Technical Report Documentation Page

1. Report No.	2. Government Accession No.	3. Recipient's Catalog No.
FHWA/TX-04/0-4421-1		

4. Title and Subtitle	5. Report Date
METHODOLOGY FOR DETERMINATION OF OPTIMAL TRAFFIC RESPONSIVE PLAN SELECTION CONTROL PARAMETERS	September 2003 Resubmitted: February 2004
	6. Performing Organization Code

7. Author(s)	8. Performing Organization Report No.
Montasir M. Abbas, Nadeem A. Chaudhary, Anuj Sharma, Steven P. Venglar, and Roelof J. Engelbrecht	Report 0-4421-1
9. Performing Organization Name and Address	10. Work Unit No. (TRAIS)
Texas Transportation Institute The Texas A&M University System College Station, Texas 77843-3135	11. Contract or Grant No. Project No. 0-4421

12. Sponsoring Agency Name and Address	13. Type of Report and Period Covered
Texas Department of Transportation Research and Technology Implementation Office P. O. Box 5080 Austin, Texas 78763-5080	Research: September 2002-August 2003
	14. Sponsoring Agency Code

15. Supplementary Notes

Research performed in cooperation with the Texas Department of Transportation and the U.S. Department of Transportation, Federal Highway Administration.

Research Project Title: A Simplified Approach for Selecting Optimal Traffic Responsive Control Parameters

16. Abstract

Closed-loop traffic control systems can be operated by either Time-of-Day (TOD) mode or Traffic Responsive Plan Selection (TRPS) mode. When properly configured, the TRPS mode has the greatest potential to provide an optimal operation due to its ability to accommodate abnormal traffic conditions such as incidents, special events, and holiday traffic. Most importantly, the TRPS mode can reduce the need for frequent redesign/updates to signal timing plans. Although TRPS mode can provide a more optimal and a snappier operation than the TOD mode, numerous parameters (e.g., cycle level parameters, directionality parameters, smoothing factors, weighting factors, etc.) have to be set up correctly for the system to work as intended. Otherwise, TRPS mode may select inappropriate timing plans or cause the closed-loop system to run in a continuous transitioning state. To date, there have not been any formal guidelines for selection of robust and optimal TRPS system parameters and thresholds. Due to the lack of formal and clear comprehensive guidelines, traffic engineers usually revert to the TOD mode of operation for its ease of setup. As a result, the benefits of closed-loop systems are not fully utilized.

This report provides a novel methodology for robust and optimal selection of TRPS parameters and thresholds. The report discusses the application of the methodology using data from two closed-loop systems in Texas and demonstrates that the proposed methodology can result in up to 100 percent accurate identification of optimal timing plans. The report also shows potential benefits ranging from an annual savings of $27,630 to $5,042,200 per intersection in delay reduction alone.

17. Key Words	18. Distribution Statement
Traffic Control, Closed-Loop Signal Systems, Optimization, Parametric Analysis, Discriminant Analysis, Genetic Algorithms, Traffic Signal Timing	No restrictions. This document is available to the public through NTIS: National Technical Information Service 5285 Port Royal Road Springfield, Virginia 22161

19. Security Classif.(of this report)	20. Security Classif.(of this page)	21. No. of Pages	22. Price
Unclassified	Unclassified	84	

METHODOLOGY FOR DETERMINATION OF OPTIMAL TRAFFIC RESPONSIVE PLAN SELECTION CONTROL PARAMETERS

by

Montasir M. Abbas, Ph.D., P.E.
Assistant Research Engineer
Texas Transportation Institute

Nadeem A. Chaudhary, Ph.D., P.E.
Research Engineer
Texas Transportation Institute

Anuj Sharma
Graduate Research Assistant
Texas Transportation Institute

Steven P. Venglar, P.E.
Associate Research Engineer
Texas Transportation Institute

and

Roelof J. Engelbrecht, P.E.
Associate Transportation Researcher
Texas Transportation Institute

Report 0-4421-1
Project Number 0-4421
Research Project Title: A Simplified Approach for Selecting Optimal Traffic Responsive Control Parameters

Sponsored by the
Texas Department of Transportation
In Cooperation with the
U.S. Department of Transportation
Federal Highway Administration

September 2003
Resubmitted: February 2004

TEXAS TRANSPORTATION INSTITUTE
The Texas A&M University System
College Station, Texas 77843-3135

DISCLAIMER

The contents of this report reflect the views of the authors, who are responsible for the facts and the accuracy of the data presented herein. The contents do not necessarily reflect the official view or policies of the Federal Highway Administration (FHWA) or the Texas Department of Transportation (TxDOT). This report does not constitute a standard, specification, or regulation. Its contents are not intended for construction, bidding, or permit purposes. The use and names of specific products or manufacturers listed herein does not imply endorsement of those products or manufacturers. The principal investigator of this research was Dr. Montasir M. Abbas. The engineer in charge was Dr. Nadeem A. Chaudhary, P.E. # 66470.

ACKNOWLEDGMENTS

This project was conducted in cooperation with TxDOT and FHWA. The researchers acknowledge the support and guidance provided by the project directors, Mr. Brian Van De Walle and Mr. Henry Wickes, as well as the members of the Project Monitoring Committee, including: Mr. Larry Colclasure (the program coordinator), Mr. Chuck Ansley, Mr. Don Baker, Mr. David Danz, Mr. Robert Guydosh, Mr. Gordon Harkey, Mr. Dan Maupin, and Mr. David Mitchell.

We also acknowledge the guidance and assistance provided to us by other members of TxDOT, especially Mr. Dexter Turner and Mr. Wayne Carpenter. We thank Mr. Todd Hausman from Texas Transportation Institute (TTI) for his help during data collection. Finally, we thank Mr. Nader Ayoub of Texas Highway Products, Inc.; Mr. John Black of Naztec, Inc.; Mr. Arnold McLaughlin; and Mr. Bo Gao of Eagle Traffic Control Systems for their valuable discussions and demonstration of their closed-loop system software.

TABLE OF CONTENTS

Page

LIST OF FIGURES

Page

LIST OF TABLES

Page

CHAPTER 1: INTRODUCTION

OVERVIEW

Closed-loop traffic control systems can be operated by either Time-of-Day (TOD) mode or Traffic Responsive Plan Selection (TRPS) mode. When properly configured, the TRPS mode has the greatest potential to provide an optimal operation due to its ability to accommodate abnormal traffic conditions such as incidents, special events, and holiday traffic. Most importantly, the TRPS mode can reduce the need for frequent redesign/updates to signal timing plans. Although TRPS mode can provide a more optimal and a snappier operation than the TOD mode, numerous parameters (e.g., cycle level parameters, directionality parameters, smoothing factors, weighting factors, etc.) have to be set up correctly for the system to work as intended. Otherwise, TRPS mode may select inappropriate timing plans or cause the closed-loop system to run in a continuous transitioning state. To date, there have not been any formal guidelines for selection of robust and optimal TRPS system parameters and thresholds. Due to the lack of formal, clear, and comprehensive guidelines, traffic engineers usually revert to the TOD mode of operation for its ease of setup. As a result, the benefits of closed-loop systems are not fully utilized. This research was conducted to develop guidelines for selection of TRPS parameters and thresholds based on a scientific procedure. This first-year report documents the methodology used in this research.

RESEARCH OBJECTIVES

The objective of this research was to develop guidelines for selection of optimal and robust TRPS control parameters and thresholds for arterial networks. The developed guidelines were desired to 1) be based on a scientifically sound procedure as opposed to a system fine-tuning approach, and 2) be presented in a simplified manner in the form of charts or tables for ease of implementation. This objective was achieved through the following activities:

- Study the TRPS control mechanism.
- Evaluate the state of the practice in TRPS setup.
- Develop a procedure for optimal overall system performance.

- Develop a scientific procedure for determination of the TRPS system parameters and thresholds.
- Develop guidelines for the selection of optimal TRPS system parameters and thresholds.
- Present the developed guidelines in tables or graphs for ease of implementation.

RESEARCH APPROACH

This report documents a novel and comprehensive methodology for robust and optimal selection of TRPS parameters and thresholds. The approach discussed here proposes that only a few timing plans are needed for the subset of all traffic networks that share the same characteristics (arterial versus grid network, protected lefts versus permitted lefts, lead-lead versus lead-lag operation, etc.). Once the timing plans for certain network characteristics have been identified, TRPS parameters need to be selected such that the most suitable plan in the controllers' database is selected to match the existing traffic conditions. This approach, and making sure that plans for handling extreme conditions are stored in the controllers, will reduce the effect of plan "aging." The goal is to have engineers implement these sets of timing plans and TRPS parameters in closed-loop systems. If the engineers have excess time and they prefer to implement a more customized system for each closed-loop (for instance, to improve efficiency from 80 percent to 95 percent), they can conduct a detailed study following the steps detailed in this report. Otherwise, they can still feel "comfortable" that the closed-loop system is operated with a reasonably good performance.

The proposed approach, while not claiming to achieve 100 percent system efficiency, will provide a "blanket" of good performance that will serve several purposes:

- Encourage traffic engineers to implement TRPS systems that will achieve good performance rather than a possible poor performance due to outdated TOD plans.
- Save engineers and technicians valuable time that is otherwise required to develop timing plans for each TOD traffic pattern.
- Reduce the effects of timing plans "aging" through the implementation of traffic responsive mode.

The proposed approach is illustrated by designing TRPS system parameters and thresholds for two closed-loop systems in Texas. One of the closed-loop systems studied consisted of three intersections in a suburban setting where traffic patterns did not exhibit a high degree of variation. The closed-loop system was used to illustrate the methodology for selecting optimal and robust TRPS parameters. The second closed-loop system consisted of five intersections in an urban setting with highly variable traffic demand levels and patterns. The closed-loop system was used to illustrate the optimization process required for selecting optimal timing plans for the overall system as well as the multi-level (cycle, split, and offset) TRPS system setup required for highly variable demands.

CHAPTER 2: TRPS CONTROL MECHANISM

BACKGROUND

Traffic signals can be interconnected together forming what is known as closed-loop traffic signal systems. A closed-loop system consists of a master controller connected to a series of traffic signal controllers using hard wire connections, fiber-optic cables, or spread spectrum radio. The on-street master supervises the individual intersection controllers and issues commands to implement timing plans stored in the local controllers. The master controller can also report detailed information back to a traffic management center using a dialup telephone or other similar communications channel for monitoring purposes.

