long loops continuously register the presence of any vehicles that are waiting, causing the controller to extend the

green until the entire queue is dissipated. This results in a signal operation that promptly responds to rapid changes in traffic demand.

### **Effects of Coordination Using Actuated Control**

In 1986, Jovanis and Gregor (9) studied the coordination of actuated arterial traffic signal systems. Using bandwidth maximization as a starting point, a new procedure was developed by Jovanis and Gregor that specifically accounts for actuated timing flexibility. Yield points and force offs at non-critical intersections were adjusted so that they just touched the edges of the through band while the critical intersections were unmodified. This method was applied to a data set describing midday traffic conditions on an urban arterial system of six signals in central Illinois. Simulation was used to evaluate these timing plans and compare them with corresponding pretimed alternatives. They were very surprised to find out that, in general, the pretimed coordinated control performed better than the actuated coordinated control in this experiment. They also concluded that the level of service provided on the minor street was much more important than with pretimed strategies.

In 1989, Courage and Wallace (10) developed guidelines for implementing computerized timing designs from computer programs such as PASSER II, TRANSYT-7F and AAP in arterial traffic control systems. The coordination of a group of traffic actuated signals must be some form of supervision which is synchronized to a background cycle length with splits and offsets superimposed. External and internal coordination were two general methods to perform this objective. This report focused on the external coordination of traffic signal controllers. Permissive periods were introduced. If the computed splits were longer than the minimum phase times, it might have been possible to establish a permissive period without further sacrifice or compromise on the rest of the sequence. The effect

of phase skipping due to lack of demand was also presented. The Timing Implementation Method for Actuated Coordinated Systems (TIMACS) program was developed to perform permissive period computations.

In 1994, Chang and Koothrappally (3) performed a field study to demonstrate the operational effectiveness of using coordinated, actuated control. They conducted their study in Kingsville, Texas. Their research considered different kinds of control strategies. The timings and offsets obtained from the combined PASSER-TRANSYT runs were further transformed into force-offs and yield points.

They indicated that there was an impressive operational improvement while using coordinated semi-actuated control as compared to coordinated pretimed or uncoordinated full-actuated control.

Some of their conclusions were as follows:

1. There was significant improvement, based on both delay and number of stops, observed between semi-actuated control and pretimed coordinated timing during the study.
2. There were no significant differences in performance among all the semi-actuated operations as long as the progression-based signal coordination timings were developed correctly.
3. The use of longer coordination cycle lengths generally caused less arterial stops. However, longer cycles would generate higher overall system delays.

Their study indicated that the early green return strategy sometimes used during actuated operations may create additional progression opportunities. They mentioned that the controller splits during early return could be used by applying a hold to the arterial through phase when platoons were expected to arrive. Other phases could then be forced off to provide a guaranteed green for arterial progression.



This design could also minimize long delays that were created by arterial gap-outs that frequently take place using full actuated control just before a platoon arrives for arterials that are predominantly through traffic.

### **Evaluation of Actuated Traffic Control by Simulation**

Computer simulation models have been extensively used, as an analysis tool, to evaluate the effects of alternative traffic control strategies. Simulation modeling has become an extremely important approach in analyzing complex systems. In 1984, Lin and Percy (8) investigated the interactions between queuing vehicles and detectors for actuated control, which govern the initiation, extension and termination of a green duration. They emphasized that a model used in the simulation analysis should be calibrated in terms of observed characteristics such as queue discharge headway, arrival headway, the relationship between the arrival time of a queuing vehicle and the departure of its leading vehicle, the number of queuing vehicles in a defined area at the onset of a green duration, and the dwell time of a vehicle on the detection area. They also indicated that under presence control, the chance for premature termination of a green duration increased when detector lengths were shortened. A detector length longer than 80 ft was found to efficiently eliminate premature termination. Using longer detectors, however, will result in longer dwell times and may reduce control efficiency.

Later, Lin (11) evaluated queue dissipation simulation models for analyzing presence-mode, full-actuated signal control. The queue dissipation models used in the NETSIM program and the Value Iteration Process-Actuated Signals (VIPAS) program were evaluated. He indicated that both models were capable of producing realistic departures of queuing from the detector area. The models were rather weak, however, in representing other aspects of vehicle-detector interactions. A major

weakness of the model in NETSIM was that the simulated movements of queuing vehicles have little to do with the discharge times generated from a probability distribution. The weakness of VIPAS was that the car-following model used in VIPAS did not provide a flexible model structure for calibration. Therefore, the outputs of the model could not be made to conform easily with observed departure, arrival and dwell characteristics of queuing vehicles.

### **Delay Models for Actuated Traffic Control**

The evaluation of the performance of signalized intersections for signal timing and geometric design improvements is an important undertaking in traffic engineering. In 1988, Akcelik (12) evaluated the 1985 HCM delay formula for signalized intersections. He stated that the HCM formula predicted higher delays for oversaturated conditions than what is realistic. An alternative equation to the HCM formula was proposed. This formula gave values close to the HCM formula for degrees of saturation less than 1.0 and at the same time, was similar to the Australian, Canadian and TRANSYT formulas in producing a delay curve asymptotic to the deterministic delay line for a degree of saturation greater than 1.0.

The signalized intersection methodology presented in the 1985 HCM introduced a new delay model. Lin (13) evaluated the delay estimated by the HCM with field observed delay in 1989. Some inconsistency existed in the delay values between the HCM results and field observations. He suggested improving the progression adjustment in the HCM procedure and using a reliable method to estimate average cycle lengths and green durations for traffic-actuated signal operations.

A delay model was recommended in the HCM for level-of-service analysis at signalized intersections. The use of this model for the evaluation of traffic-actuated signal operations required the knowledge of the average cycle lengths and green intervals associated with the signal operation being analyzed. Lin (6) proposed an improved method for estimating average cycle lengths and green durations in 1990. The method was limited to semi-actuated signal operations. Lin stated that the method, which was developed through analytical modeling and computer simulation, was sufficiently simple and reliable. Realistic examples were used to illustrate the application of this method.

In 1994, Li, Roupail and Akcelik (5) developed an analytical delay model for traffic under basic actuated signal control using a fixed unit extension (gap time) setting and passage detection. They reviewed the HCM methodology with regard to the operational analysis of this type of control. They concluded that the quantification of the effect of actuated control on overflow delay, given that random queues can be better absorbed in an actuated system by virtue of the phase extension feature, was yet to be done. They used a macroscopic, stochastic simulation model developed in earlier work for the study of capacity and delays for basic two phase fully actuated operation.

### **Estimation of Green Times and Cycle Length for Actuated Traffic Control**

Estimation of average green times and cycle lengths at vehicle-actuated signals is essential for the prediction of the performance characteristics such as capacity, degree of saturation, delay, queue length and stop rates. For actuated control, green splits and cycle length fluctuate with respect to the traffic demand. In 1982, Lin (14) developed a model to estimate the average phase duration for full-actuated signals. The model was primarily developed on the basis of probabilistic interactions between

traffic flows and the signal control. He assumed that the arrival at the upstream end of an intersection is random, so the arrival pattern in each lane was represented by a Poisson distribution.

In 1994, Akcelik (15) proposed an analytical methodology for the estimation of green times and cycle time for vehicle-actuated signals. The examination in this paper was limited to the operation of a basic actuated controller that uses passage detectors and a fixed gap time setting. Both fully actuated and semi-actuated control cases were discussed. A discussion of the arrival headway distributions was presented since the estimation of arrival headways is fundamental to the modeling of actuated signal timings. Formulas were derived to estimate the green times and cycle time based on the bunched exponential distribution of arrival headways. The procedure given in this paper provides essential information for predicting the performance characteristics of intersections controlled by actuated signals and for investigating the optimization of actuated controller settings. The methodology presented in this paper still needs to be validated using real-time traffic data and simulation study results.

### **Traffic Engineering Models**

A number of algorithms and computer models have been developed to aid the traffic engineer in evaluating and designing signal timing plans. The following three computer programs are available for analyzing coordinated and actuated operations.

#### **PASSER II 90**

PASSER II 90 is a macroscopic traffic signal timing optimization and simulation model. PASSER II 90 can be used to assist transportation professionals to analyze (16):

1. Isolated intersection timing evaluations;
2. Arterial progression signal timing optimization; and
3. "Existing" timing evaluations.

PASSER II 90 was developed by Texas Transportation Institute. PASSER II 90 can simulate and optimize arterial signal timing operations under pretimed control. PASSER II has the capability to optimize cycle lengths, phase sequences, green splits and offsets. PASSER II-90 does not account for the variability that occurs in traffic flow and the analyses are based on macroscopic modelling rather than on individual vehicle's interactions. PASSER II 90 does not have the features necessary to optimize or simulate the arterial operation under actuated control. It inputs the information on whether a signal is pretimed or actuated to adjust the delay estimation. Features of PASSER II-90 include an assistant key that calculates saturation flow rates based on the HCM methodology and it has the capability to model permitted left turns. PASSER II 90 uses bandwidth maximization as the primary optimization objective and calculates the delay of vehicles traveling on the arterial. The system offset can be referenced to a particular movement on the arterial street *in contrary to the common belief* that it can only be referenced to the first movement of the phase sequence. The user also has the option to input the master intersection. PASSER II 90 provides a wide range of output to aid the traffic engineer in his/her analysis. Some of them include average intersection delay, total system delay, stops, queues,  $v/c$  ratios, arterial progression evaluation criteria etc.

#### TRANSYT - 7F

Dennis Robertson of the Transport and Road Research Laboratory in England developed the Traffic Network Study Tool (17). Version 7 was modified to reflect

North American nomenclature by the University of Florida for the Federal Highway Administration.

TRANSYT - 7F is a macroscopic traffic signal timing simulation and optimization model. The existing version of TRANSYT can simulate and optimize intersections, arterials and networks. The optimization technique involves minimizing systemwide delays and stops. It identifies the optimal offsets, cycle length and phase splits through the minimization of a performance index (PI) - a linear combination of stops and delays (18). Data is input into TRANSYT-7F as to whether a signal is actuated or pretimed. However, this information is used only to adjust the degree of saturation of relative movements. Similar to PASSER II-90, TRANSYT-7F models traffic on a macroscopic approach rather than on individual vehicle interactions. The primary difference between TRANSYT-7F and PASSER II-90 is that PASSER II-90 provides better performance on arterials, while TRANSYT-7F tries to improve the entire network without favoring any particular direction. The outputs produced by TRANSYT-7F include total volumes, saturation flow rates, delays, average travel time, uniform stops, queue measurements and effective green time for each link. TRANSYT-7F also produces overall systemwide MOEs.

#### TRAF-NETSIM

TRAF-NETSIM was originally developed in the early 1970's and since then the Federal Highway Administration (FHWA) has made several improvements to it. TRAF-NETSIM is a stochastic, microscopic simulation model. It is capable of simulating isolated intersections, diamond interchanges, arterial streets and networks (19). TRAF-NETSIM has the capability to simulate pretimed and actuated control. Since TRAF-NETSIM is microscopic, a wide range of variables such as geometric characteristics and signal control can be used as input for simulation. A wide range of

actuated control features can be input into this model. Variables such as detector setback, passage gap, minimum green, maximum green, etc., can be used as input for actuated control. TRAF-NETSIM is a versatile simulation tool which has the capability to simulate arterial coordination using actuated control. Features such as permissive periods, force-offs and yield points can be used as inputs in simulating arterial coordination using actuated control.

TRAF-NETSIM offers several advantages over the previous simulation models, including the ability to graphically animate the system to check the configuration of the network and the effectiveness of the control strategy, and the ability to manipulate embedded data to represent observed field data. Outputs from the TRAF-NETSIM simulation model include a variety of measures of effectiveness (MOEs). They can be classified as aggregated and disaggregated variables. Very detailed outputs for every link in a network are produced which include average speed, number of stops, average delay per vehicle, travel time, number of vehicles in queue and number of lane changes executed during the simulation. TRAF-NETSIM also produces a simulation clock time as part of the actuated control output which will enable the calculation of the average green splits per cycle during the simulation.

Thus, it can be seen that TRAF-NETSIM is a very powerful tool to simulate and analyze different signal control strategies using actuated control. Hence, TRAF-NETSIM was selected as the controller and data collector for this study.

## CHAPTER III

### STUDY METHODOLOGY

#### Introduction

The main objectives of this research were twofold. The first objective was to investigate the effects of phase green split variation on the performance of an arterial system. The second objective was to develop strategies to improve the performance of the arterial using coordinated actuated concepts based on the above results. This chapter documents the methodology adopted in attaining these objectives. The study methodology has been divided into different stages. The following sections describe these stages.

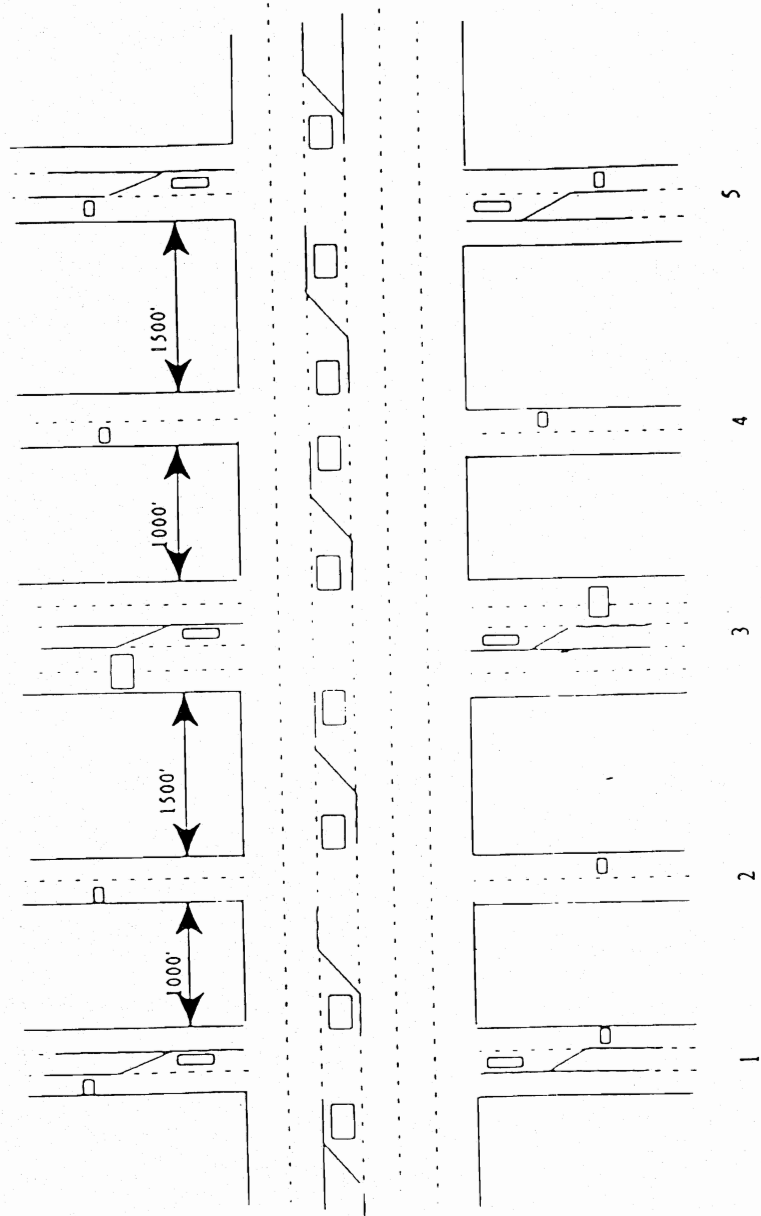
#### Stage 1: Development of an Experimental Testbed

An experimental testbed was set up for conducting a thorough testing and evaluation of traffic actuated signal control used on arterials. Representative traffic control problems were modeled into the statistical testbed using the latest microscopic traffic simulation program available, currently TRAF-NETSIM. TRAF-NETSIM Beta version 5.0 has the capability to effectively model coordinated arterial operations using actuated control. This capability is essential to develop strategies for efficient coordinated operations using actuated control. TRAF-NETSIM Beta version 5.0 was therefore used as the *controller, data collector and evaluator* in this research.