Coordinating traffic signals in a closed-loop system can provide significant reductions in travel and delay times. A study published in 1997 found that interconnecting previously uncoordinated signals or pre-timed signals with a central master controller, and providing newly optimized timing plans, could result in a travel time reduction of 10-20 percent *(1)*. In addition to significantly reducing travel time, properly timed closed-loop systems will also reduce stops, fuel consumption, and vehicle emissions. Another study evaluating the impact of properly timing a closed-loop system in Texas reported a 13.5 percent (20.8 million gallons/year) reduction in fuel consumption, a 29.6 percent (22 million hours/year) reduction in delay, and an 11.5 percent (729 million stops/year) reduction in stops *(2)*. The study estimated total savings to the public of approximately $252 million in the following year alone. These kinds of benefits, however, require the operation of the closed-loop system such that the implemented timing plans are most suitable to the existing traffic conditions in the field, which in turn require that timing plans be varied in a timely manner as the traffic conditions change.

CLOSED-LOOP SYSTEMS MODES OF OPERATION

There are four modes under which closed-loop systems can be operated:

- The "free" mode. In this mode, each intersection is running independently, usually under a fully actuated isolated signal control.

- TOD mode. In this mode, all intersections are coordinated under a common background cycle length. The timing plans are selected at specific times based on historical traffic conditions.
- TRPS mode. This mode is similar to TOD mode except that plans are switched in response to changes in some measures of traffic demand variation.
- Manual mode. Under this mode, the closed-loop system is operated under a constant plan, unless changed by the system operator. This mode is rarely used.

The free mode of operation can only be efficient if no coordination is needed. It is not recommended for intersections included in a closed-loop system unless under late night light traffic conditions.

The TOD is a common mode of operation. The TOD mode assumes that traffic patterns are repetitive. Therefore, a particular TOD plan is implemented at the same time every day, regardless of the existing traffic condition. TOD mode can provide a stable and good performance when traffic patterns are predictable, in terms of when and where they occur in the network *(3, 4, 5, 6)*. However, in networks where traffic patterns are not predictable, or where demands shift with time, TOD can cause the signal system to implement plans that are totally inappropriate for the actual traffic patterns. A great disadvantage of the TOD mode is that engineers need to continually update the timing plans such that the plans match the temporal distribution of the traffic patterns—a very time- and effort-consuming task.

Closed-loop system vendors developed the TRPS mode, which is the subject of this research, to assure that the traffic signal system implements timing plans that are most suitable to the current traffic condition. In the TRPS mode, system detectors are used to measure occupancy and counts in the closed-loop system network. The occupancy and count information is then aggregated using certain TRPS parameters. The master controller keeps track of the calculated TRPS parameters and continuously compares them to some corresponding thresholds. If any of the new values exceed their corresponding thresholds, the control system selects a different timing plan from a pre-stored library of timing plans.

WHY THE TRPS MODE?

Timing plans are typically developed on the basis of historical vehicle demand data. In reality, the actual demands that are experienced at any time on any specific day are random samples from some statistical distribution. For example, the average weekday traffic demand at an intersection approach is likely to vary temporally in response to peak commuting periods. In addition, the underlying statistical distribution itself is not constant and changes over time as a result of changes in population and/or area development. Environmental impacts such as adverse weather may cause people to change modes, change routes, or change departure times. Also, adverse weather increases travel times, changing the time at which drivers arrive at intersections along their route. As a result of these sources of variation in traffic demand, TOD mode is sub-optimal for most actual conditions.

The TRPS mode, on the other hand, provides a mechanism by which the traffic signal system is able to change timing plans in real time in response to changes in traffic demands. The objective is to enable the signal controller to implement timing plans that are optimal for the traffic conditions that currently exist, rather than for some set of average conditions—conditions that may be very different from those that currently exist.

The TRPS mode can provide the most optimal and snappiest operation over all the other closed-loop system operation modes. The TRPS mode switches the closed-loop system's current plan to a better plan when unexpected events, incidents, or temporal changes in traffic volumes occur. Most importantly, TRPS mode reduces the need for frequent redesign/update of the signal timing plans for new traffic patterns as required if running the TOD mode. This later statement stems from the fact that the TRPS system automatically switches plans in response to changes in traffic patterns.

A recent study conducted in Netherlands showed that a traffic-responsive control based on the real-time use of the Traffic Network Study Tool (TRANSYT) software resulted in 15 percent delay reduction over application of a fixed-time or vehicle-actuated control *(7)*. The city of Milwaukee, Wisconsin, has installed a closed-loop traffic-responsive system to manage congestion and reduce traffic accidents *(8)*. The study used only two cycle lengths of 90 and 120 seconds and a detector data sampling of 6 minutes. The study reported a significant reduction in adjusted frequency of congestion-related intersection accidents. It also reported an increase in approach capacity and vehicle speed over system detectors.

A study of two networks in Lafayette, Indiana, compared TRPS and TOD modes. Six different traffic scenarios were used for the analysis with the assumption that traffic responsive pattern change would occur at times not usually expected on a typical day. Each scenario was run for an hour. The scenarios replicated midday, morning, afternoon, event-inbound, and event-outbound traffic patterns.

The study found that TRPS mode reduced total system delay by 14 percent compared to TOD mode for midday traffic pattern. It was also found that the TRPS system reduced the total system delay for morning traffic by 38 percent. However, due to the fact that there are no guidelines on the selection of TRPS parameters and thresholds, a fine-tuning process was performed in the lab until the TRPS mode behaved as expected. Nevertheless, the study reported that TRPS frequently resulted in unexpected time plan changes reducing the overall system performance *(9)*.

SETUP OF THE TRPS MODE: WHERE IS THE CATCH?

As previously discussed, the TRPS mode of operation can provide the most optimal and snappiest operation of closed-loop systems. However, the TRPS mode has to be set up correctly for it to provide such a performance. The catch here is the numerous factors and parameters to be set up correctly. Although all controller manufacturers agree on the conceptual settings of the TRPS, each manufacturer has its own mechanism for implementing the TRPS mode. The following sections provide brief reviews of the requirements and mechanisms of setting up the TRPS mode of operation.

System Detectors

The TRPS mode uses information collected from system detectors (occupancy and counts) to measure the traffic conditions in the closed-loop system network. The occupancy and count information is aggregated into certain TRPS parameters (cycle level parameter, directionality, arterial/nonarterial, etc.). The number and names of the TRPS parameters differ from one controller manufacturer to another, but the concept is the same. The master controller calculates control parameters (cycle, offset, and split parameters) from the TRPS parameters. The control parameters are continuously compared to their corresponding pre-set thresholds. If the new values of the control parameters exceed their corresponding thresholds, the control system selects a different timing plan from a library of pre-stored timing plans to match the existing traffic condition.

The Federal Highway Administration provided limited guidelines in locating system detectors *(10)*. As a result, many agencies have found it more cost-effective to install detectors at all feasible locations at the time of initial installation. The agencies later determine which subset of these detectors to use as system detectors *(11)*.

There is a common understanding among the traffic controller manufacturers, as reflected in their TRPS mechanism design, that system detectors can be categorized into three groups. Each of these categories would serve a different purpose in the TRPS mechanism:

- Cycle level detectors: the information from these detectors is used for determining the appropriate cycle level and, therefore, should be located near the critical intersection(s).
- Arterial detectors or directionality detectors: the information from these detectors is used to determine the appropriate offset level and, therefore, should be placed in the inbound and outbound directions on the arterial.
- Non-arterial detectors: the information from these detectors is usually used to determine the appropriate splits level and, therefore, should be placed on the side streets.

The general guidelines require that the system detectors be located relatively far from the traffic signal to eliminate the effects of the signal timing on the collected data *(10)*. The Indiana study, for example, used 10 system detectors with setback distances greater than 650 feet from the stop line *(9)*. This requirement is of concern to TxDOT districts that have been implementing Video Image Vehicle Detection Systems (VIVDS)-based intersection control. VIVDS cannot provide reliable data for detectors too far away (approximately 400 feet or more). Therefore, it would be of interest to know the extent of the effect of location of system detectors on the optimality of the TRPS mode.

TRPS Factors and Functions

Once the count and occupancy data are collected from system detectors, the information is aggregated by means of certain master controller functions using *smoothing*, *scaling*, and *weighting* factors *(12, 13, 14)*. These TRPS factors are used to calculate the TRPS parameters to select the most appropriate timing plan.

Scaling Factors

Scaling factors are used to convert counts and occupancy data into a combined value that is independent of the value of the approach capacity. The scaled value will range from 0 percent to 100 percent indicating how close the approach is to its capacity. Controller manufacturers usually require two sets of scaling factors: one for the count and the other for the occupancy. Some literature provides ranges for which the two scaling factors should be set. Others provide a recommendation to set the values to the highest observed occupancy value for the system detector over a long period of time *(15)*.

Smoothing Factors

Smoothing refers to producing a weighted average of the count and occupancy in order to eliminate the effect of short-term fluctuation of traffic patterns. Each controller manufacturer uses a different approach for smoothing data. However, these approaches are generally based on two mathematical functions. The first approach is called filtering. The filtering method calculates the new value of a variable x (e.g., count) by multiplying the difference between the old smoothed value and the newly collected value of the same variable by a smoothing factor, and adding the result to the last smoothed value of the variable. The following equation shows how the new value is calculated:

$$\bar{x}_{new} = \bar{x}_{old} + k(x_{new} - \bar{x}_{old})$$

Where:

$\bar{x}_{new}$ = new smoothed value;

$\bar{x}_{old}$ = old smoothed value;

x_{new} = new raw value; and

k= smoothing factor.

Smaller values of the filter *k* give more weight to past data and results in sluggish system response to changes in the variable *x*. On the other hand larger values of *k* cause the system to be more responsive to changes in data, but that might also lead the system to be more affected by noise in traffic data. Thus, the filter value must be selected to provide maximum responsiveness while maintaining system stability. Although the *k* value can have a major impact on the transitioning of the signal system, there is no theoretically based recommendation of the *k* value in order to minimize the transitioning effects.

The other smoothing approach is to average the values of the variable *x* over the previous *n* time intervals. Clearly, the greater the number of previous time intervals used, the less sensitive the smoothed value is to changes.

The literature merely recommends that smoothing factors be set to 50 percent at the initial implementation of the TRPS system. Previous research recommends that the smoothing factors be fine-tuned later in the field. However, fine-tuning a TRPS system in the field is a very difficult task. Unlike isolated intersections where engineers can observe changes in traffic conditions causing certain controller behaviors, changes causing the closed-loop system to implement a different timing plan might be occurring at another intersection. There is clearly a need for formal, sound, and properly tested guidelines on how to select smoothing factors that would lead to optimal performance.

Weighting Factors

Each system detector is assigned a weighting factor by which its data is multiplied during the aggregation process. Unlike the name implies, a weighting factor does not emphasize the importance of an individual system detector as will be discussed later in this report. Some manufacturers allow assigning different weighting factors to occupancy and counts as well as a weighting factor at the detector itself. Although selection of the weighting factors is crucial to the operation of the TRPS mode, no guidelines have been offered to help achieve this task.

TRPS Mechanism and Thresholds Selection

TRPS utilizes several Computational Channel (CC) and Pattern Selection (PS) parameters to arrive at the final selected timing plan. Figure 1 shows a general TRPS mechanism where occupancy and count information from a group of *n* system detectors (n differs from one manufacturer to another, e.g., eight in Eagle controllers) are aggregated into a CC parameter (i.e., by multiplying each system detector by its corresponding weight W). Note that system detectors used with a CC parameter may or may not be the same system detectors used with another CC parameter. The name and number of CC parameters in a TRPS system differs from one manufacturer to another. Most TRPS manufacturers, however, agree on the names and number of the PS parameters, namely cycle, split, and offset PS parameters. Each PS parameter is calculated as a function of several CC parameters. Some of these functions are user selected where others are predefined by the controller manufacturer.

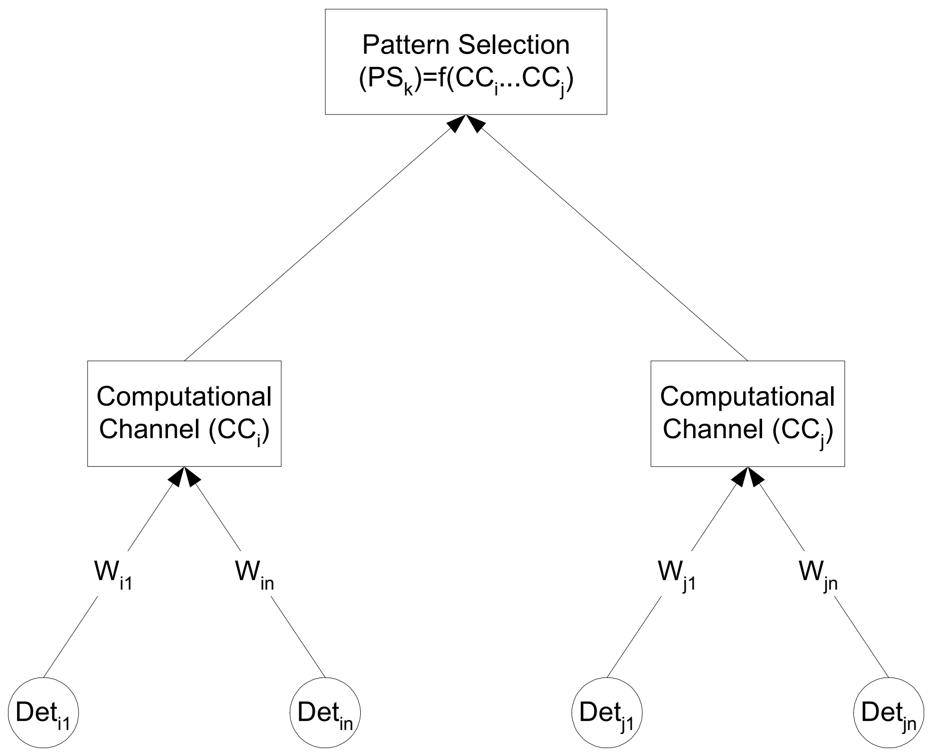


Figure 1. General TRPS Mechanism.

In addition, the TRPS mode requires the operator to pre-define "entering" and "exiting" thresholds for each PS parameter. The definition of a different "entering" and "exiting" threshold provides a hysteresis control. In the context of control systems, hysteresis is defined as a retardation of the system reaction (i.e., selection of a new timing plan) to changes applied to the system (i.e., increased traffic demand). This hysteresis control enhances system stability when the thresholds for each TRPS parameter are set up correctly.

The master controller compares each PS parameter value to its corresponding threshold to identify the appropriate PS level. The three PS levels are used as index values in a table lookup procedure. The lookup table entries determine which one of the pre-stored timing plans will be selected.

This cycle-split-offset PS parameter nomenclature can be somewhat confusing to the user. Each PS parameter value merely specifies an index into the TRPS lookup table and not the actual cycle, splits, and offset values. In addition, it is not necessary to use all PS parameters in the TRPS mechanism. For example, if four timing plans are to be implemented in a closed-loop system and they were differentiable by one PS parameter, then only one PS parameter is needed for TRPS operation. This PS parameter could be any one of the cycle, split, or offset PS parameters.

Each controller manufacturer uses different types and numbers of CC parameters, along with a different mechanism for implementing the TRPS mode. Researchers developed the following flowcharts to summarize the operation of the TRPS mode for each of the two TxDOT-approved manufacturers.

Eagle TRPS

The Eagle closed-loop system TRPS (shown in Figure 2) processes the occupancy (OCC) and count information at the local controller level. The master controller can be programmed to utilize up to 64 system detectors. Of these 64 system detectors, up to eight detectors can be assigned to each CC parameter. The count and occupancy data from each system detector are scaled and smoothed over a specified sampling period. The Eagle system weighs the occupancy and count data at the detector as well as at the CC parameter level. The Eagle system allows the use of either the average or the maximum value of the detectors assigned to each CC parameter. The user must pre-select which option the system will use. The Eagle system has the following 10 CC parameters:

- Cycle Select One (CS1),
- Cycle Select Two (CS2),
- Directionality One (DR1),
- Directionality Two (DR2),
- Non-Arterial One (NA1),

- Non-Arterial Two (NA2),
- Queue One (Q1),
- Queue Two (Q2),
- Occupancy One (OC1), and
- Occupancy Two (OC2).

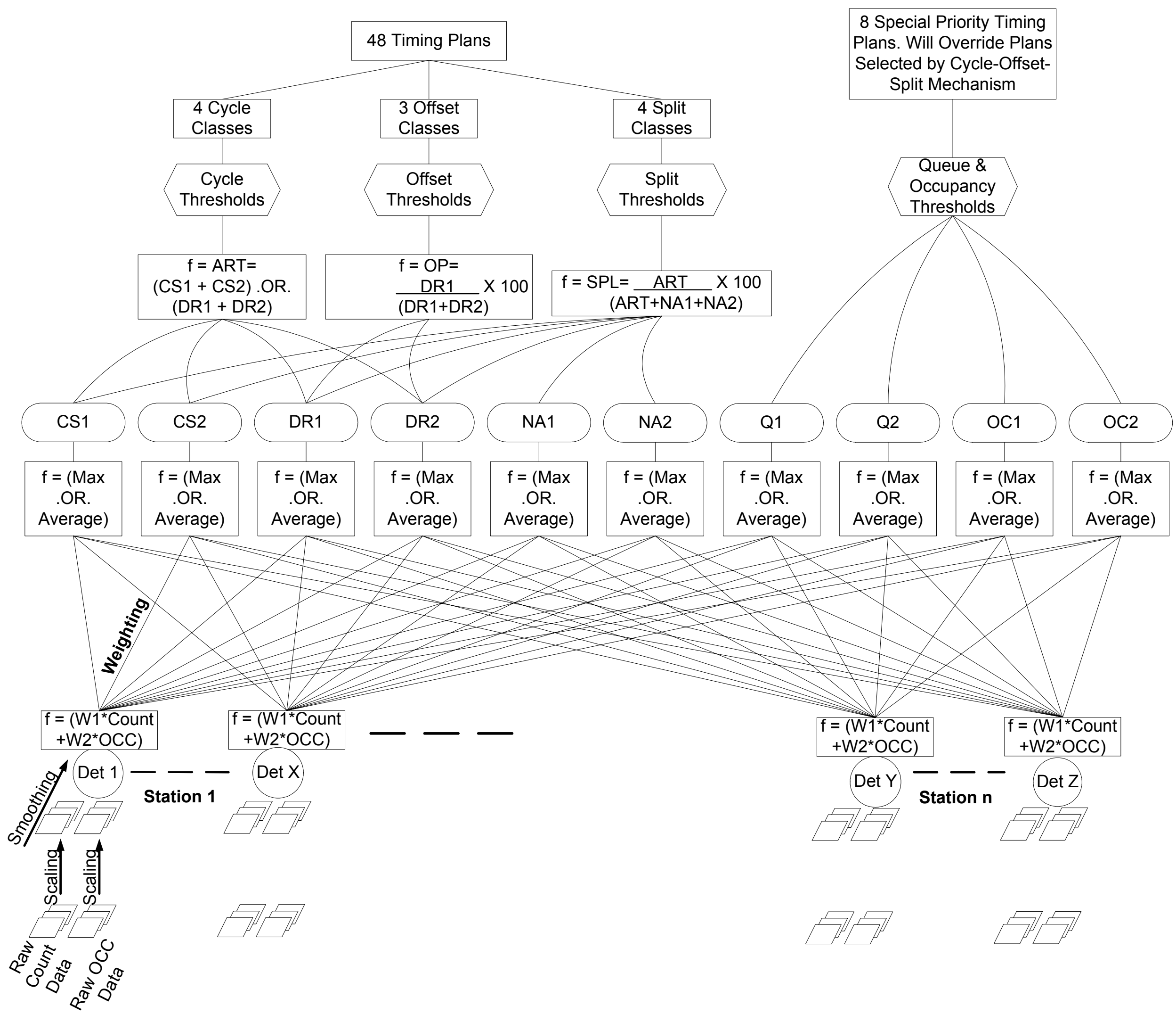


Figure 2. Eagle TRPS Parameters and Mechanism.