#### *Description of the Testbed*

The testbed shown in Figure 2 is representative of a typical arterial in Kingsville, Texas (3). The second half of the testbed is a mirror image of the first half.





**Figure 2 Schematic Representation of the Experimental Testbed.**

The testbed has five intersections with spacings of 1000 ft and 1500 ft between intersections 1 & 2, 3 & 4 and 2 & 3, 4 & 5, respectively. Intersections 1 & 5, 2 & 4, are similar in geometry. Intersection 1 has two lanes and left turn bay on the major street and one lane and a left turn bay on the minor street. Intersection 2 has two lanes and a left turn bay on the major street and one lane on the minor street. Intersection 3 has similar geometry on the major street as well as on the minor street. It has two lanes and a left turn bay on both the major street and the minor street.

Coordinated semi-actuated control was used for all the intersections, in the testbed. This decision was based on earlier research findings noted in the literature survey. Also, it has been proven time and again that the semi-actuated detection is the best form of signal control when coordination is desired. All the phases except the coordinated phases (NEMA movements 2 and 6 ) were actuated in a semi-actuated signal control mode.

The location of the detectors is also shown in Figure 2. Approach speeds of 38 mph were used as input for all the intersections. Since the approach speeds were less than 40 mph, typically a single detector is sufficient for vehicle actuation and multi-point detection system will not be required. As is usually the practice, detectors were located at the stop line for the left turn approaches. A 40 x 6 loop was used for all the left turn approaches and these were kept on presence mode. For the through approaches 6 x 6 loops were used. On the minor street, detectors were located at 200 ft from the stop line. The left turn bays were 250 ft long. This geometric configuration and detector placement would avoid any false calls when a left turning vehicle makes a maneuver into the left turn bay.

## **Stage 2: Generation of a Pretimed Optimized Coordinated Timing Plan from PASSER II-90**

PASSER II-90 version 2.0 was used to provide an optimized pretimed coordination timing plan as it was deemed to give reliable and efficient pretimed coordinated timing plans. It is widely utilized by traffic engineers nationwide for this purpose.

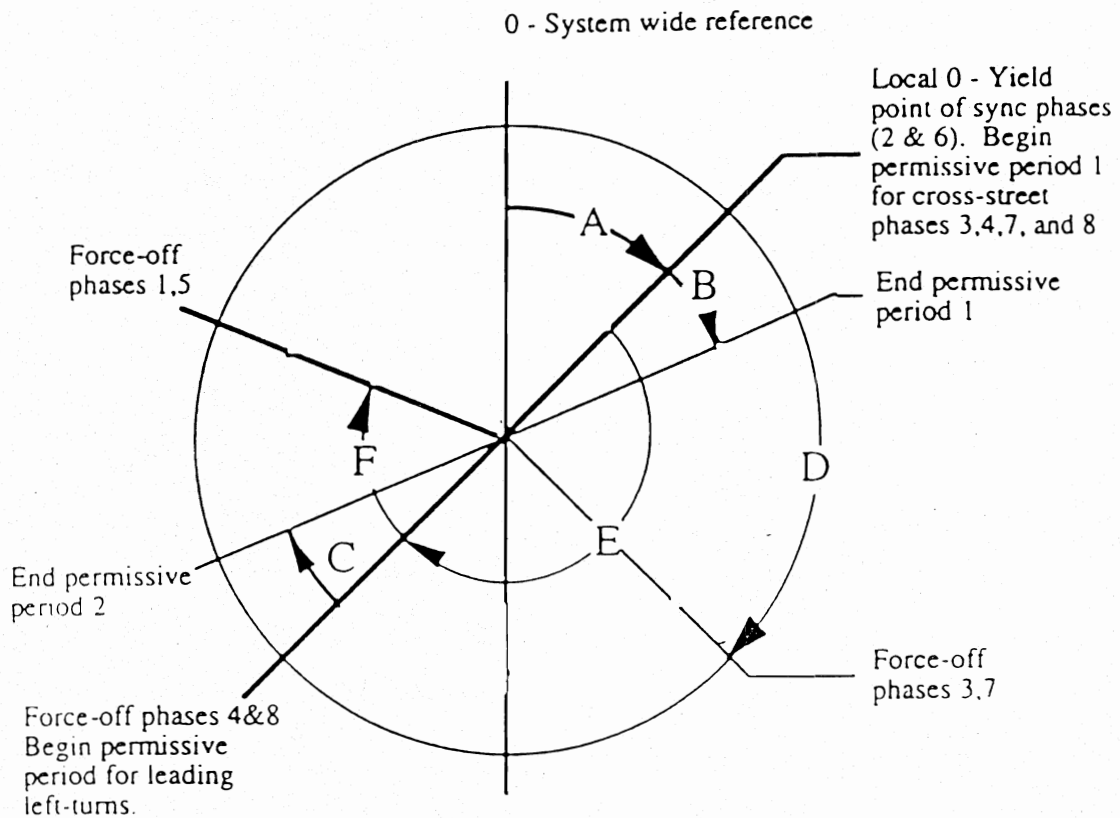
### *Input Parameters and Signal Control*

It was determined from the various PASSER II-90 runs that a cycle length of 90 seconds was optimal for the experimental testbed under the existing conditions. Dual lefts leading was used on the arterial street for all the intersections. Split phasing was used for the minor street at intersections 2 and 4 as the minor street had just one lane for all the movements. Saturation flow rates of 1800 vphgpl were used for all the runs. To begin the proposed study, the network of five intersections was loaded with traffic volumes producing v/c ratios of 0.8 on the main street and 0.8 on the cross street. These volumes entering the experimental testbed were based on a cycle length of 90 seconds, saturation flow rates of 1800 vphgpl, v/c ratio of 0.8, and phase green split ratio of 55:45 on the major street and the minor street, respectively. Default 2 in PASSER II-90 was used for offsetting the beginning of the green to various intersections. Intersection 1 was used as the master intersection and the beginning of the green of NEMA movement 2 at other intersections was referenced to the beginning of the green of NEMA movement 2 at intersection one. The offsets and the phase timings were optimized for the network at the existing volume conditions. Thus, a pretimed optimized coordinated timing plan was generated from PASSER II-90.

### **Stage 3: Transforming the Pretimed Coordinated Timing Plan into an Actuated Timing Plan in TRAF-NETSIM**

Since this research did not have the luxury of field data, the input values were carefully selected based on past research and findings. An input file for TRAF-NETSIM can be put together using an editor such as Edlin on a computer's DOS applications. Input data is either link or node data entered on certain record types. Every aspect of a road network is divided into different record types for the ease of coding the entire network to suit the user's requirements. The data that had to be input into TRAF-NETSIM was vast and included coding the simulation time period, geometric conditions, vehicle paths, entry and exit volumes, pretimed signal control, and actuated signal control apart from many other simulation details. In coding the actuated control data, the user had to input several record types pertaining to approach configuration, detector configuration, detector placements, coordination data, and phase operations for actuated controller. Once an input file is coded, changes could be easily made to the input parameters. The input file could then be renamed and used in TRAF-NETSIM simulation. This feature makes TRAF-NETSIM easy and efficient to use as a research tool where hundreds or thousands of simulation runs may be conducted.

Since TRAF-NETSIM requires the input as either link or node data, a link-node configuration that represents the experimental arterial testbed was used as shown in Figure 2. The green timings and offsets obtained from PASSER II-90 runs were further transformed into yield points and force-offs. Figure 3 shows the phase parameters for a sample 8-phase coordinated actuated controller in TRAF-NETSIM.



- A = Signal offset.
- B = Duration of cross-street permissive period. Sync phase (2 & 6) will yield to calls from phase 3,4,7, & 8 during this period.
- C = Duration of permissive period for leading left-turn phases (1 & 5).
- D = Elapsed time from yield point to the time that phases 3 & 7 must terminate regardless of traffic.
- E = Elapsed time from yield point to the time that phases 4 & 8 must terminate regardless of traffic
- F = Elapsed time from leading left-turn permissive period begin time to the time that phases 1 & 5 must terminate, regardless of traffic.

**Figure 3 Phase Parameters for a Sample 8-phase Coordinated Actuated Controller in TRAF-NETSIM.**

The optimal green splits obtained from PASSER II-90 were set to be the force-offs in TRAF-NETSIM. Yield point values were based on the end of arterial green from the pretimed offset as the start of the yellow interval for the actuated

phases. A type 44 record must be introduced when actuated coordination is present in the TRAF-NETSIM subnetwork. In the coordination mode, NEMA phases 2 and 6 are coordinating phases (also called the sync phases), i.e., they are the phases that yield during the permissive periods to allow a conflicting phase to be served if there is a vehicle demand. The sync phases always exist and are forced off whenever a call occurs on a conflicting phase which is in a permissive period. Thus, in the absence of a call, the controller will rest in main street green, phases 2 and 6. The offset time for coordination is defined by the sync phases. When the offset point is reached, the sync phases are allowed to yield, if in a permissive period. After sync phase termination, the other phases are allowed to serve in their normal sequence (28). The non-sync phases can terminate by gapout, maxout or by force-off, whichever occurs first. Three permissive periods have been defined in this study, where the sync phases can yield to the other defined phases. Minimum phase durations of 10 seconds and 15 seconds were used for the left turns and through movement, respectively, for all the intersections. Either maximum phase durations of 1.5 times the pretimed optimal split or a maximum of 40 and 60 seconds were used for the left turn and through movement, respectively. Vehicle extensions of 1.5 seconds and 2.4 seconds were used for the lefts turns and throughs, respectively. The maximum green times and vehicle extension times were input based on the previous research done in this area. These input values were believed to be typical values for an actuated controlled intersection.

#### **Stage 4: Calibration of PASSER II-90 and TRAF-NETSIM**

It was important to calibrate both of these models before embarking on any further study. Whereas PASSER II-90 is a deterministic, macroscopic model, TRAF-NETSIM is a stochastic and microscopic model. Vehicle paths can be clearly defined in TRAF-NETSIM to suit the user's requirements. Once both of these models are well calibrated, study scenarios can be developed and a variety of conditions can be

studied with reasonable accuracy. Calibration is a process where certain parameters are adjusted or varied so that there is a reasonable proximity between the results of the two models. PASSER II-90 and TRAF-NETSIM were visually calibrated using the graphics animation feature of TRAF-NETSIM. The time-space diagrams obtained from PASSER II-90 were drawn on a big sheet. The arrivals and departures of platoons at each of the intersections were closely monitored in TRAF-NETSIM and compared with those of PASSER II-90. The offsets and green splits were fine tuned in PASSER II-90 such that there was a reasonable similarity in arrival and departure patterns of both these models. Once it was determined that both these models were well calibrated to one another, various study scenarios were developed for further investigation which are discussed in the next stage.

#### **Stage 5: Development of Study Scenarios**

The primary objective of this study was to develop strategies and to verify these strategies over a wide range of volume conditions. Also, in order to obtain data that could be analyzed, the study on arterial coordination using actuated control was divided into several scenarios. To realize this goal, different study scenarios were developed as shown in Table 1. For all these scenarios, the arterial testbed was first coded into PASSER II-90, as discussed under Stage 2, and then optimized pretimed coordinated timing plans were obtained for these runs. These pretimed optimized timing plans were transformed into *coordinated actuated* input files for TRAF-NETSIM as discussed in Stage 3. The effects of varying the green splits for the coordinated phases (NEMA movements 2 and 6), keeping the cycle length constant, was studied extensively for these different volume conditions. This was primarily done to explore the possibility of a more optimal allocation of the arterial green splits.

**Table 1. Study Scenarios.**

Scenario	V/C Ratios	
	Main Street	Cross Street
1	0.8	0.8
2	0.8	0.5
3	0.8	0.2
4	0.5	0.8
5	0.5	0.5
6	0.5	0.2
<b>Green Split Adjustments</b>		
	-30%	
	-20%	
	-10%	
	0%	
	10%	
	20%	
	30%	

The effects of varying the green splits under different volume conditions might lead to some interesting findings about the allocation of green splits under *coordinated actuated control*. The *v/c* ratios were varied from 0.5 to 0.8 on the main street and from 0.2 to 0.8 on the cross streets. Different combinations of the *v/c* ratios were studied as shown in Table 1. For each of these scenarios, the green splits of the coordinated phases were varied, ranging from -30% to +30% (as shown in Table 1), in increments of 10% from the optimized green splits given by PASSER II-90, keeping the cycle length constant. The simulated timing plan for each of these cases from PASSER II-90 was transformed into an input file for TRAF-NETSIM. The purpose of doing this was to scrutinize the performance of the network and identify any key points when either more green time or less green time was given to the arterial



coordinated phases. In order to account for the stochastic nature of the TRAF-NETSIM output, 10 runs were executed for each individual case simulated, by varying the random number seed. Each scenario produced distinct differences in the output, and the results are presented in the next chapter.

Some of the measures of effectiveness collected include average phase durations, link/node delays and system delays. TRAF-NETSIM produces an enormous amount of output for actuated signal control. It produces a simulation clock in binary mode, which gives information regarding the actuated signal operation second by second. Processing this output manually becomes very tedious and laborious as the number of cases simulated is vast. Valuable assistance was sought from Dr. Ken Courage and Mr. Pei Sung-Lin of the University of Florida, in processing this output. They had developed a software called RANGER which went into the TRAF-NETSIM output file containing all this actuated signal control data and processed the data in a way which can be easily understood and readily used for all the analyses. Similarly, another FORTRAN program was coded, which will search through the TRAF-NETSIM output file for certain user-specified outputs and write them to a new file. The files created by the FORTRAN program were then loaded into a MS-Excel spreadsheet such that the data could be plotted and tabulated for analyses and comparison.