The master controller compares the PS parameter values (calculated using the above CC parameters) to their corresponding thresholds to identify the appropriate PS parameter level (cycle, offset, and split). The combination of cycle-offset-split PS parameter levels is used to select the most appropriate timing plan for the existing traffic condition. The Eagle master controller uses the cycle select CC parameters to calculate the cycle PS parameter. The directionality CC parameters are used to calculate the offset PS parameter. The non-arterial CC parameters along with the cycle and directionality CC parameters are used to calculate the split PS parameter. In addition to selecting timing plans using cycle, offset, and split PS parameter levels, the Eagle system can also select up to eight additional timing plans using the optional queue and occupancy CC parameters. When activated, these additional plans will override the standard plans chosen by the cycle-offset-split PS parameters combination.

Naztec TRPS

The Naztec closed-loop system uses only three CC parameters for calculating timing plans. However, combinations of these three CC parameters are used to calculate each of the PS parameter levels (cycle, offset, and split). The three CC parameters in the Naztec system are:

- inbound,
- outbound, and
- cross-street.

The Naztec TRPS mechanism (Figure 3) uses cycle, offset, and split PS parameter values as entry indexes in a table lookup procedure. In this procedure, one of 24 different timing plans (with the option of specifying two offsets for each plan) can be assigned to each one of the 144 possible combinations of cycle-offset-split PS parameter levels.

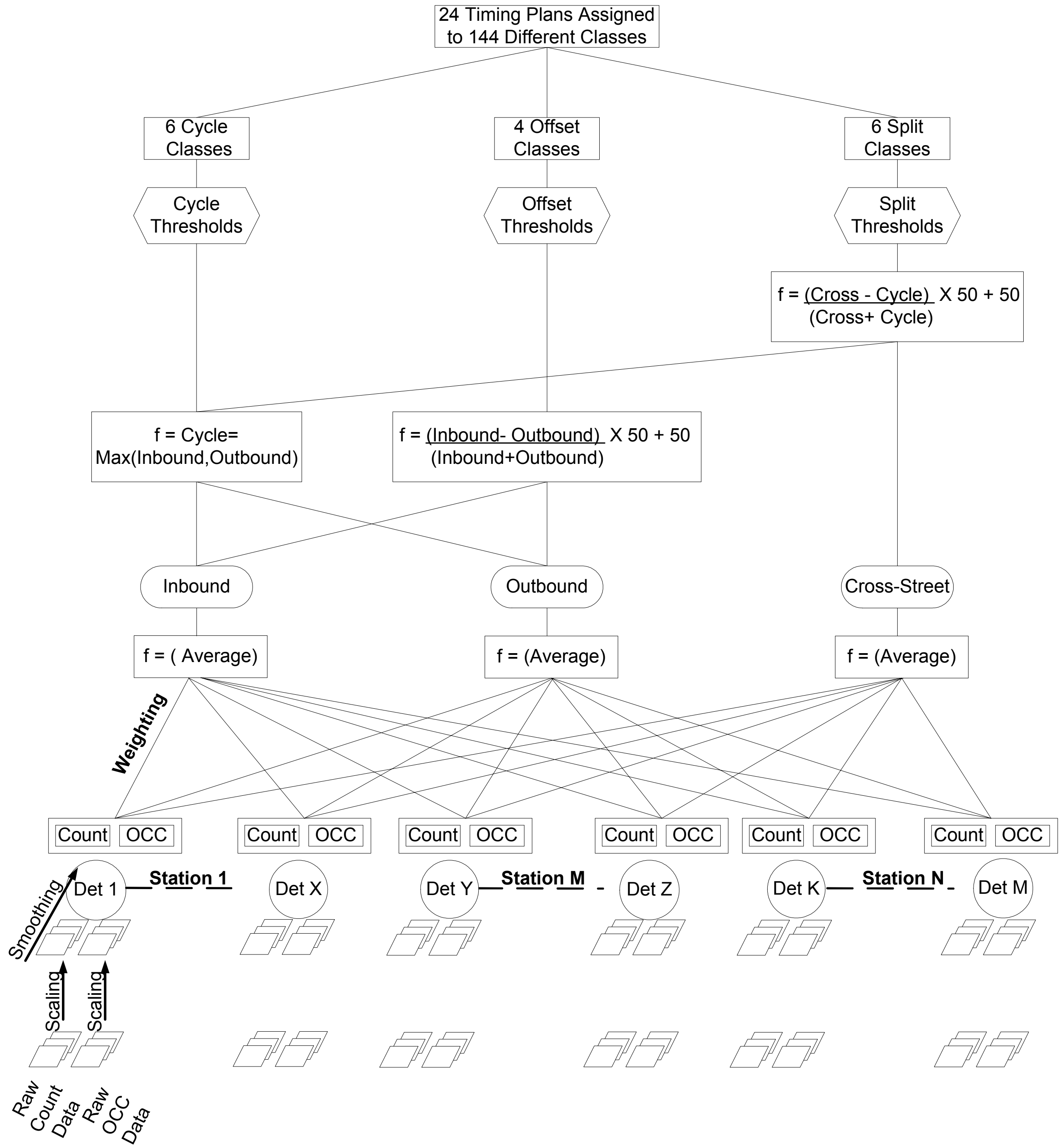


Figure 3. Naztec TRPS Parameters and Mechanism.

As can be deduced from the previous section, setting up a TRPS system to work optimally is not a trivial task. Besides the possibility of selecting incorrect plans, improper values of TRPS parameters can set the system into a perpetual transitioning state. When the system is not in a steady state, benefits of a better timing plan might be offset by the delays associated with transitioning between timing plans. Previous research had shown that only marginal benefits could be achieved over TOD mode when fluctuation in traffic demand caused frequent timing plan changes. Therefore, there is a need for statistically and theoretically sound guidelines on how TRPS parameters and thresholds can be selected such that TRPS results in an optimal and stable system operation.

SUMMARY

When properly configured, the TRPS mode has the greatest potential to provide an optimal operation utilizing existing capabilities of closed-loop systems. The TRPS mode is more beneficial than other operating modes due to its ability to accommodate abnormal traffic conditions such as incidents, special events, and holiday traffic. Most importantly, the TRPS mode can reduce the need for frequent redesign/updates to signal timing plans.

There are no formal guidelines for optimal setup of TRPS systems. The lack of guidelines can result in the selection of inappropriate timing plans or in the closed-loop system running in continuous transitioning states. Due to the lack of formal, clear, and comprehensive guidelines for selecting traffic responsive parameter thresholds, traffic engineers usually revert to the TOD mode of operation for its ease of setup. As a result, the benefits of closed-loop systems are not fully utilized.

CHAPTER 3: STATE OF THE PRACTICE IN TRPS CONTROL SETUP

INTERVIEW OF CITY AND STATE AGENCIES IN TEXAS

State of the practice in setting up a TRPS mode in Texas was assessed through communication with TxDOT engineers and technicians. Information was sought about the problems experienced with the TRPS mode and closed-loop systems in general. Another objective was to help identify three candidate closed-loop systems for this project: two closed-loop systems to be used for the purpose of guidelines development, and a third system to be used at a later stage for the purpose of guidelines evaluation.

Engineers and technicians with five districts were either visited or interviewed by phone to collect their experience with TRPS (Table 1). These districts have mainly Eagle and Naztec controllers.

Table 1. TxDOT Contacts.

TxDOT Contact	District
Mr. Howard Holland	Brownwood
Mr. Dexter Turner	Corpus Christi
Mr. Doug Vanover	Houston
Mr. Stuart Jenkins	Pharr
Mr. Gilbert Myers	San Antonio

Information obtained during the interviews suggested that TxDOT had limited experience with operation of closed-loop systems with TRPS mode. The research team was able to identify only two closed-loop systems that were being operated with TRPS. These two systems were located in Bastrop (Austin District) and Universal City (San Antonio District). However, TxDOT had a successful experience with the traffic responsive control with the legacy TxDOT Flexible Advanced Computer Traffic Signal System (FACTS) (*16*).

The closed-loop system in Universal City had 14 intersections and was adjacent to railroad preemption. The system was in the "fine-tuning" stage but was showing promising results. The system in Bastrop consists of five intersections. The system had been operated with TRPS plans designed by Eagle Traffic Control Systems. All of the interviewees have indicated their interest in operating their closed-loop systems with TRPS. There were, however, some concerns about the amount of setup time the TRPS requires such that it operates in an efficient and stable manner. The advantages and disadvantages of TRPS, as indicated by the TxDOT engineers and technicians, are discussed in the following section.

Advantages of TRPS

The TRPS mode was reported to perform better than the TOD mode during special events (symphony, sales, sports events, etc.). The Houston District had a pleasant experience with the traffic responsive control with the TxDOT FACTS system. The districts, however, were not operating their closed-loop systems with TRPS mode due to the different setup and operation mechanism of commercial TRPS mode and the lack of detailed guidelines.

Disadvantages of TRPS

Experience with the TRPS mode indicated that it was not always clear which system detectors need to be used in order to recognize changes in traffic patterns in a timely manner. System detectors in mid blocks are not always functional. These detectors tend to be maintained only when they are used for TRPS mode, with a lower maintenance priority otherwise.

Several TxDOT engineers and technicians have indicated that by the time a TRPS implements a different timing plan, the traffic event that warranted the change would be almost over. Previous TRPS operated systems have also shown tardiness in returning to normal uncongested timing plans. This condition typically results in complaints from the drivers waiting on side-street approaches who are denied the right-of-way due to long cycle lengths. Another major concern was the system instability resulting in too frequent changes between timing plans that would eventually lead to an increase in the overall system delays. However, the Houston District has indicated past success in controlling instability with hysteresis control when they were using the TxDOT FACTS system.

INTERVIEW OF CITY AND STATE AGENCIES OUTSIDE OF TEXAS

The objective of this task was to learn from the experience of engineers and technicians in other U.S. states. The interviews took place by telephone. Table 2 shows the list of agencies and the contact persons.

Table 2. Out-of-State Agency Contacts.

Agency Contact	Transportation Agency
Mr. Larry Rust	Indiana DOT
Mr. Terry Rammacher/Mr. Jim Ellis	Illinois DOT
Ms. Tricia Gabriel	California DOT
Mr. Mark Plass	Florida DOT
Mr. Steve Misgen	Minnesota DOT

Out-of-state agencies had several types of traffic controllers including Eagle, Naztec, Econolite, 170s, and 2070s. Some of these agencies used advance intersection detectors in place of system detectors and reported reasonable success.