#### **Stage 6: Development of Strategies for Coordinated Actuated Signal Control**

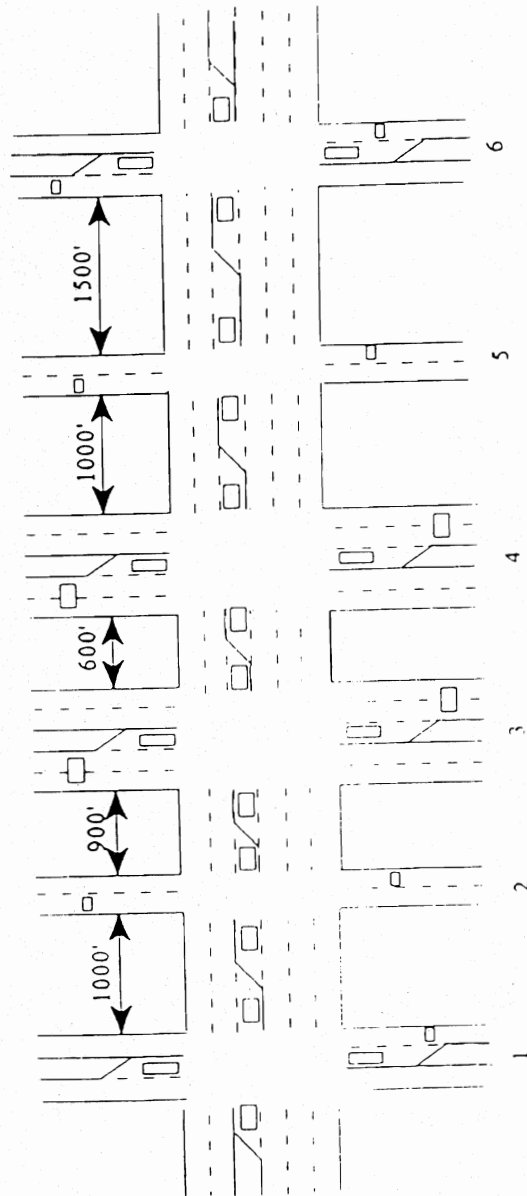
Once simulation was completed, the various files generated by the FORTRAN program were analyzed for any obvious and striking trends. Later, detailed analyses of these cases were conducted to observe any hidden trends. Since there were multiple runs of each case, certain values like the link/node delays at every intersection had to be averaged for these multiple runs pertaining to a case. Several plots were drawn to

analyze the enormous amount of data. Various trends were observed and the critical details were carefully noted. This led to the formulation of certain strategies and in verification of certain other actuated control concepts. At this stage, these findings had to be verified for their plausibility and statistical accuracy. Regression analysis and t-tests were conducted to determine if there were statistical differences among the several cases studied. These trends and results are discussed in the next chapter.

### **Stage 7: Modification of the Existing Testbed and Verification of the Signal Control Strategies**

The different study scenarios were then simulated in TRAF-NETSIM PRETIMED control. This was done to ascertain that the differences in results between PASSER II-90 and TRAF-NETSIM COORDINATED ACTUATED control existed due to the control strategy and not due to the modeling differences. A similar procedure, as explained above, was adopted in arriving at some of the results.

The next objective was to expand these results to other geometric configurations and not specifically to this arterial testbed. A larger arterial testbed having six intersections was developed from the original one, as shown in Figure 4. An intersection was inserted between intersections two and three making the testbed more variable. This new intersection has the same geometric configuration and signal control parameters as intersection three in the original network. Steps 2 through 6 were repeated for the modified network and conclusions were drawn on the basis of comparisons of the new network with the original network.



**Figure 4 Modified Arterial Testbed.**

## **Stage 8: Conclusions and Recommendations**

At this stage of the research, certain concrete conclusions and recommendations could be drawn using the above results. The strategies developed using the original network were applied to the new network. The results obtained were similar in both cases. Thus, it could be concluded that the results are more generic and are not specific to any geometric configuration. Certain alternatives were identified to improve the arterial signal coordination using actuated control. The conclusions and recommendations are presented in Chapter 5. Further avenues for future research in this area have also been recommended.

## CHAPTER IV

### STUDY RESULTS AND DISCUSSION

#### Introduction

This chapter documents the findings from the simulations of the experimental arterial testbed using PASSER II-90 and TRAF-NETSIM. This chapter has been divided into two major sections. The first section presents the results from the simulation of the original testbed and the modified testbed using PASSER II-90, TRAF-NETSIM for pretimed control, and TRAF-NETSIM for actuated control. The second section presents the results from different statistical analyses conducted on the simulation results.

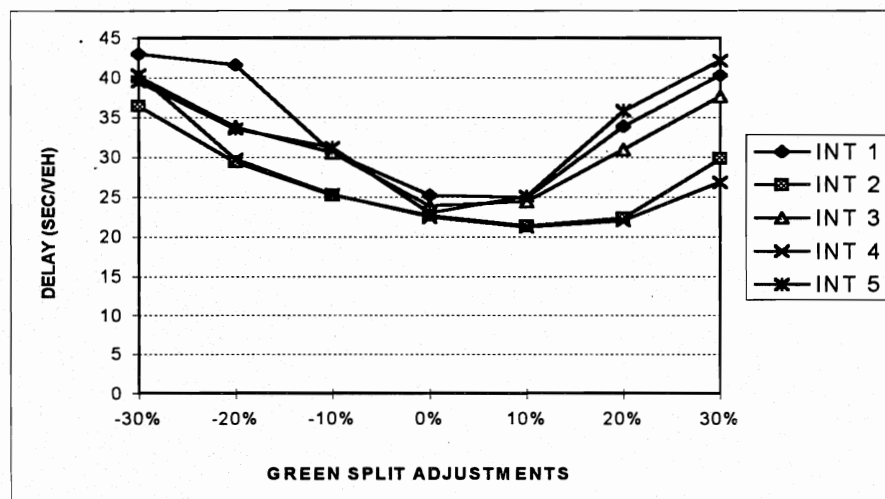
#### Traffic Delay

The next section presents the analysis of simulation outputs from PASSER II-90 and TRAF-NETSIM performed on the original five intersection testbed shown in Figure 2. Level of service for signalized intersections is defined in terms of *delay*. Delay is a measure of driver discomfort, frustration, fuel consumption, and lost travel time to motorists (20). Delay is a complex measure, and is dependent on a number of variables, including the quality of progression, the cycle length, the green ratio, and the v/c ratio for the lane group or approach in question. The link delays generated in the TRAF-NETSIM output were converted into intersection delays by taking a volume weighted average of link delays of all the approaches.

## Scenario 1 Outputs

Intersection delays calculated for the different green split adjustments for pretimed control as well as actuated control were plotted as shown in the following figures. Scenario 1 represented volume conditions where the  $v/c$  ratio for the major street and the minor street was 0.8. For this volume condition, the original testbed was first optimized in PASSER II-90, which represented the 0% green split adjustment. Later, the testbed was simulated in PASSER II-90 for the various green split adjustments. These timings plans obtained from PASSER II-90 were then transformed into a coordinated actuated timing plan, to be input into TRAF-NETSIM.

Figure 5 shows the delay results as simulated and evaluated by PASSER II-90 for the various green split adjustments for the five intersections.

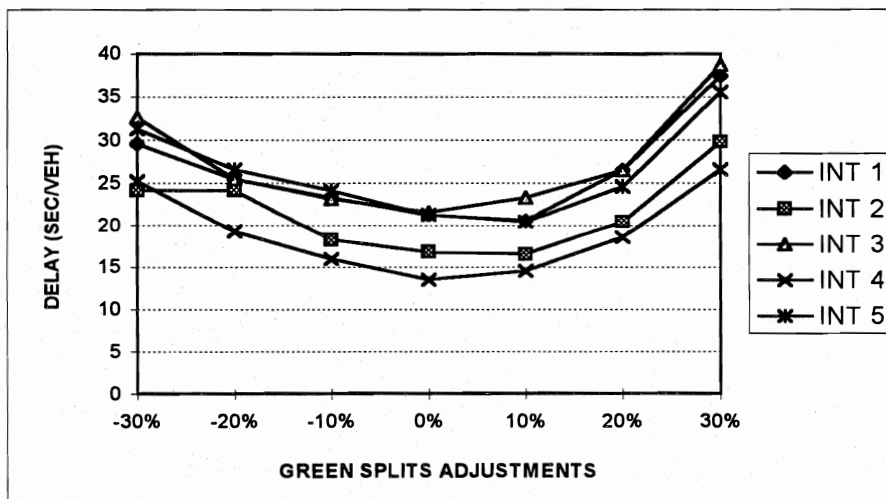


**Figure 5 Average Intersection Delays for the Original Testbed Simulated in PASSER II-90 for V/C Ratios of  $M=0.8$ ,  $C=0.8$ .**

The X-axis represents the various green split adjustments and the Y-axis represents average intersection delays calculated by PASSER II-90. The green split adjustments are made keeping the cycle length constant. An adjustment of 10%

implies that the coordinated phases receive 10% more green time than the optimized splits, while an adjustment of -10% implies that the coordinated phases receive 10% less green time than the optimized splits. The five delay curves in the figure represent the five intersections in the testbed. Examination of Figure 5 reveals that the average intersection delays had a tendency to increase as the green splits were varied from PASSER II-90's optimal green splits. This is reasonable as the 0% adjustment is the optimized timing plan, while the other adjustments are simulated to explore the possibilities of a more optimal allocation of the green splits. When the green splits are shifted from the optimal timing plan, the smooth flow of traffic on the arterial is disrupted and the progression efficiency goes down.

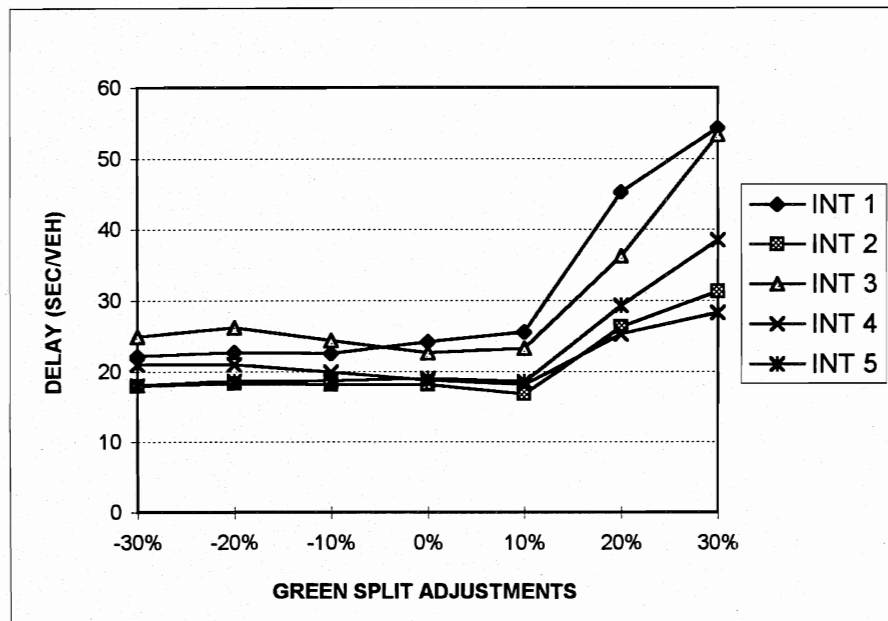
The plot of average intersection delay values versus green split adjustments as simulated in TRAF-NETSIM for pretimed control is shown in Figure 6. This was primarily done to determine and assess whether any differences between PASSER II-90 and NETSIM for coordinated actuated control existed due to the control strategy or due to modeling differences.



**Figure 6 Average Intersection Delays for the Original Testbed Simulated in NETSIM for Pretimed Control for V/C Ratios of M=0.8, C=0.8.**

Examination of Figure 6 reveals a *similar trend* as noted in Figure 5. Any deviation from the optimum green splits resulted in extra delays. An important observation from this research was the closeness in the simulation results between PASSER II-90 and NETSIM for pretimed control. This result ascertains the finding that there exist no modeling differences.

The results from the simulation of the arterial testbed using NETSIM's coordinated actuated signal operation is shown in Figure 7.



**Figure 7 Average Intersection Delays for the Original Testbed Simulated in NETSIM for Actuated Control for V/C Ratios of M=0.8, C=0.8.**

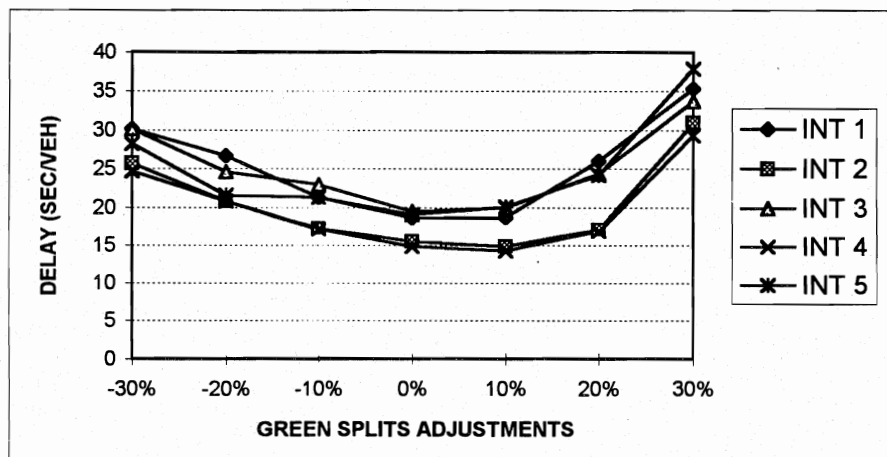
The most important finding of this research was that, though there was a reduction in the green time allocated to the major street (phases 2 and 6), there was no increase in average intersection delay. But, an increase in average intersection delay was observed when green time allocated to the major street was increased beyond the 0% setting. This observation was particularly noticeable for high v/c ratios. This is because any extra green time given to the minor street was always going back to the



major street when there is not enough demand; whereas, any extra time given to the major street was never coming back to the minor street when the minor street needed more green time, as the major approach was not actuated (30). The variations in the simulation results between NETSIM for coordinated actuated control and PASSER II-90 could be attributed to the control strategy employed and *not* to the modeling differences.

### Scenario 2 Outputs

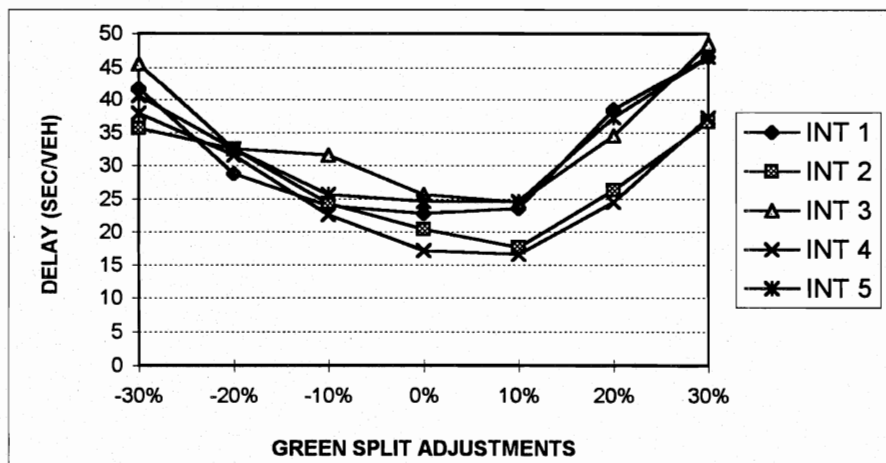
Scenario 2 represented volume conditions where the  $v/c$  ratio of the major street was 0.8 and that of the minor street was 0.5. This scenario represents lower volumes on the minor street than scenario 1. Similar sets of plots were drawn as described in scenario 1. Figure 8 shows the delay results as simulated in PASSER II-90 for the various green split adjustments. Similar trends in the delay values can be observed.



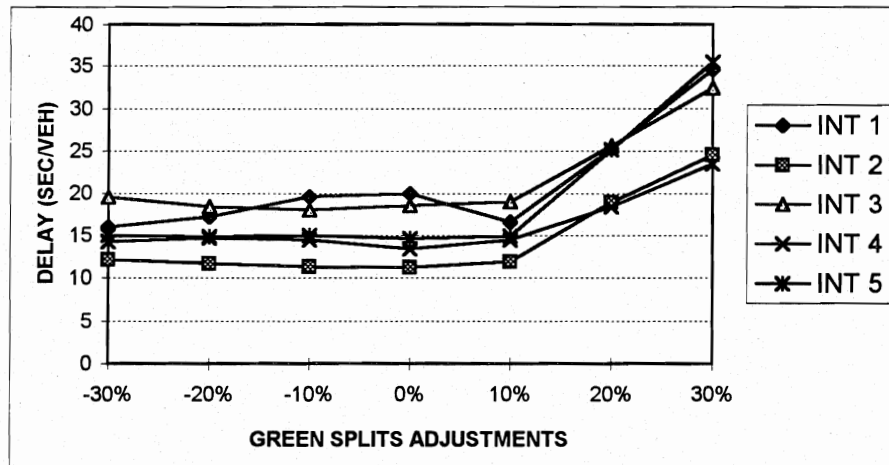
**Figure 8 Average Intersection Delays for the Original Testbed Simulated in PASSER II-90 for V/C Ratios of  $M=0.8$ ,  $C=0.5$ .**

As expected, there is a marginal reduction in the overall delay values because of the lower volumes on the minor street. The average intersection delay increases only marginally when the green splits on the arterial through phases are adjusted by either 10% or 20%. However, a sharp rise is noticed when the green splits are adjusted by 30% on the arterial through phase.

The plot shown in Figure 9 has the average intersection delay values against green split adjustments as simulated in TRAF-NETSIM for pretimed control. Similar trends are observed as explained in scenario 1. Figure 10 shows the plot of average intersection delay values versus green split adjustments as simulated in TRAF-NETSIM for actuated control. Comparable trends can be observed as explained in scenario 1. The average intersection delays remain more or less the same as for the optimal case when less green time is allocated to the major street. This is because any extra green time given to the minor street was always coming back to the major street when there is not enough demand; whereas, any extra time given to the major street was never coming back to the minor street when the minor street needed more green time, as the major approach was not actuated.



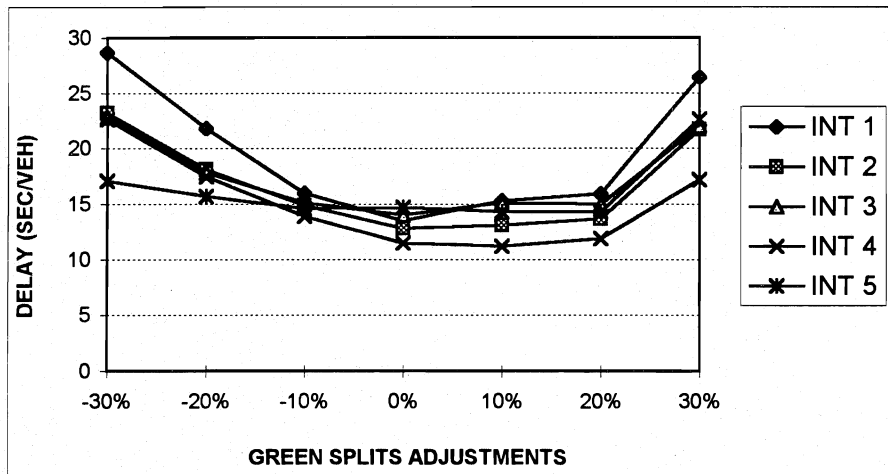
**Figure 9 Average Intersection Delays for the Original Testbed Simulated in NETSIM for Pretimed Control for V/C Ratios of M=0.8, C=0.5.**



**Figure 10 Average Intersection Delays for the Original Testbed Simulated in NETSIM for Actuated Control for V/C Ratios of M=0.8, C=0.5.**

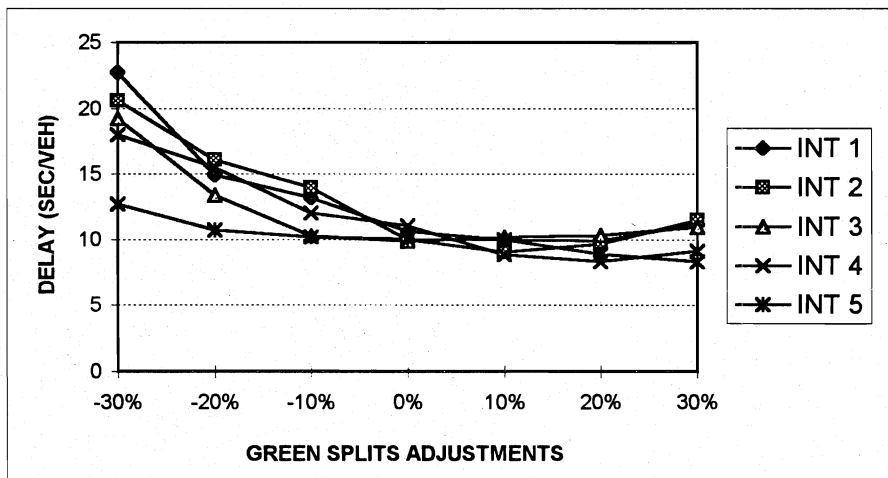
### Scenario 3 Outputs

Scenario 3 represented volume conditions where the  $v/c$  ratio of the major street was 0.8 and the  $v/c$  of the minor street was 0.2. This scenario represents very low volumes on the minor street. Similar sets of plots were drawn as described in previous scenarios. Figure 11 shows the delay results as simulated in PASSER II-90 for the various green split adjustments. The trend is not very significant as observed in the previous cases because of the low minor street volumes. The average intersection delay values remain constant within an adjustment of -10% to 20% of the arterial through phase green splits. But, a sharp increase is noticed beyond the above mentioned range. PASSER II-90 views this range as a flexible range where any adjustments made to the optimized timing plan should not hamper the efficient operation of the network.



**Figure 11 Average Intersection Delays for the Original Testbed Simulated in PASSER II-90 for V/C Ratios of M=0.8, C=0.2.**

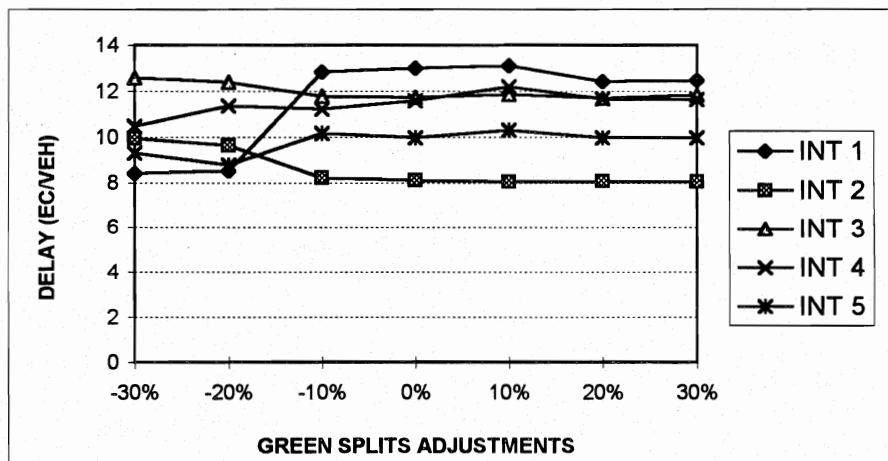
The relationship between average intersection delay values and green split adjustments as simulated in TRAF-NETSIM, for pretimed control and for the light traffic condition is shown in Figure 12.



**Figure 12 Average Intersection Delays for the Original Testbed Simulated in NETSIM for Pretimed Control for V/C Ratios of M=0.8, C=0.2.**

The trend seen here is different from the previous findings. The average intersection delays remain the same as long as more green time is given to the arterial through phase because of low volumes on the minor street. When the arterial through phase is given less green time than the optimized green time, the delays increase due to wasted green time on the minor street.

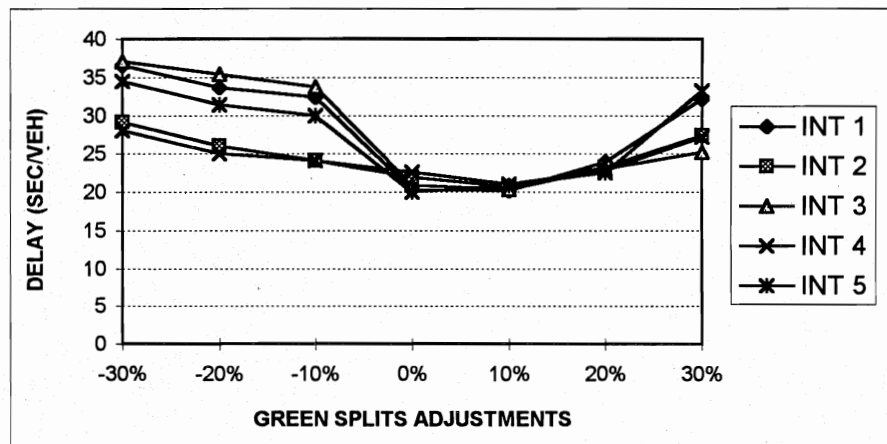
The following plot shown in Figure 13, is the plot of average intersection delay values versus green split adjustments as simulated in TRAF-NETSIM for actuated control. The plot shows that almost all of the green split variations performed similarly. This is reasonable to believe. Since the minor street has very low volumes, minimum green time given to it would suffice; whereas, if less green time were to be given to the arterial through phase, the extra green time would come back to it due to lack of demand on the minor street. Under such flexible and low volume conditions, the actuated control can perform efficiently as it is designed to respond to random traffic flow.



**Figure 13 Average Intersection Delays for the Original Testbed Simulated in NETSIM for Actuated Control for V/C Ratios of M=0.8, C=0.2.**

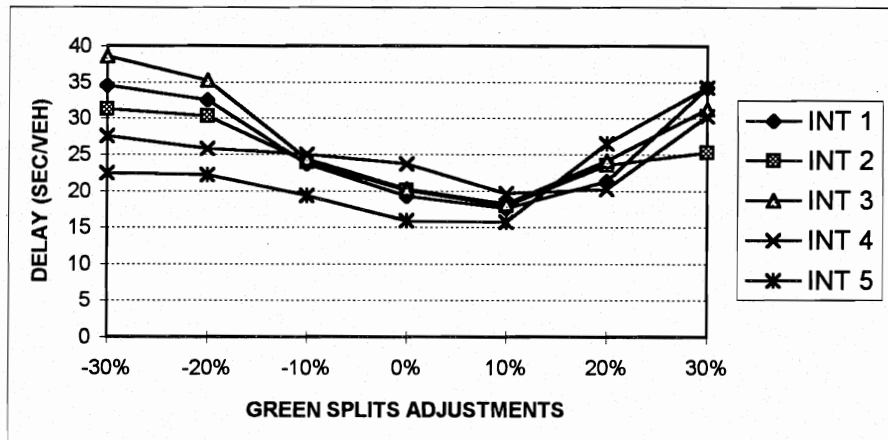
## Scenario 4 Outputs

Scenario 4 represented volume conditions where the  $v/c$  ratio of the major street was 0.5 and the  $v/c$  of the minor street was 0.8. This is an unusual case because the minor street volumes are seldom higher than the major street volumes. This case was taken into consideration to verify how the arterial behaves under such unusual circumstances. Figure 14 presents the results of the arterial testbed as simulated in PASSER II-90. As was observed in the previous case, the average intersection delays remained constant within a range from -10% to 20%. It is interesting to observe a similar trend in the results.



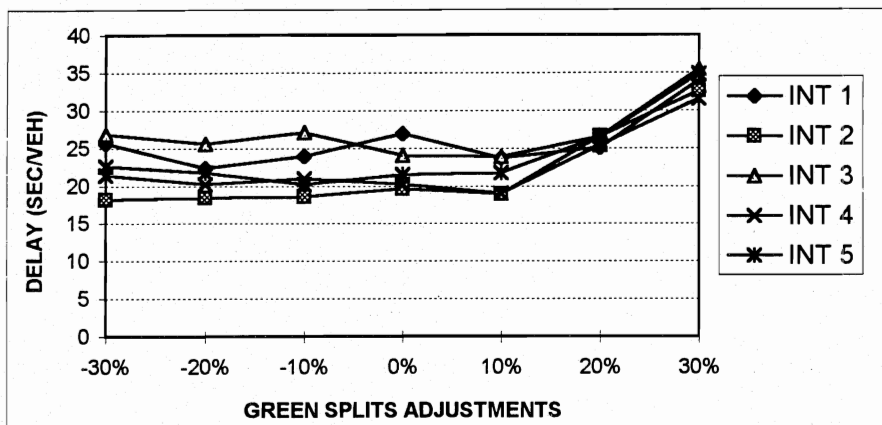
**Figure 14 Average Intersection Delays for the Original Testbed Simulated in PASSER II-90 for V/C Ratios of M=0.5, C=0.8.**

The plot of average intersection delay values versus green split adjustments as simulated in TRAF-NETSIM for pretimed control is shown in Figure 15. Examining this figure, the important observation that can be made is the closeness of the results between PASSER II-90 and TRAF-NETSIM for pretimed control. The average intersection delays remain the same within a range of -10% to 20%.