The main advantage of TRPS over the TOD as reported by the out-of-state agencies is the better capability of TRPS to accommodate long-term temporal changes in traffic patterns with less need to retime the closed-loop signal systems. This capability stems from the fact that the TRPS system will simply use timing plans that are more suitable to the current traffic patterns if such plans are stored in the controllers. With the TOD mode, the engineers would have to modify the TOD schedule to implement the more suitable timing plans at the correct times.

Issues encountered were system instability—controller bouncing between different timing plans—and the complexities in setting up the TRPS systems. Minnesota DOT has reported that they were able to address this problem by implementing a limited number of timing plans such that the controller will switch to another timing plan only when there is a significantly large change in traffic conditions.

INTERVIEW OF VENDORS OF CLOSED-LOOP SYSTEMS

The objective of this task was to gather up-to-date information about the TxDOT-approved controllers' TRPS systems. The vendor contacts listed in Table 3 provided valuable information in the form of latest guidelines and procedure manuals and software demonstration of their TRPS systems.

Table 3. Vendor Contacts.

Vendor Contact	Vendor
Mr. Arnold McLaughlin	Eagle Traffic Control Systems
Mr. John Black	Naztec, Inc.

CHAPTER 4: SITE SELECTION AND FIELD STUDIES

OVERVIEW

This chapter documents the activities conducted for collection of field data for two closed-loop systems. The first part of this chapter identifies the site selection criteria. The second part summarizes the findings from field visits to two closed-loop systems.

SITE SELECTION CRITERIA

The scope of this research was limited to closed-loop systems on arterial network. It was, therefore, determined that for a closed-loop system to qualify as a study site, it must meet the following qualifications:

- Urban/suburban arterials with moderate-to-high volumes (normal-to-congested conditions) are preferred.
- The system should consist of three to five intersections.
- Intersection must be of typical geometry (two lanes, four-leg intersections, etc.).
- System must not include interchanges.
- Closed-loop system must have working system detectors. System detectors can be either loops or possibly wireless VIVDS.
- Preferable available system characteristics include:
    - network geometry drawings,
    - phase sequence and ring structure, and
    - traffic variation throughout the day (15-minute counts).

SITE SELECTION AND FIELD DATA COLLECTION

Since the TRPS system achieves its benefits by adapting to variations in the traffic demand, it was critical to assess the benefits of a TRPS system with realistic variations in the traffic flows. The objective of the field data collection was to collect realistic traffic volume variations from two sites. A site was defined as a closed-loop system and therefore consisted of several intersections. The collected data was used to study the behavior and impact of TRPS. The data sought included: 1) network geometry, 2) phase sequences and ring structure, and 3) traffic variation throughout the day.

Sites Investigated

Engineers and technicians with six districts were either visited or interviewed by phone. These districts have mainly Eagle and Naztec controllers. Table 4 lists the individuals that the research team contacted.

Table 4. TxDOT Staff Contacted for Study Sites Identification.

TxDOT Contact	District	Number of Closed-Loop Systems	Closed-Loop Systems Operated with TRPS
Mr. Chuck Ansley	Austin	7	1
Mr. Howard Holland Mr. Gordon Harkey	Brownwood	2	0
Mr. Dexter Turner Mr. Wayne Carpenter	Corpus Christi	15	0
Mr. Doug Vanover	Houston	40	0
Mr. Stuart Jenkins	Pharr	3-4	0
Mr. Gilbert Myers	San Antonio	6-7	1

Information obtained during the interviews suggested that TxDOT had limited experience with operation of closed-loop systems with TRPS mode. All of the interviewees, however, have indicated their interest in operating their closed-loop systems with TRPS. The research team identified only two closed-loop systems that were being operated with TRPS. These two systems were located in Bastrop in the Austin District and Universal City in the San Antonio District.

The closed-loop system in Universal City had 14 intersections and was adjacent to railroad tracks, experiencing frequent preemptions. The system was in the “fine-tuning” stage but is showing promising results. This system was not qualified as a study site because it consisted of too many intersections. The system in Bastrop consists of five intersections. The system has been operated with TRPS plans designed by Eagle Traffic Control Systems.

Sites Selected

The two sites selected for further study were the site in Bastrop along SH 71 and a site in Odem along US 77. The Bastrop system has been previously operated with TRPS prior to the start of this research project. VIVDS cameras mounted on median poles were used to provide system detection. The cameras were pointed at both lanes downstream of the intersections along

SH 71, and were wired back to the controller in a common lead-in cable. The research team had access to traffic count data from the Bastrop system. Researchers collected data during Labor Day and Memorial Day holidays. In addition, Mr. Chuck Ansley provided the research team with network sketches, turning-movement counts during normal conditions for most of the intersections, and original timing plans. Figure 4 shows the Bastrop closed-loop system.

The second system was in Odem in the Corpus Christi District. This system consisted of three VIVDS-operated intersections. Although the Odem system was not operated with the TRPS mode, it was selected because it is operated with VIVDS. The VIVDS cameras allowed the research team to record video for two weeks at one intersection. Data were used later in the project to ground truth the vehicle counts obtained from the VIVDS detectors. Figure 5 shows the Odem system.

For the Bastrop system, the research team had turning-volume counts during normal and holiday traffic conditions. For the Odem system, the research team collected detector counts during nine days including the Sunday following the Thanksgiving holiday. In addition, the team collected a video recording of the intersection of US 77 and Willis Street for a two-week period that spanned the detector log period.

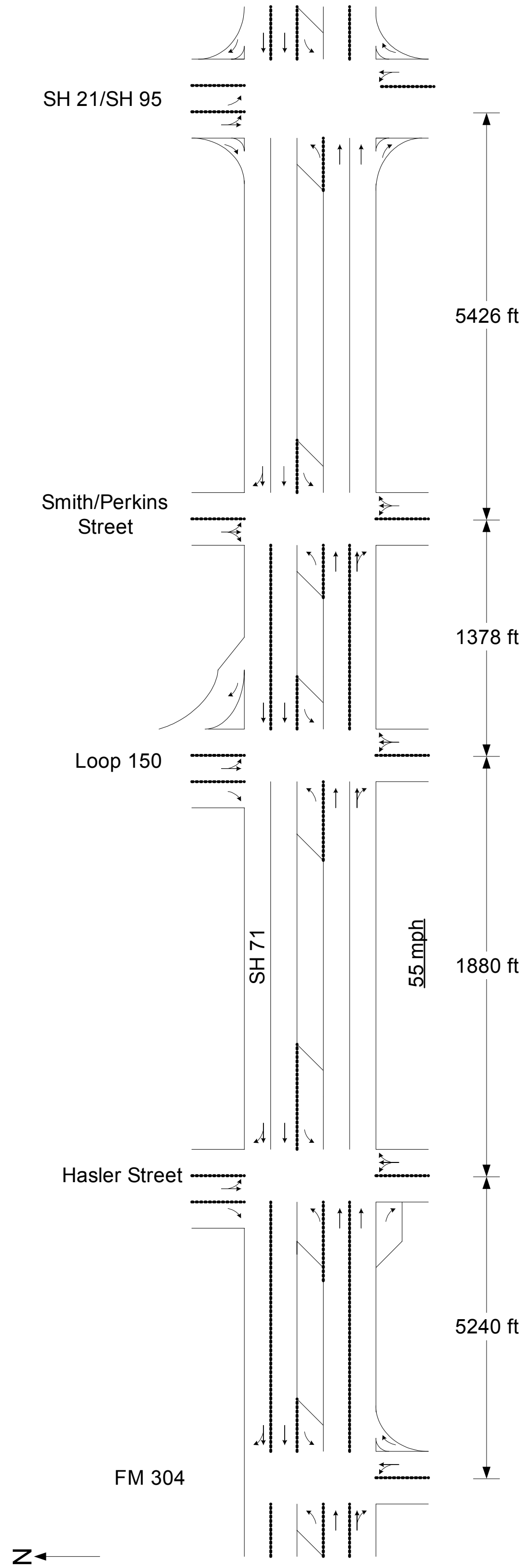


Figure 4. Bastrop Closed-Loop System.