**Figure 15 Average Intersection Delays for the Original Testbed Simulated in NETSIM for Pretimed Control for V/C Ratios of  $M=0.5$ ,  $C=0.8$ .**

A similar graph in Figure 16 shows the plot of average intersection delay values versus green split adjustments as simulated in TRAF-NETSIM for actuated control. Examination of Figure 16 reveals a similar trend in the results. The average intersection delays remain constant within an adjustment range of -30% to 10%. But when more green time is given to the major street, it is resulting in extra delays as this green time is being wasted because of the lower volumes on the major street; whereas when more green time is given to minor street, it is being used efficiently and the unused green time is coming back to the major street.



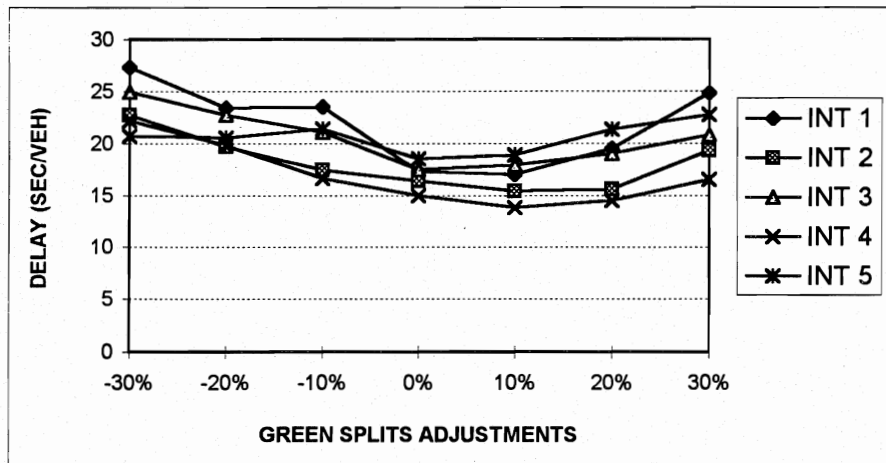
**Figure 16 Average Intersection Delays for the Original Testbed Simulated in NETSIM for Actuated Control for V/C Ratios of M=0.5, C=0.8.**

### Scenario 5 Outputs

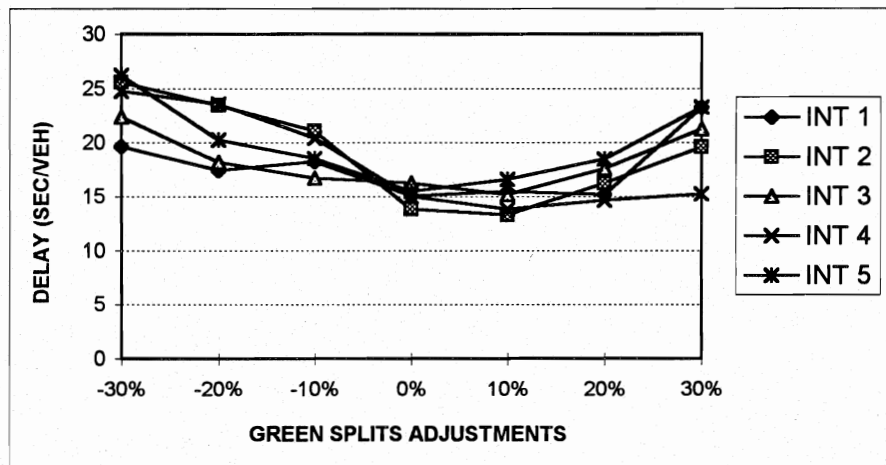
Scenario 5 represented moderate volume conditions on the major street and the minor street with a  $v/c$  ratio of 0.5. Figure 17 presents the results of the experimental testbed as simulated in PASSER II-90 for scenario 5. As this is a case of moderate volumes on both the major street as well as the minor street, any deviation from the optimized timing plan does not significantly hamper the performance of the network. There is a marginal increase in average intersection values when the green splits are modified, which is reasonable to believe.

Similar plots of scenario 5 simulated in TRAF-NETSIM for pretimed control as well as actuated control are shown in Figures 18 and 19. The trends here are consistent with the previous findings.

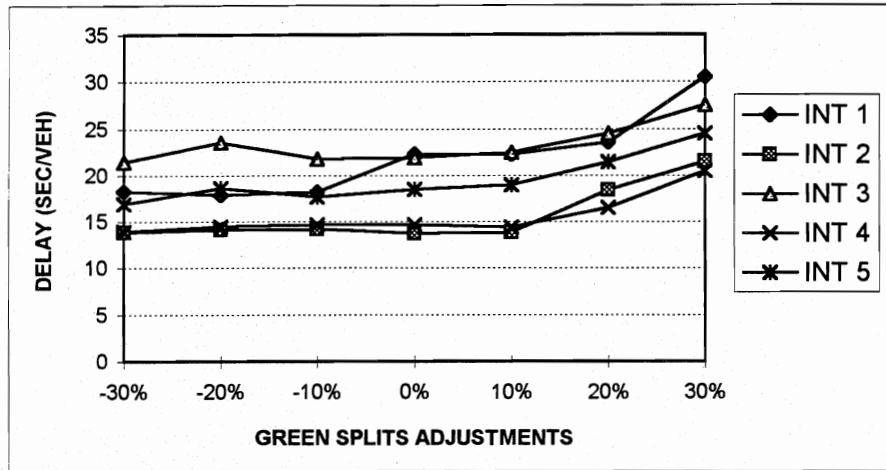




**Figure 17 Average Intersection Delays for the Original Testbed Simulated in PASSER II-90 for V/C Ratios of M=0.5, C=0.5.**



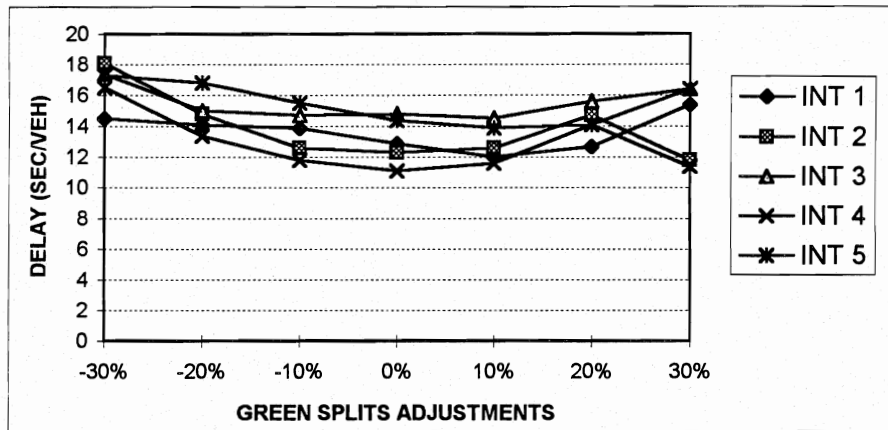
**Figure 18 Average Intersection Delays for the Original Testbed Simulated in NETSIM for Pretimed Control for V/C Ratios of M=0.5, C=0.5.**



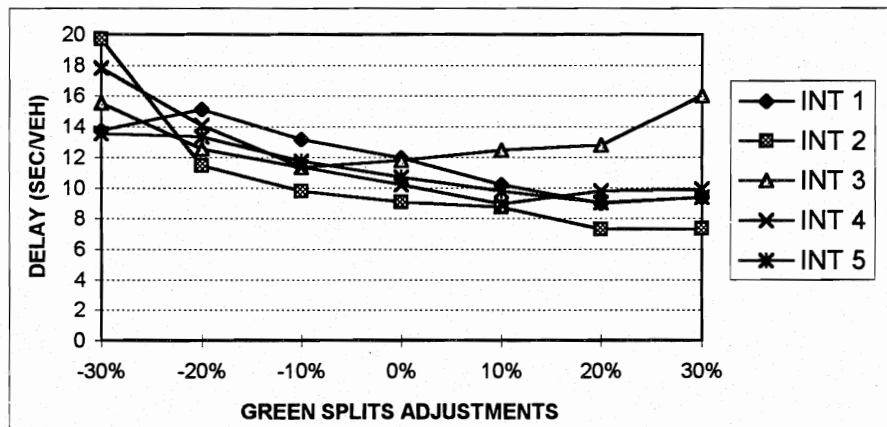
**Figure 19 Average Intersection Delays for the Original Testbed Simulated in NETSIM for Actuated Control for V/C Ratios of M=0.5, C=0.5.**

### Scenario 6 Outputs

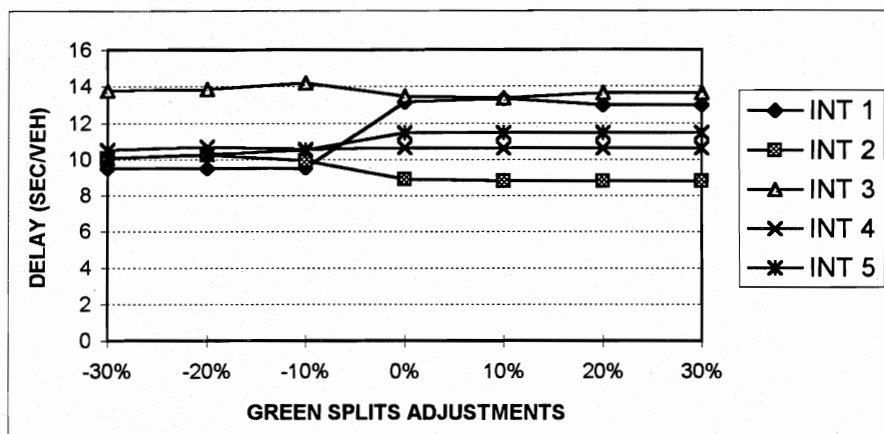
Scenario 6 represented volume conditions where the  $v/c$  ratio of the major street was 0.5 and the  $v/c$  of the minor street was 0.2. This is a case which represents low volumes on the major street as well as on the minor street. Figure 20 presents the results of the experimental testbed as simulated in PASSER II-90 for scenario 6. As seen in the previous low volume case, any deviation from the optimized timing plan does not significantly depreciate the efficient performance of the arterial. Similar plots of the arterial testbed as simulated in TRAF-NETSIM for pretimed control and actuated control are shown in Figures 21 and 22. It can be seen that at low volume conditions, almost all of the green split variations performed consistently. Thus it can be concluded that, at low volumes, any reasonable signal timing strategy works well as long as the detectors work and coordination is used.



**Figure 20 Average Intersection Delays for the Original Testbed Simulated in PASSER II-90 for V/C Ratios of M=0.5, C=0.2.**



**Figure 21 Average Intersection Delays for the Original Testbed Simulated in NETSIM for Pretimed Control for V/C Ratios of M=0.5, C=0.2.**



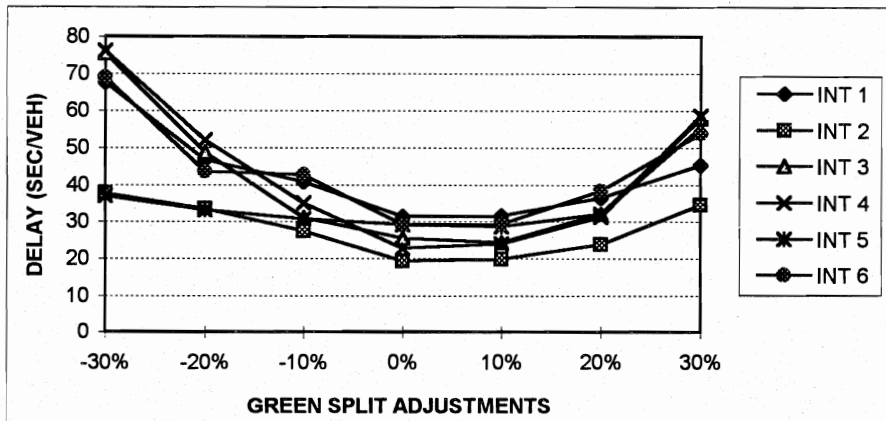
**Figure 22 Average Intersection Delays for the Original Testbed Simulated in NETSIM for Actuated Control for V/C Ratios of  $M=0.5$ ,  $C=0.2$ .**

### Extension of Testbed

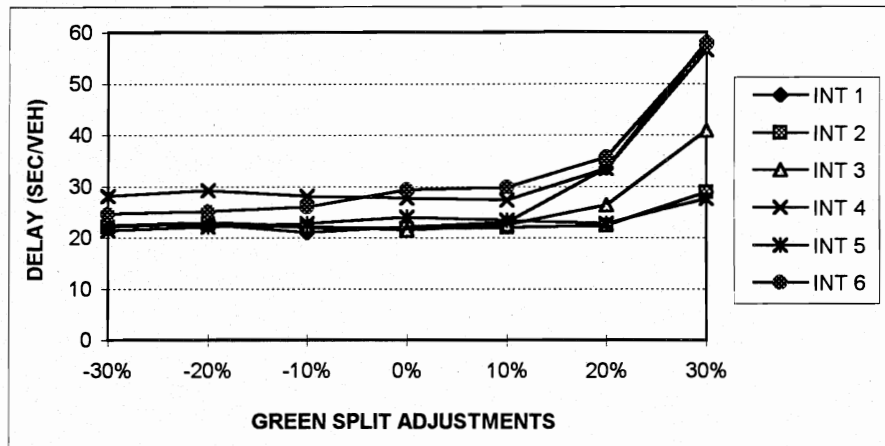
Reflecting on the fact that the main objectives of this research were twofold, some modifications to the original experimental test paln were made. The first objective was to investigate the effects of phase green split variation on the performance of an arterial system. The second objective was to develop strategies to improve the performance of the arterial using coordinated actuated concepts based on the above results. At this stage of the research, certain striking and noticeable trends were observed and more efficient timing plans could be developed using actuated control concepts and technology. To achieve this objective, the strategies developed in this research need to be verified for their accuracy. So, to expand these results to other arterial configurations and not specifically to this one arterial testbed, a larger testbed having six intersections was developed from the original one.

## Scenario 1 Outputs

The following sections present some of the findings of the six intersection simulation analysis performed using PASSER II-90 and TRAF-NETSIM for actuated control. Figure 23 shows the results of simulation performed using PASSER II-90 for pretimed coordinated control. The trend here is consistent with the earlier findings. Any deviation from the optimum green splits would result in extra delays. Thus, it can be concluded that the green splits have to be more perfectly tuned in pretimed operation for optimal performance at higher volume levels. Figure 24 shows the results of simulation performed using TRAF-NETSIM for coordinated actuated control. There is a striking similarity with the previous findings. This substantiates the earlier findings and it can be concluded that these findings are more generic rather than being true to a particular geometric configuration.



**Figure 23 Average Intersection Delays for the Modified Testbed Simulated in PASSER II-90 for V/C Ratios of M=0.8, C=0.8.**

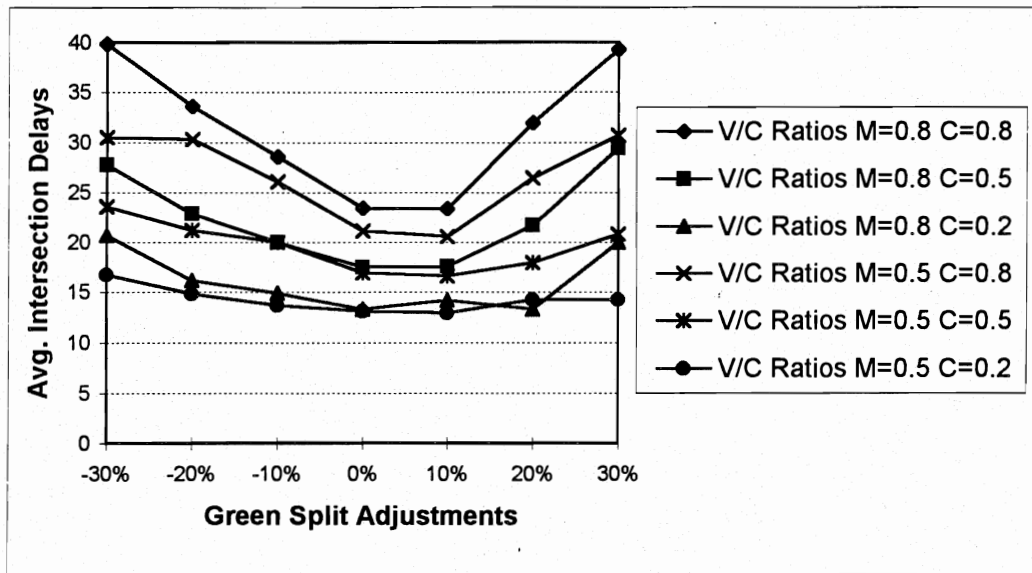


**Figure 24 Average Intersection Delays for the Modified Testbed Simulated in NETSIM for Actuated Control for V/C Ratios of M=0.8, C=0.8.**

The remaining results are consistent with the initial testbed for all other scenarios and they can be found in the appendix.

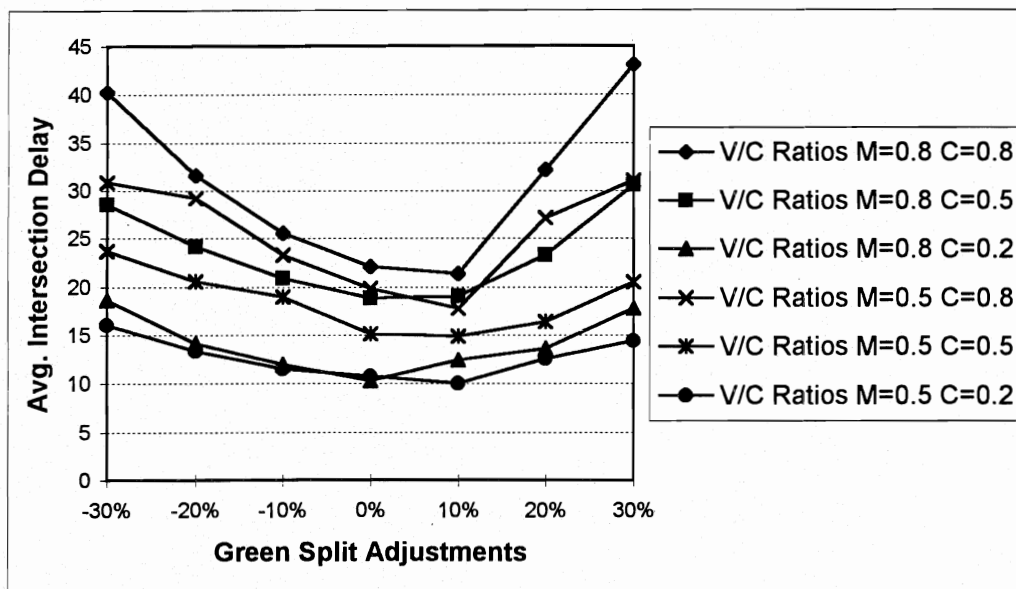
### Summary of Delay Results

The following section presents a summary of the delay results for the arterial testbed as simulated in PASSER II-90 and TRAF-NETSIM for pretimed control and actuated control. This section is presented to give an overview of the study results attained in this research study. Figure 25 is total systems plot of all the scenarios showing the simulation results of the arterial testbed in PASSER II-90 for the various green split adjustments. Each curve in the figure represents a scenario as described in the earlier sections. The figure clearly depicts how the individual curves move up as the volume increases.



**Figure 25 Average Intersection Delays for the Original Testbed Simulated in PASSER II-90 for Pretimed Control.**

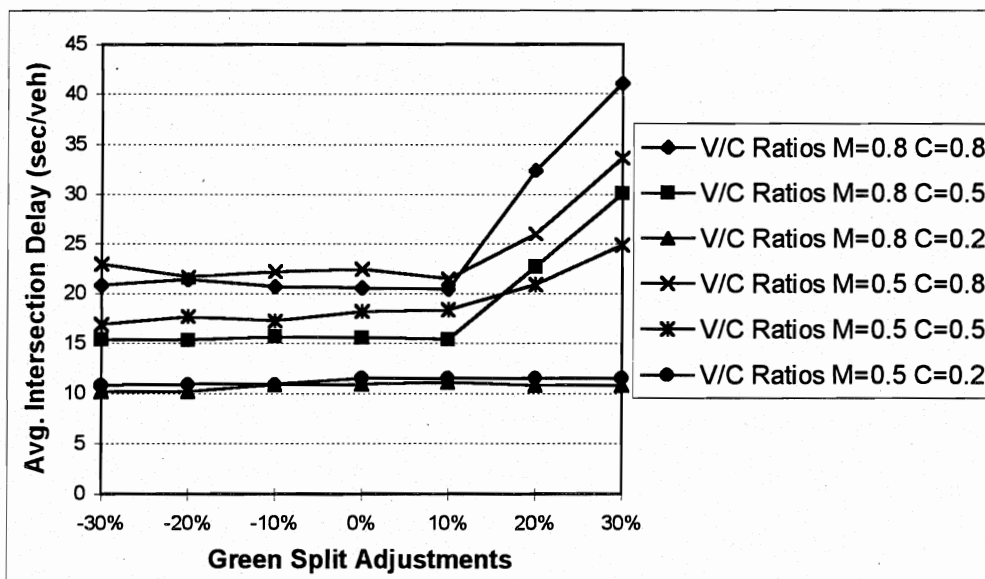
Looking at Figure 25, it can be concluded that the green splits have to be more perfectly tuned in pretimed operation for optimal performance at higher volume levels. At low volumes, any reasonable signal timing strategy works as long as the detectors work and signals are coordinated. Figure 26 is an aggregated plot of all the scenarios showing the simulation results of the arterial testbed in TRAF-NETSIM for pretimed control, for the various green split adjustments. The interesting observation the analyst can make is the closeness of the results between PASSER II-90 and NETSIM for pretimed control. A *similar trend* in results can be observed between these two models. Any deviation from the optimum green splits would result in extra delays. This signifies that the two models are well calibrated and there exist practically no differences in results exist between the two programs.



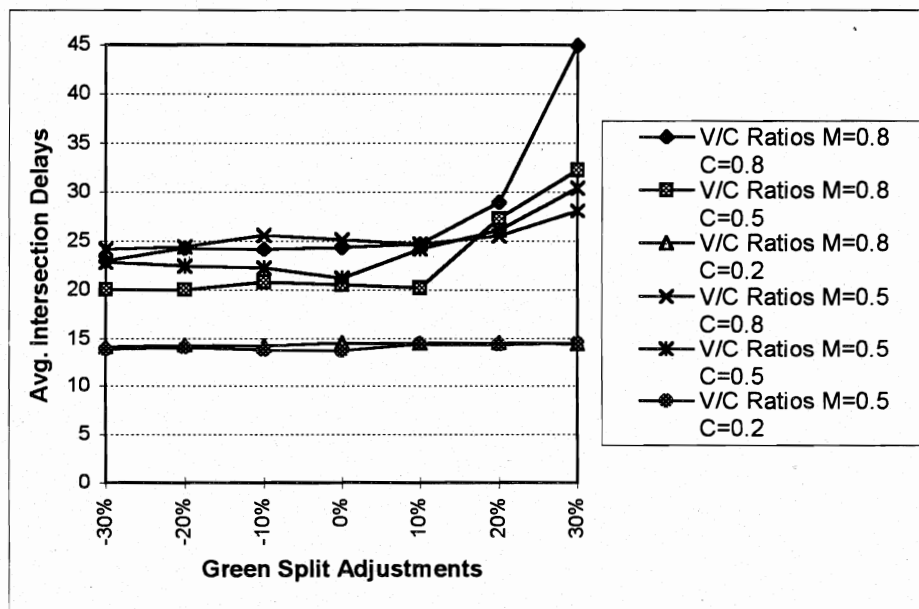
**Figure 26 Average Intersection Delays for the Original Testbed Simulated in NETSIM for Pretimed Control.**

Figure 27 is an aggregated plot of all the scenarios showing the simulation results of the arterial testbed in TRAF-NETSIM for actuated control, for the various green split adjustments. A similar plot is shown in Figure 28 for the modified arterial testbed simulated TRAF-NETSIM for actuated control. The most important finding of this research was that the average intersection delays did not increase when the initial green time allocated to the major street (phases 2 & 6) was reduced. However, the average intersection delays went up when the green time allocated to the major street was increased. This observation was particularly noticeable for high v/c ratios.



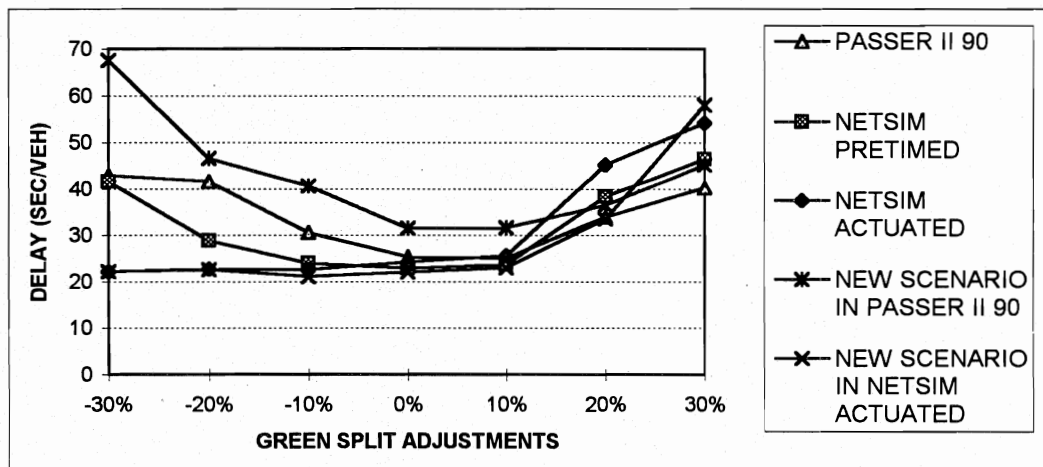


**Figure 27 Average Intersection Delays for the Original Testbed Simulated in NETSIM for Actuated Control.**



**Figure 28 Average Intersection Delays for the Modified Testbed Simulated in NETSIM for Actuated Control.**

Any surplus green time given to the minor street was always coming back to the major street when there was not enough demand; whereas, any surplus green time given to the major street was never going back to the minor street when the minor street needed more green time, as the major street was not actuated. For low volume conditions almost all of the green split variations performed similarly. The variations in the simulation results between TRAF-NETSIM for coordinated actuated control and PASSER II-90 pretimed coordinated control can be attributed to the control strategy and not to the modeling differences. Figure 29 presents an overview of the simulation results. This is an aggregated plot of all the scenarios, in which each curve represents a simulation model. It can be perceived from this figure that the curves representing NETSIM ACTUATED and NEW SCENARIO IN NETSIM ACTUATED almost coincide and depict a very similar trend as described in the earlier sections. This finding suggests that a more optimal allocation of arterial green time is possible.



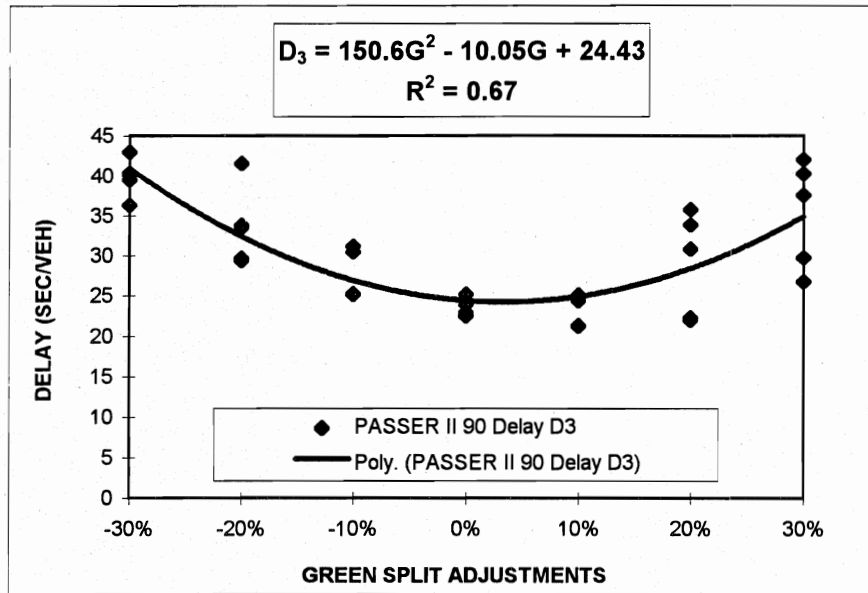
**Figure 29 Average Intersection Delays Vs Green Split Adjustments for Intersection 1.**

## **Regression Analysis**

This section presents an overview of the regression analysis performed on different sets of data to draw concrete conclusions based on these results. Regression analysis is the process of trying a fit a curve to a given set of data, so that certain trends can be observed. The primary objective of this research was to propose alternatives to improve arterial signal coordination using actuated control. Green split variations was thoroughly investigated to explore more optimal allocation of the phase green splits, which will in turn improve arterial coordination. The results indicated that a more optimal allocation of the phase green splits is possible. Regression analysis will provide the means to better allocate the phase green splits and improve arterial signal coordination. Taking a derivative of the regression equation developed will identify the points where the average intersection delay is minimum.

### *Passer II-90 Average Intersection Delays*

The first set of analysis was performed on the average intersection delays obtained in PASSER II-90 for pretimed coordinated control. Figure 30 shows the results of a non-linear regression analysis.