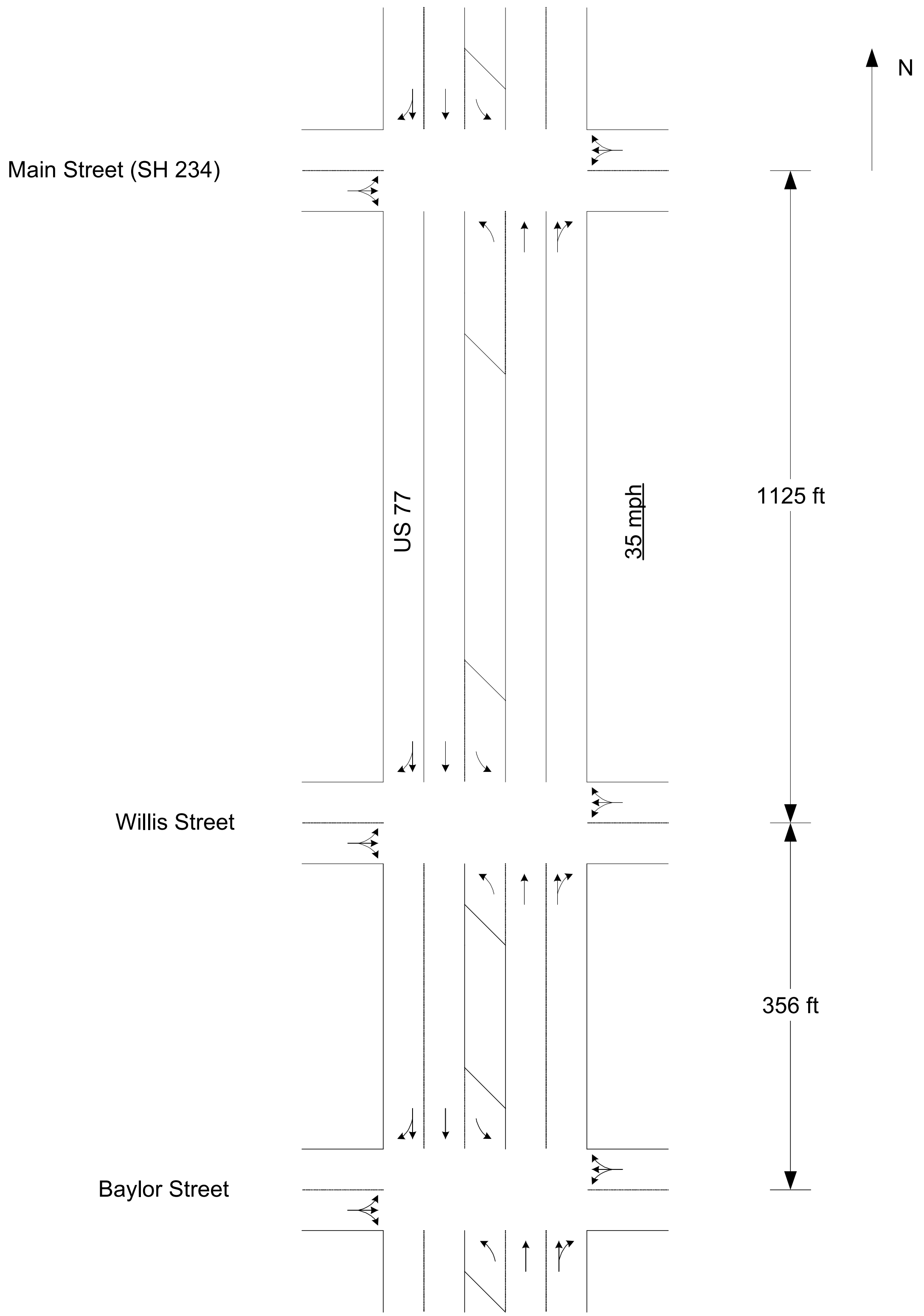


Figure 5. Odem Closed-Loop System.

CHAPTER 5: METHODOLOGY FOR SELECTION OF ROBUST TRPS SYSTEM PARAMETERS

INTRODUCTION

This chapter addresses the most important challenge in setting up a TRPS mode: robust and optimal selection of TRPS parameters and thresholds. These selections include weighting factors for each system detector as well as the thresholds corresponding to each selection level (cycle, offset, and split levels). To date, and as the name implies, weighting factors have been considered as a means for assigning an importance level to each system detector. This approach, albeit logical, leaves several questions unanswered. The determination of the importance level of each detector is quite subjective. In addition, determination of the degree of importance—the weights—is not based on any mathematical or scientific methodology.

The methodology followed in our research was based on the realization that TRPS control is essentially a pattern recognition problem of different traffic states. Every intersection approach movement in the closed-loop system is a dimension in the TRPS state space. Variation in the state variable along any of these dimensions can be potentially "sensed" through the occupancy and count information obtained from a system detector placed at that approach. The major challenge of TRPS system setup is the determination of a set of detector weights that can map the multi-dimensional state space into a uni-dimensional PS parameter ordinate. This mapping should occur such that maximum separation of different traffic states can be achieved with a set of PS parameter thresholds.

Figure 6 illustrates this concept. Figure 6 is a simplified three-dimensional space that shows samples from two different state distributions. The reader can think of these two states as low- and high-volume demand cases, respectively. The three-dimensional sample points from these two states correspond to occupancy data from three system detectors placed at three different approaches. Parts a, b, and c of Figure 6 correspond to three different sets of detector weights. Figure 6a shows a set of weights that provide poor separation of the two state distributions. Figure 6b shows a different set of weights that provides a better separation. Figure 6c shows the best set of weights which provides total separation of the two state distributions.

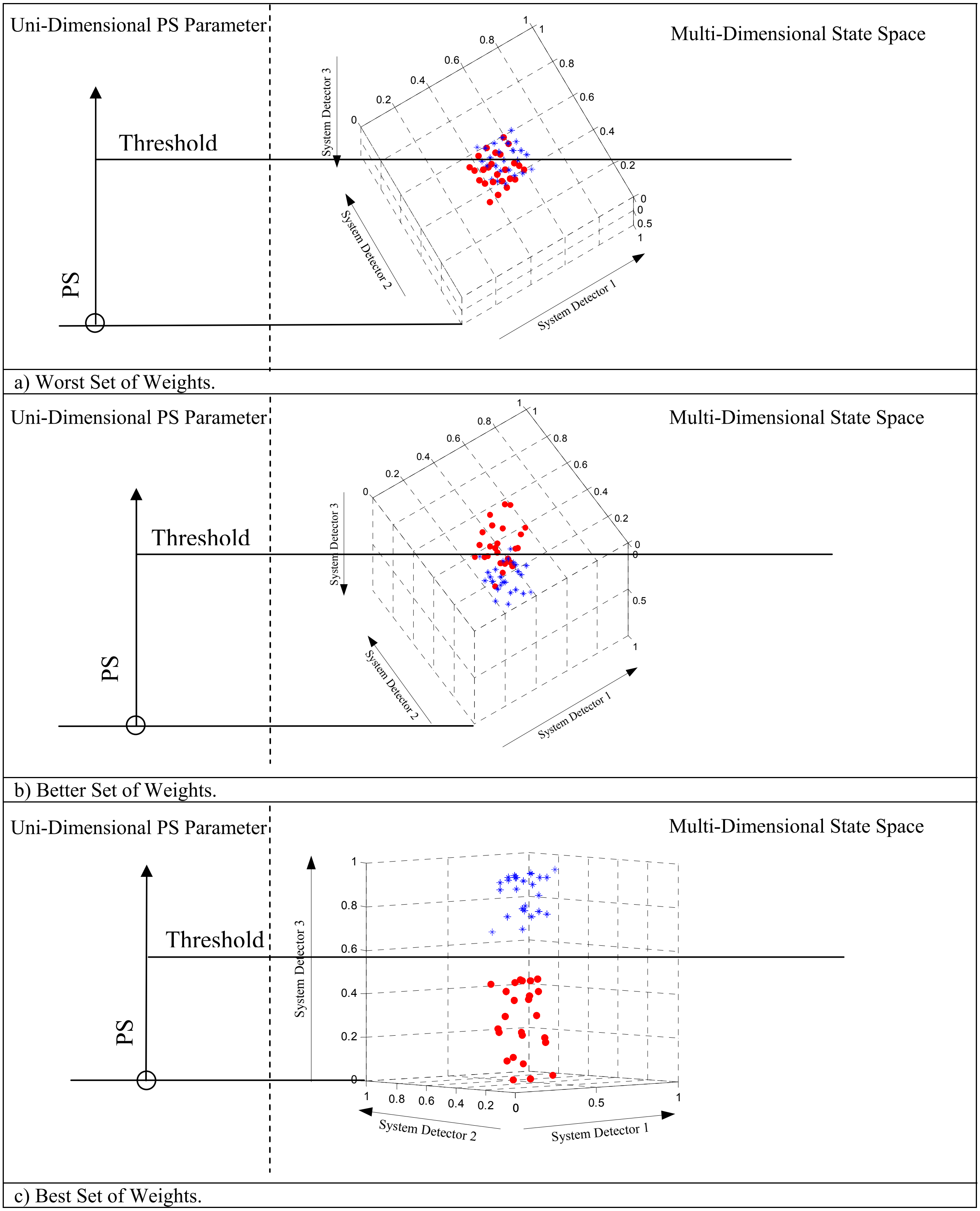


Figure 6. Effects of Detector Weights on the TRPS State Space.

The following sections discuss the methodology followed in this research to determine system detector weights such that the best possible recognition of different states can be achieved.

RESEARCH METHODOLOGY

This research uses a robust Bayesian-based approach to select the TRPS parameters and thresholds. The proposed methodology is listed as follows:

1. Design the closed-loop system to address a wide range of traffic conditions (states). This can be achieved by selecting several levels of traffic conditions and designing an appropriate timing plan for each level.
2. Group similar traffic states together (using clustering techniques) and select a representative state from each group.
3. Use a simulation program, such as CORSIM *(17)*, to simulate the closed-loop system with system detectors placed at all candidate approaches. Obtain the system detectors' occupancy and counts for each simulated state.
4. Select system detectors that allow best discrimination of different states. This objective can be achieved by using stepwise discriminant analysis *(18)*.
5. Determine the weights associated with the selected system detectors such that the CC parameter calculated using these weights captures most of the variability between different states. This objective can be achieved by using canonical discriminant analysis *(18)*.
6. Using the PS parameter calculated from the relevant CC parameters, obtain the discriminant functions that can distinguish between different states.
7. Plot the discriminant functions and determine the points of their intersections. These points of intersections define the TRPS thresholds for different states.

The following sections illustrate the above procedure and show the results of applying it to the Odem closed-loop system.

ODEM CLOSED-LOOP SYSTEM

The closed-loop system in Odem, Texas, was studied and analyzed following the proposed methodology. Figure 7 shows the locations and identities (IDs) of system detectors as they were placed in the CORSIM network. These system detectors were placed 400 feet upstream of each intersection, except for between Willis and Baylor streets where the spacing between the intersections did not allow placing the detectors at 400 feet upstream. These specific detectors were placed mid-distance between the two intersections.

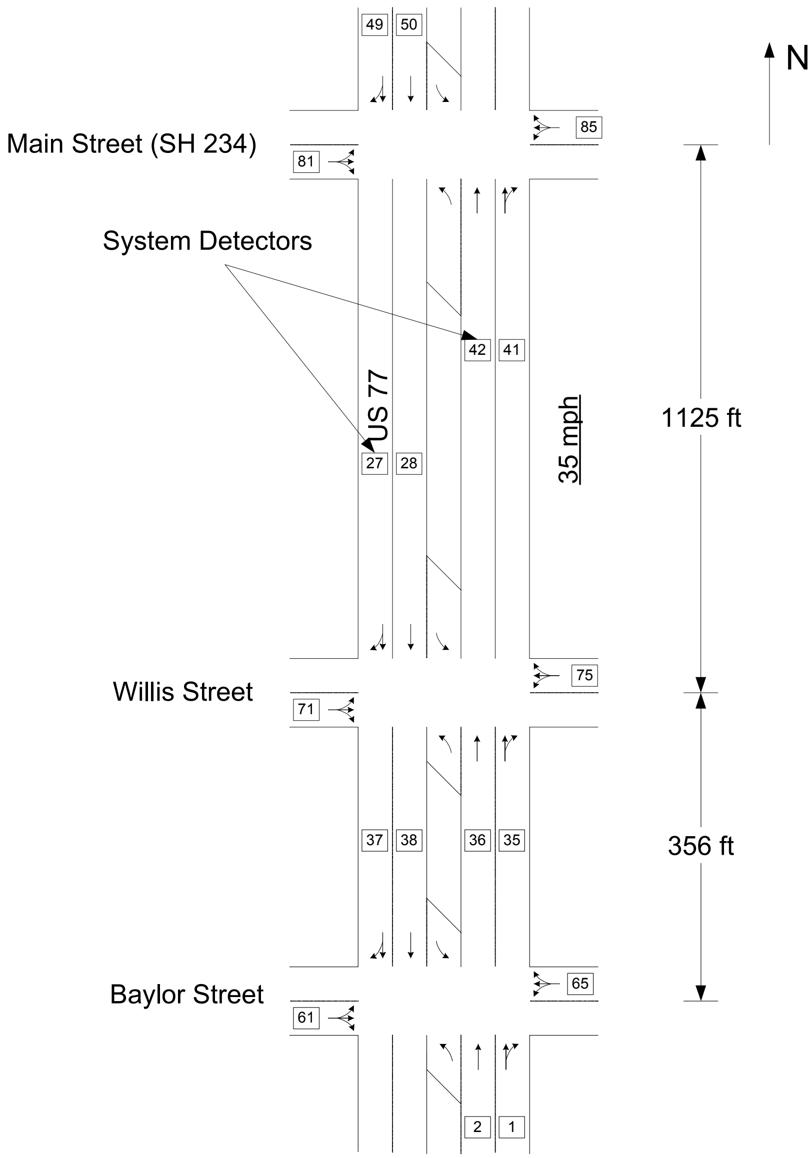


Figure 7. System Detector Locations on Odem Closed-Loop System.

Design of Timing Plans

Table 5 shows the traffic states for the Odem system. These states are representative of normal and holiday traffic conditions. Timing plans corresponding to each of these states were developed using SYNCHRO 5.0 *(19)*. The final plans are listed in Table 6. Figure 8 shows an example of the association of Odem temporal traffic distribution with the designed timing plans. The traffic distribution shown in the figure corresponds to 29 hours of data following the Thanksgiving holiday to show an example of traffic volume variation. After placing system detectors in the Odem CORISM network, simulations were performed for all plan-state combinations. Detectors' count and occupancy values were collected over 5-minute intervals for all of the simulation files. These values were then used to determine detector weights and TRPS thresholds as will be explained in the next sections.

Table 5. Traffic Volume States on the Odem Network.

State	Intersection with US77	Traffic Volume (vph)					
		EB	NB	NBL	WB	SB	SBL
1	Baylor	56	847	11	85	1462	13
	Willis	50	1030	14	94	1742	1
	Main St	24	1305	22	52	1836	40
2	Baylor	61	828	9	115	1369	23
	Willis	60	926	15	64	1571	0
	Main St	33	1371	4	73	1969	24
3	Baylor	71	567	14	63	574	8
	Willis	46	620	17	52	688	4
	Main St	27	984	25	68	808	57
4	Baylor	21	199	0	14	100	0
	Willis	24	175	0	14	80	0
	Main St	18	261	1	19	131	9
5	Baylor	17	225	1	14	60	0
	Willis	21	187	0	14	80	0
	Main St	16	299	1	20	88	4
6	Baylor	70	494	26	62	429	9
	Willis	45	534	14	49	514	4
	Main St	33	883	38	66	607	61

Table 6. Designed Timing Plans on the Odem Network.

Plan	Intersection with US77	Cycle (sec.)	Split (sec.)						Offset (sec.)
			SBL	NB	EB	NBL	SB	WB	
	Baylor	90	9	48	33	9	48	33	0
	Willis	90	9	48	33	9	48	33	83
1	Main St	90	9	48	33	9	48	33	65
	Baylor	70	10	34	26	9	35	26	0
	Willis	70	9	35	26	9	35	26	63
2	Main St	70	9	36	25	9	36	25	40
	Baylor	85	9	58	18	10	57	18	0
	Willis	85	9	58	18	9	58	18	82
3	Main St	85	10	57	18	9	58	18	65
	Baylor	125	9	86	30	9	86	30	0
	Willis	125	9	86	30	9	86	30	120
4	Main St	125	9	86	30	9	86	30	8
	Baylor	60	9	31	20	9	31	20	0
	Willis	60	9	31	20	9	31	20	55
5	Main St	60	9	31	20	9	31	20	31
	Baylor	115	9	62	44	9	62	44	0
	Willis	115	9	62	44	9	62	44	111
6	Main St	115	9	62	44	9	62	44	105

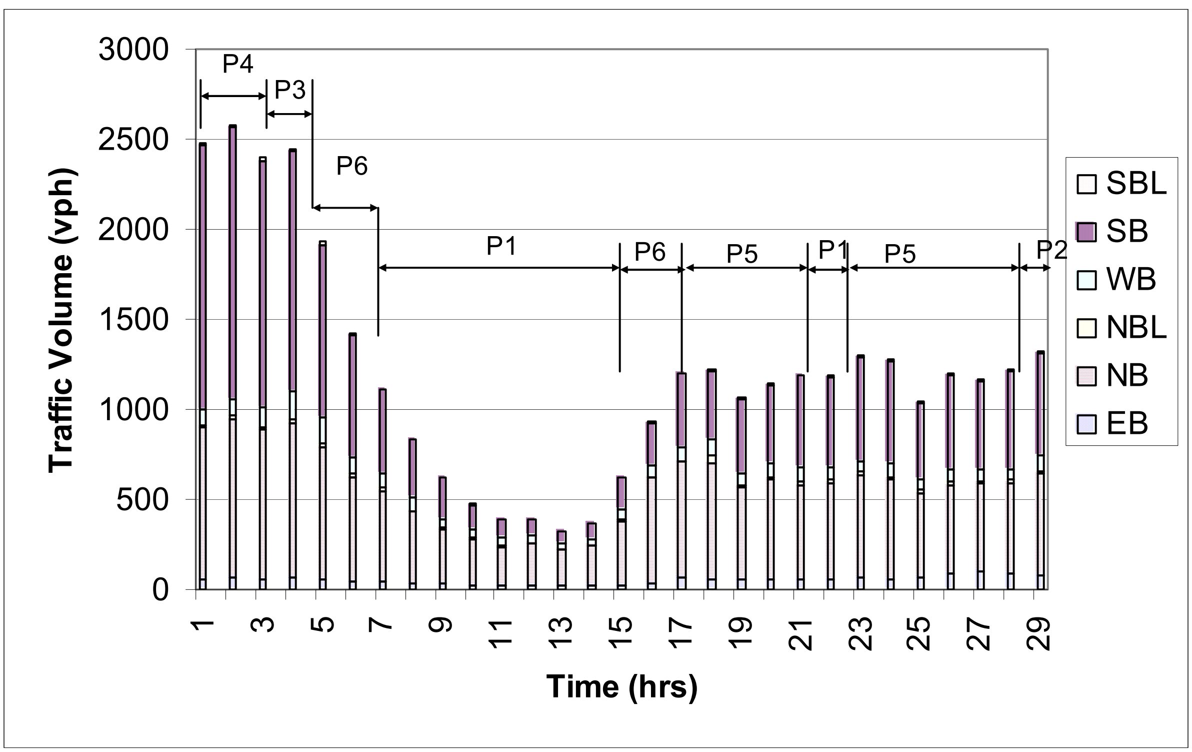


Figure 8. Assignment of Timing Plans to Different Traffic States.

Discriminant Analysis

Discriminant analysis is a Bayesian-based procedure where previous knowledge of observations' states is used to formulate a discriminant function for each state. These discriminant functions, in turn, can be used to classify future observations into one of the known states. Predicting states of observations with known classifications (e.g., re-substitution of original data) using the formulated discriminant functions can be used to estimate the rates of correct classifications. These rates of correct classifications are typically used to evaluate the performance of the discriminant functions.

The canonical discriminant analysis, on the other hand, is a dimensionality reduction technique similar to principal component analysis that can be used to determine the best linear combinations of variables such that the differences between classes are well-defined. These two procedures were used in this research to obtain PS thresholds and TRPS detector weights, respectively.

Selection of System Detectors

One of the limitations imposed by the TRPS control mechanism implemented by the traffic controller vendors is the maximum number of system detectors that can be assigned to each TRPS channel. To address this limitation, stepwise discriminant analysis was used to select the group of eight system detectors that has the most correlation with the changes in state variable. The selected detectors are listed in the next section with their associated weights.

Determination of Detector Weights

Determination of a canonical variable is especially important since each of the PS parameters (cycle, offset, and split level) are calculated based on one combination of system detector actuations (occupancy and count). Theoretically, each PS parameter can have its own canonical variable such that most of the differentiation power is achieved. In the Odem network, only the cycle level parameter was used (and needed). The Statistical Analysis Software (SAS *[20]*) canonical discriminant procedure was used. The results of the canonical analysis are listed in Table 7. Note that final detector weights do not show negative values since negative values cannot be entered as weights in the current setup of traffic controllers (another limitation of the TRPS mechanism). The final discriminant functions were plotted using the modified weights to account for this limitation.

The count scaling factor is calculated in the controller as the raw volume divided by the maximum approach capacity as input by the user. Since the analysis used volumes accumulated over 5 minutes sampling rate and the controller will convert the raw volume back to a volume per minute, the maximum approach capacity should be entered as 20 (100/5) vehicles per minute. For example, if the raw volume over 5 minutes was 10 vehicles, the controller will divide that by the sampling period as 10/5=2 vehicles per minute. The controller will then divide that by the maximum capacity of 20 vehicles per minute to arrive at 2/20=10 percent, which is the value used in the analysis. The maximum occupancy rate should be kept at 100 percent since the controller will always interpret occupancy as a rate in percent. For example, if the raw occupancy over the 5 minutes sampling period was 30 percent, the controller will divide that by the maximum occupancy rate to arrive at 30/100=30 percent.

Table 7. System Detector Weights.