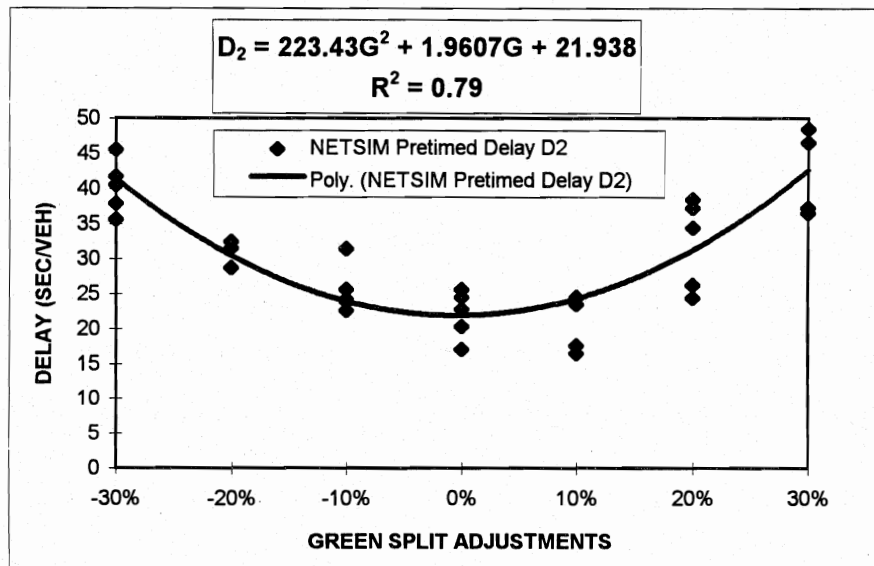
**Figure 30 Non-Linear Regression Analysis Performed on PASSER II-90  
Average Intersection Delays for a V/C ratio of M=0.8, C=0.8.**

The value of  $R^2$  was very low when a straight line was fitted. This gave an indication that the data was following a non-linear trend. Also, by observation, it could be seen that the data follows a non-linear trend. A second degree polynomial and a third degree polynomial was also fitted to the data points. But increasing the complexity of the curve to third degree was not justified as it did not significantly improve the value of  $R^2$ . A data point in the figure is an average intersection delay for an intersection, simulated by PASSER II-90. Some data points in the figure are scattered, which can be attributed to the geometry of the intersections.  $D_3$  represents the average intersection delay in PASSER II-90.  $G$  represents an adjustment to PASSER II-90's optimum green splits. The  $R^2$  value was calculated to be 0.67. This is not a strong indication of the non-linear trend, but surely is a good indication that these data points follow a curvilinear trend. This is logical to believe as PASSER II-90 thinks that any deviation from the optimum green splits will result in extra delays. The curve also shows that the average intersection delays seem to go up more, when

less green time is given to the arterial's coordinated phase than when more green time is given to the arterial's coordinated phase.

*Average Intersection Delays in TRAF-NETSIM for Pretimed Control*

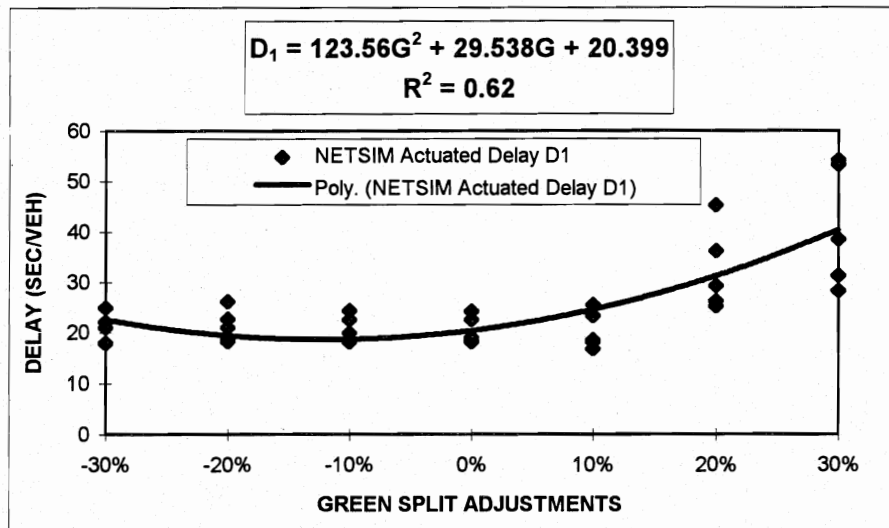
A similar non-linear regression analysis was performed on the average intersection delays obtained in TRAF-NETSIM for pretimed control. Figure 31 shows the curve and the equation obtained when such an analysis was performed. Examination of this figure reveals the curvature of these data points, which is very nearly similar to PASSER II-90 results. The  $R^2$  value in this case was 0.79 which indicates a stronger correlation. The curve resembles the sliced half of a circle with a low point and two high points. The low point corresponds to the optimum green splits or 0% adjustment and the two high points correspond to -30% and +30% adjustments.



**Figure 31 Non-Linear Regression Analysis Performed on Average Intersection Delays Simulated in TRAF-NETSIM for Coordinated Pretimed Control for a V/C ratio of M=0.8, C=0.8.**

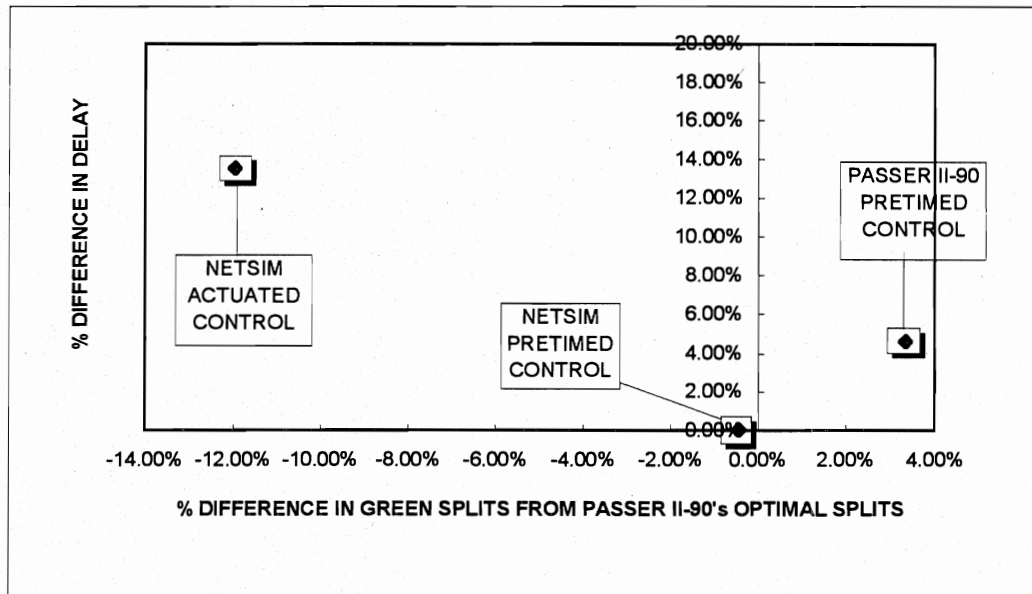
### *Average Intersection Delays in TRAF-NETSIM for Actuated Control*

The value of  $R^2$  was very low when a straight line was fitted. This gave an indication that the data was following a non-linear trend. Also, by observation, it could be seen that the data follows a non-linear trend. A second degree polynomial and a third degree polynomial was also fitted to the data points. But increasing the complexity of the curve to third degree was not justified as it did not significantly improve the value of  $R^2$ . Figure 32 represents the second degree non-linear regression analysis performed on the average intersection delays obtained in TRAF-NETSIM for actuated control.  $D_1$  represents the average intersection delay in NETSIM for actuated control. The  $R^2$  in this case was 0.62 which is a reasonably good indication of the curvature. The low  $R^2$  value can be attributed to some outliers on the right side of the curve. But the points on the left side of curve are more compact and follow a definite trend. Examination of this figure reveals an interesting trend. The curve remains flat beginning from a green split adjustment of -30% to a green split adjustment of 0%. Beyond that point, it increases sharply. This trend is in contrast to what has been observed in PASSER II-90 and TRAF-NETSIM for pretimed control. This curvature supports the finding that the actuated system performance remains the same when the arterial's coordinated pretimed phase was reduced from its optimum pretimed value. This finding indicates that a more optimal allocation of the phase green splits is possible by taking a derivative of the regression equation.



**Figure 32 Non-Linear Regression Analysis Performed on Average Intersection Delays Simulated in TRAF-NETSIM for Coordinated Actuated Control for a V/C ratio of M=0.8, C=0.8.**

Taking a derivative of the regression equation and equating it to zero will result in a green split value which produces the least average intersection delay. This green split value was computed using the regression equation developed from PASSER II-90 simulation results. The delay corresponding to this green split value was calculated and compared with the delay values obtained using PASSER II-90's optimum green splits (0% green split adjustment). Similar comparisons were made using the regression equations developed from NETSIM simulation results for pretimed and actuated control. Figure 33 summarizes this idea. On the X-axis, the percent difference in green splits from PASSER II-90's optimum splits are shown. On the Y-axis, the percent difference in delays in using the modified green splits are shown.



**Figure 33 Estimated Average Intersection Delays Using the Modified Green Splits.**

The percent of improvement that can be made to the arterial using the modified green splits are shown in Table 2.



**Table 2 Estimated Improvement in the Performance of the Arterial Using the Modified Green Splits.**

<b>Simulation Model</b>	<b>% Difference in Green Splits from PASSER II-90's Green Splits</b>	<b>% Difference in Avg. Int. Delay from using the Modified Splits</b>
<b>PASSER II-90</b>	<b>3.34%</b>	<b>4.64%</b>
<b>TRAF-NETSIM for Pretimed Control</b>	<b>-0.44%</b>	<b>0.02%</b>
<b>TRAF-NETSIM for Actuated Control</b>	<b>-11.95%</b>	<b>13.53%</b>

It can be seen from Table 2 that an improvement of 4.64% can be made to the arterial when PASSER II-90's optimal splits are modified by 3.34%. NETSIM simulation results for pretimed control illustrate that PASSER II-90's optimal splits need to be adjusted by -0.44% to achieve a possible improvement of 0.02%. This result demonstrates that no significant reduction in the average intersection delay is possible and PASSER II-90's green splits are optimum for pretimed control. NETSIM simulation results for coordinated actuated control indicate that a reduction of 13.53% in the average intersection delay can be attained by reducing PASSER II-90's optimal splits by 11.95%. This result demonstrates that if PASSER II-90's splits are to be used for coordinated actuated control, they need to be modified by -11.95% to attain optimality.

## **CHAPTER V**

### **CONCLUSIONS AND RECOMMENDATIONS**

The main objectives of this research were twofold. The first objective was to investigate the effects of phase green split variation on the performance of an arterial system. The second objective was to develop strategies or alternatives to improve the performance of the arterial using coordinated actuated concepts based on the above results.

A five intersection experimental testbed was initially designed to conduct this research study. PASSER II-90 was used to generate a series of optimal timing plans. The optimal timing plans were transformed into a coordinated actuated timing plan using the latest actuated control technology and was simulated in TRAF-NETSIM (version 5). Different scenarios were developed covering a wide range of volumes and phase green split adjustments.

The primary focus of this study was on the performance of the network when the arterial's coordinated pretimed phase was varied from its optimal timing, keeping the cycle length constant. The results obtained by performing this simulation study was extended to a modified arterial testbed. Statistical analysis was performed on the various results to statistically substantiate these findings. The conclusions and recommendations addressed the study objectives and are based on the results of the PASSER II-90 and TRAF-NETSIM simulations.

## CONCLUSIONS

As mentioned before, the simulation study was designed to identify strategies to improve arterial coordination using actuated control. The most significant finding of this research was that the actuated system performance remained the same when the arterial's coordinated pretimed phase was reduced from its optimum pretimed value using existing actuated control technology. Whereas, there is considerable deterioration in the actuated system performance when the arterial's coordinated pretimed phase was increased from its optimum value. This observation was particularly noticeable for high v/c ratios. This result is because any extra green time given to the minor street was always coming back to the major street when there was not enough demand; whereas, any extra time given to the major street was never going back to the minor street when the minor street needed more green time, as the major approach was not actuated. This finding suggests that a more optimal allocation of arterial green times is possible.

The following conclusions were drawn from the overall simulation study:

- The green splits have to be more perfectly tuned in pretimed operation as volumes increase, to achieve optimal performance of the arterial. This is very difficult to achieve in reality, due to the constant fluctuations in traffic. In pretimed operation, the controller is not very smart and does not adapt itself to constantly fluctuating demands and hence may result in inefficient operation.
- The simulation results of PASSER II-90 for pretimed control and TRAF-NETSIM for actuated control forecasted varying trends. This was attributed to the control strategy employed.

- At low volumes, any reasonable signal timing strategy works well as long as the detectors work and the traffic signals are coordinated.
- The actuated system performance remained essentially the same when the arterial's coordinated pretimed phase was reduced from its optimum pretimed value using existing actuated control technology.
- NETSIM simulation results for pretimed control demonstrate that PASSER II-90's green splits are optimal and any significant improvement to the arterial is only possible by employing traffic actuated control. An overall improvement of about 14% is possible when PASSER II-90's optimal splits are reduced by 11.95%, where coordinated actuated control is used.

## RECOMMENDATIONS

Based upon the results of this study, the following recommendations are made:

- This research study has led to some practical findings to guide future signal strategy formulation and development. NETSIM simulation results for actuated control indicated that an improvement in the performance of the arterial can be attained when PASSER II-90's green splits are reduced from its current optimal value. This finding suggests that the arterial coordinated phases need less green time than what PASSER II-90's says is optimal. Development of an advanced signal controller to implement the above signal control strategies has been envisioned. The arterial's coordinated street phase would be divided into two durations. The first duration would be a fixed one equivalent to X % of the current PASSER II-90 optimal pretimed green and the second interval would have a variable (extension) period upto a maximum of (100 - X %) green extension.

Extension detectors would be placed on the arterial to extend the phase during this second interval when platoon demand is detected. This may result in more efficient operation of the system.

- This research study did not involve the use of field data. It is recommended that these research findings be verified with field data to lend authenticity to the signal strategies developed.
- The regression equations developed to estimate the delay in TRAF-NETSIM for coordinated actuated control also need to be verified with field data. Once these equations are verified, they could potentially be used in a model that evaluates coordinated actuated controlled operation.
- This research study should be extended to oversaturated volume conditions. It will be interesting to observe the performance of the system when the strategies developed for undersaturated volume conditions are applied to oversaturated volume conditions.
- The development of an advanced signal controller is in its conceptual stage. Further study needs to be done to determine the feasibility of such a controller.

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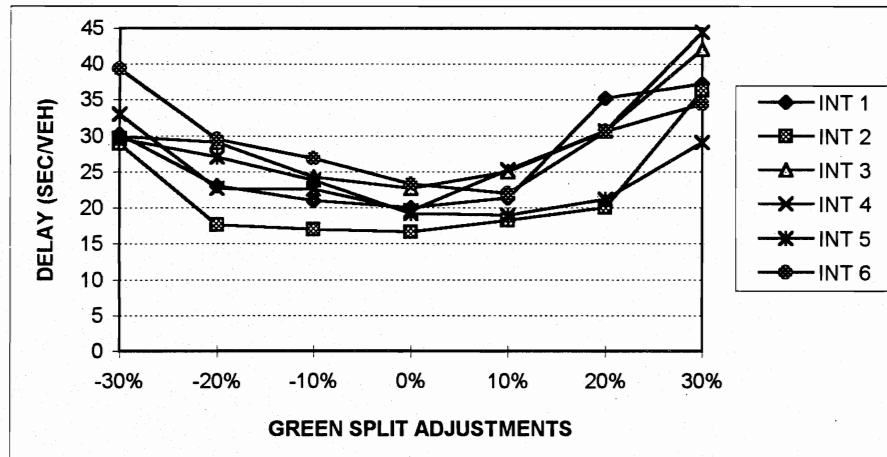
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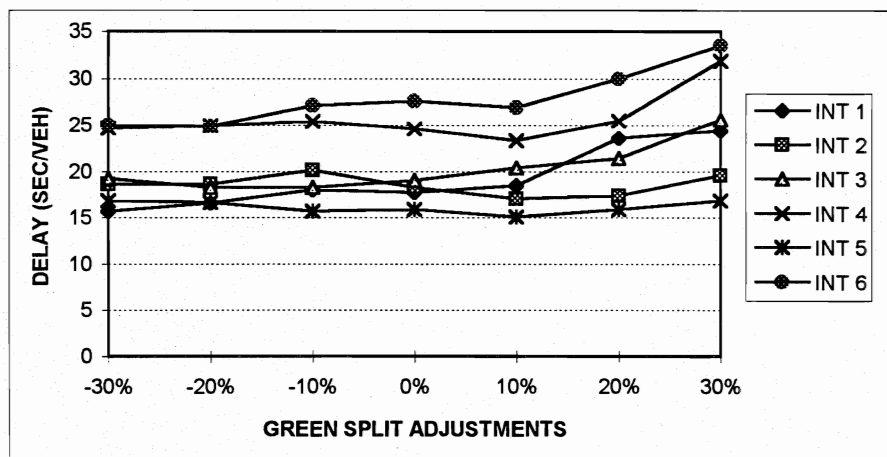
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**APPENDIX A**

## Scenario 2 Outputs

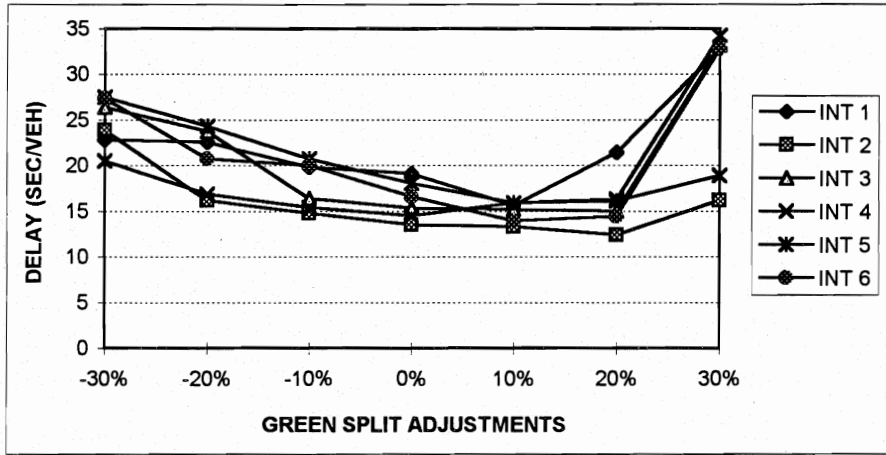


**Figure A-1 Average Intersection Delays for the Modified Testbed Simulated in PASSER II-90 for V/C Ratios of M=0.8, C=0.5.**

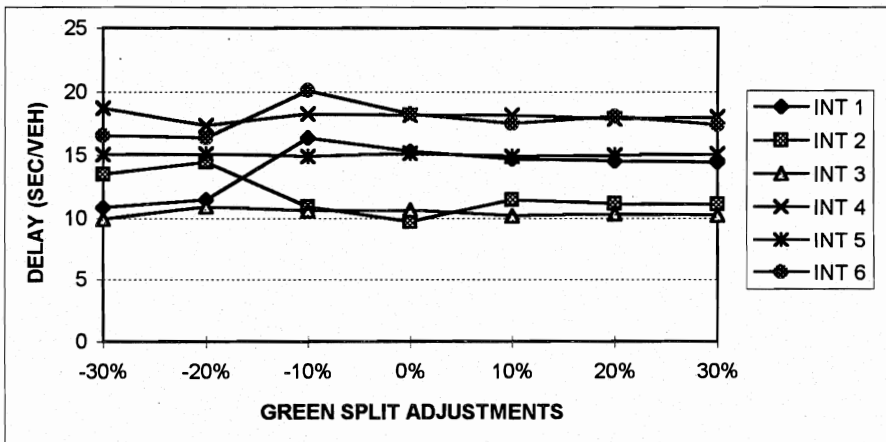


**Figure A-2 Average Intersection Delays for the Modified Testbed Simulated in TRAF-NETISM ACTUATED CONTROL for V/C Ratios of M=0.8, C=0.5.**

**Scenario 3 Outputs**

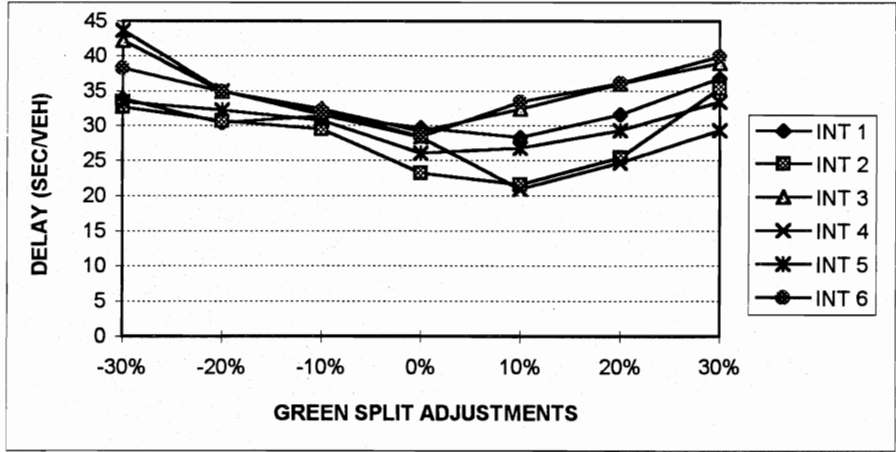


**Figure A-3 Average Intersection Delays for the Modified Testbed Simulated in PASSER II-90 for V/C Ratios of M=0.8, C=0.2.**

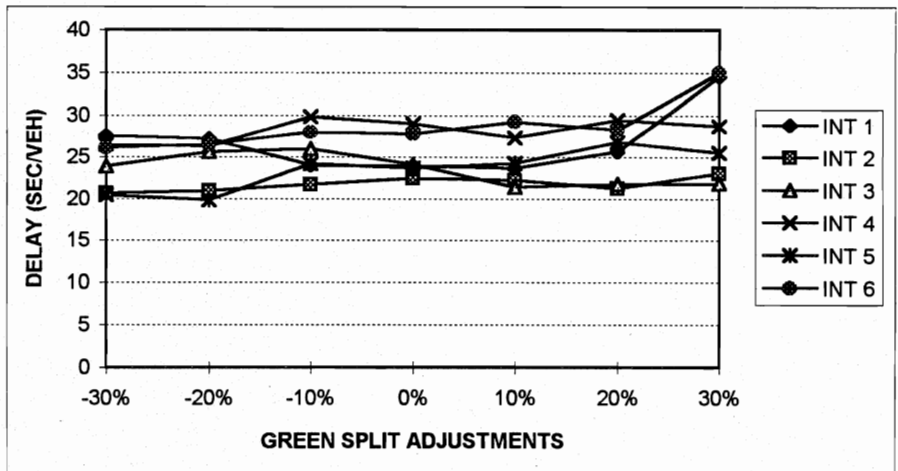


**Figure A-4 Average Intersection Delays for the Modified Testbed Simulated in TRAF-NETISM ACTUATED CONTROL for V/C Ratios of M=0.8, C=0.2.**

**Scenario 4 Outputs**

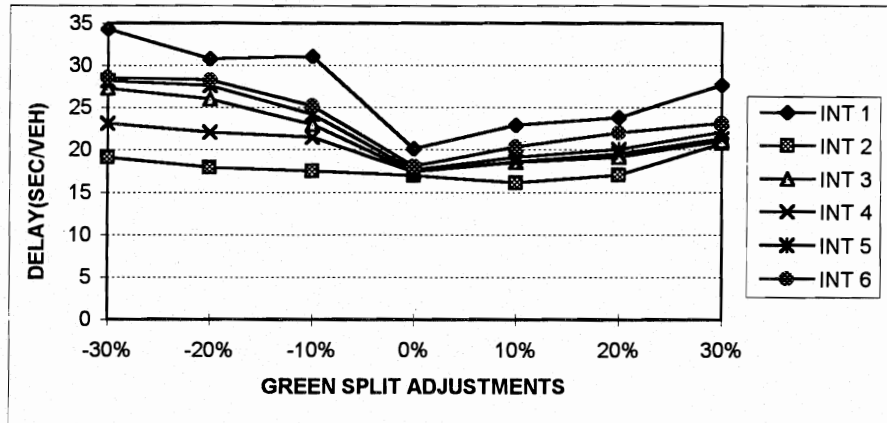


**Figure A-5 Average Intersection Delays for the Modified Testbed Simulated in PASSER II-90 for V/C Ratios of M=0.5, C=0.8.**

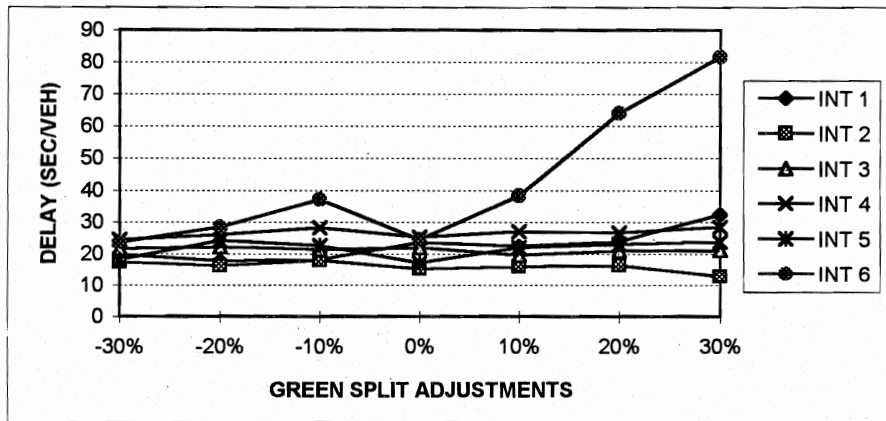


**Figure A-6 Average Intersection Delays for the Modified Testbed Simulated in TRAF-NETISM ACTUATED CONTROL for V/C Ratios of M=0.5, C=0.8.**

**Scenario 5 Outputs**

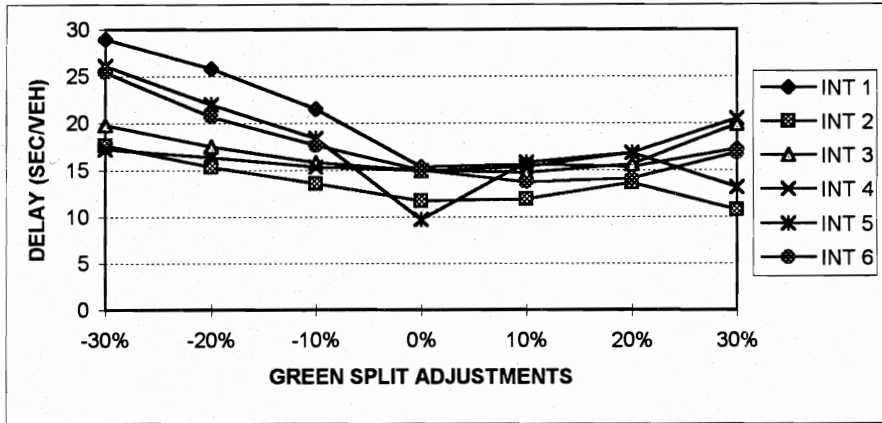


**Figure A-7 Average Intersection Delays for the Modified Testbed Simulated in PASSER II-90 for V/C Ratios of M=0.5, C=0.5.**

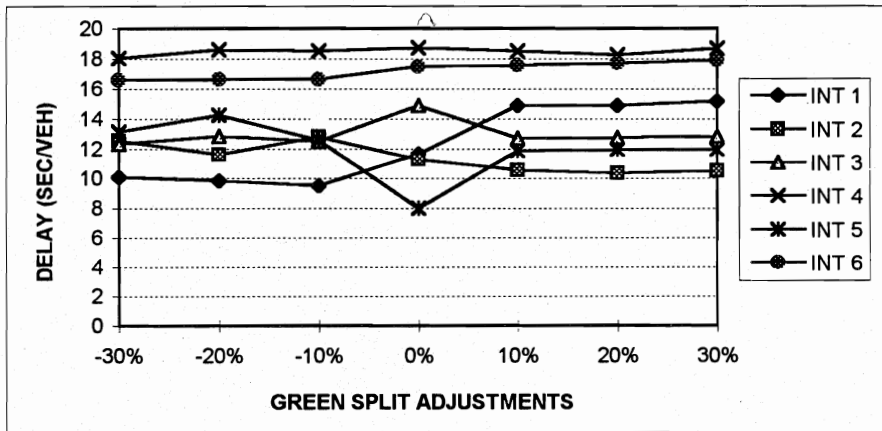


**Figure A-8 Average Intersection Delays for the Modified Testbed Simulated in TRAF-NETISM ACTUATED CONTROL for V/C Ratios of M=0.5, C=0.5.**

**Scenario 6 Outputs**



**Figure A-9 Average Intersection Delays for the Modified Testbed Simulated in PASSER II-90 for V/C Ratios of M=0.5, C=0.2.**



**Figure A-10 Average Intersection Delays for the Modified Testbed Simulated in TRAF-NETISM ACTUATED CONTROL for V/C Ratios of M=0.5, C=0.2.**