System Detector Number	Raw Weight		Detector Weight	
	Count	Occupancy	Count	Occupancy
2	0.136	0.095	14	10
38	-0.006	0.006	0	1
61	-0.063	0.007	0	1
42	0.039	0.007	4	1
50	0.072	0.149	7	15

Determination of State Discriminant Functions

Once the canonical variable coefficients were determined, discriminant analysis was performed on the new defined variable, i.e., each observation in the data set had an associated state as well as a PS parameter value calculated as the summation of each system detector actuation multiplied by the final weight assigned to that detector. The misclassification rates for each state, as obtained from the discriminant analysis, are shown in Figure 9. Note that Figure 9 shows a high misclassification rate of state 1 into state 2 and vice versa, with 0 misclassification rate of the two states into other states. This result suggests that states 1 and 2 should actually be considered as one state. States 3 and 4, and states 5 and 6, show the same results; suggesting that states 3 and 4 should be considered as another state; and states 5 and 6 should be considered as the third state. The similarity of states 1 and 2 as far as detector actuation is concerned is probably due to the actuated operation of the signal in CORSIM that might not have been fully accounted for by SYNCHRO when timing plans were designed. This explanation is evident in Table 8, where minimum control delay resulting from applying each of the timing plans to every state is shown in the shaded cells. Note that total control delay resulting from implementing plan 2 with state 1 is actually less than the delay resulting from implementing plan 1 with state 1 (which is supposed to be the optimal plan for state 1). Other entries in the table support the same argument. Note also that the misclassification error from the suggested groups into other groups is 0 percent. This observation means that if the six original states were treated as three states and were assigned timing plans accordingly, the TRPS will achieve 100 percent state identification accuracy.

Generalized Squared Distance Function

$$D_j^2(X) = (X-\bar{X}_{(X)j})' \, COV_{(X)}^{-1} \, (X-\bar{X}_{(X)j})$$

Posterior Probability of Membership in Each State

$$Pr(j|X) = \exp(-.5 \, D_j^2(X)) \; / \; SUM_k \, \exp(-.5 \, D_k^2(X))$$

Number of Observations and Percent Classified into State

From State	1	2	3	4	5	6	Total
1	40 55.56	32 44.44	0 0.00	0 0.00	0 0.00	0 0.00	72 100.00
2	33 45.83	39 54.17	0 0.00	0 0.00	0 0.00	0 0.00	72 100.00
3	0 0.00	0 0.00	46 63.89	26 36.11	0 0.00	0 0.00	72 100.00
4	0 0.00	0 0.00	23 31.94	49 68.06	0 0.00	0 0.00	72 100.00
5	0 0.00	0 0.00	0 0.00	0 0.00	46 63.89	26 36.11	72 100.00
6	0 0.00	0 0.00	0 0.00	0 0.00	25 34.72	47 65.28	72 100.00
Total	73 16.90	71 16.44	69 15.97	75 17.36	71 16.44	73 16.90	432 100.00
Priors	0.16667	0.16667	0.16667	0.16667	0.16667	0.16667	

Figure 9. Output of SAS Discriminant Analysis.

Table 8. Total Control Delay (Veh-Min) for State-Plan Matrix.

State	Timing Plan					
	1	2	3	4	5	6
1	159923	144345	860351	797163	146272	187125
2	174956	147681	890592	807475	169938	202559
3	142325	146893	146963	138874	194654	145279
4	162874	156435	141550	152474	195355	157304
5	164547	136740	545243	187995	134028	182488
6	191926	160047	882086	803113	155608	225721

Thresholds Selection

Discriminant analysis results in determination of discriminant functions that can be used to determine the group to which every observation belongs. Figure 10 shows a plot of the discriminant functions for each state versus the cycle PS parameter. Note that the figure clearly shows that the original six states are actually only three. For any PS parameter value, the discriminant function with the highest value determines the group to which the observation belongs. As such, the intersection of the discriminant functions determines the TRPS thresholds. The values shown in the figure suggests that thresholds of 16 and 22 are needed to switch from timing plan 1 to timing plan 5, and timing plan 5 to timing plan 3, respectively. The fact that using three states to represent the system results in a 0 percent misclassification error means that there is no need to set up different entering and exiting thresholds, as each two adjacent state distributions are almost mutually exclusive.

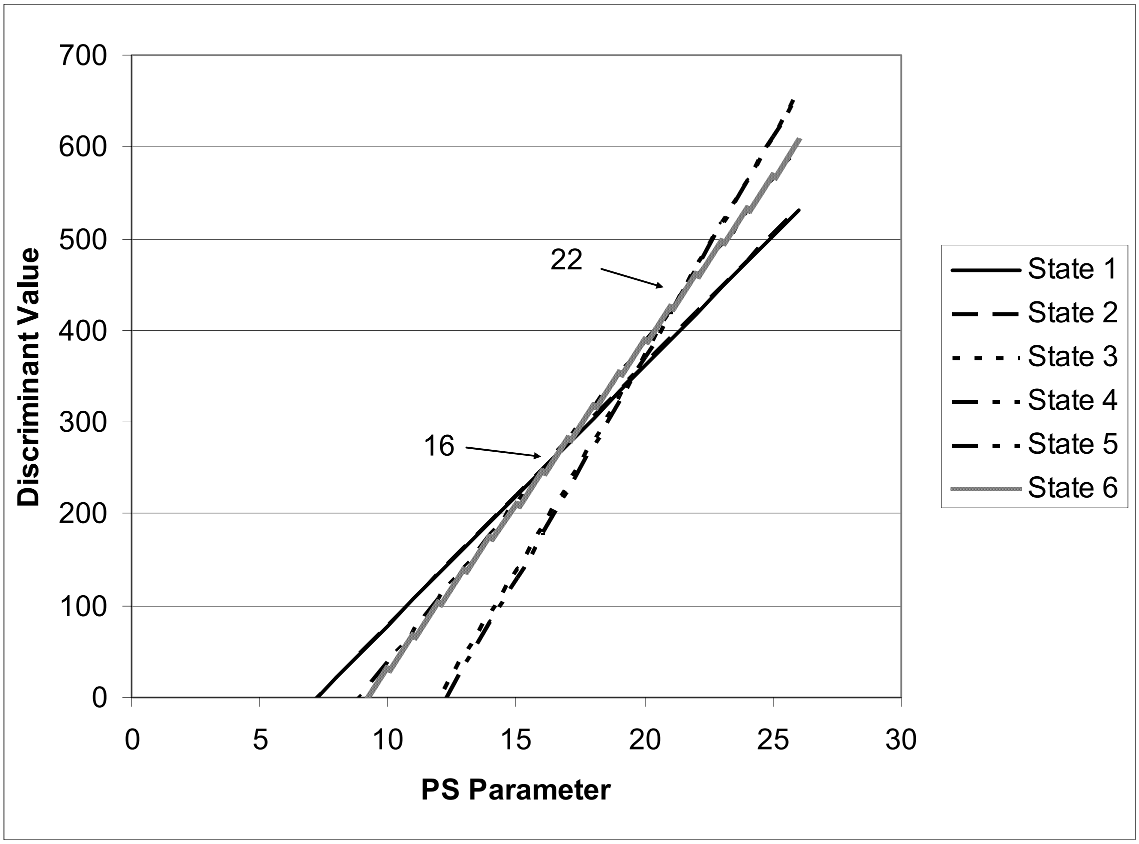


Figure 10. TRPS Threshold Determination.

SUMMARY

When properly configured, the TRPS mode has the greatest potential to provide an optimal operation utilizing existing capabilities of closed-loop systems. The TRPS mode is more beneficial than other operating modes due to its ability to accommodate abnormal traffic conditions such as incidents, special events, and holiday traffic. Most importantly, the TRPS mode can reduce the need for frequent redesign/updates to signal timing plans. However, there are no formal guidelines for optimal setup of TRPS systems. This chapter presented a novel and robust methodology for the selection of TRPS optimal parameters and thresholds. The methodology proposes that timing plans should only be assigned to distinct states. The proposed methodology was tested using field data from a closed-loop system in Odem, Texas, and achieved 100 percent classification accuracy.

CHAPTER 6: GLOBAL SYSTEM OPTIMIZATION WITH TRPS CONTROL

OVERVIEW

TRPS provides a mechanism by which the traffic signal system is able to change timing plans in real time in response to changes in traffic conditions. The objective is to enable the signal controller to implement timing plans that are optimal for the traffic conditions that currently exist. There are, however, three challenges in setting up a TRPS system:

1. development/selection of optimal timing plans that are suitable for a wide range of traffic conditions,
2. mapping/association of each one of these wide ranges of traffic conditions to one of the few available timing plans that can be stored in the traffic controllers, and
3. setting up the TRPS parameters such that the correct timing plans are always selected when traffic conditions change into one of their associated conditions.

This chapter describes a global system optimization methodology to address the first and second challenges of TRPS system operation for systems with variable traffic demands. The third challenge was addressed in the previous chapter. This chapter's methodology uses a genetic algorithm for selecting optimal system timing plans followed by discriminant analysis to set up the TRPS parameters and thresholds such that the appropriate timing plans are implemented.

METHODOLOGY

This chapter introduces a new methodology for designing TRPS strategies for closed-loop systems. Setting up a TRPS system for a particular closed-loop system requires a significant amount of time and effort. This significant undertaking usually results in engineers reverting to a TOD operation. Outdated TOD plans may result in excessive delays in the closed-loop systems. The proposed approach, while not claiming to achieve 100 percent system efficiency, will provide a "blanket" of good performance that will serve several purposes including:

- encourage traffic engineers to implement TRPS systems that will achieve good performance (for instance, 80 percent efficiency) rather than a possible poor performance due to outdated TOD plans (for instance, 50 percent efficiency),
- save engineers and technicians valuable time that is otherwise required to develop timing plans for each TOD traffic patterns, and
- reduce the effect of timing plans "aging" through the implementation of traffic responsive mode.

This chapter describes a comprehensive approach for selecting optimal timing plans and provides an example of this procedure applied to the Bastrop closed-loop system. The approach discussed here proposes that only a few timing plans are needed for all traffic networks that share the same characteristics (arterial versus grid network, protected lefts versus permitted lefts, lead-lead versus lead-lag operation, etc.). Once the timing plans for certain network characteristics have been chosen, TRPS parameters need to be selected such that the most suitable plan in the controllers' database is selected to match the existing traffic conditions. This approach, and making sure that plans for handling extreme conditions are stored in the controllers, will reduce the effects of plan "aging." The goal is to have the engineers implement these sets of timing plans and TRPS parameters in closed-loop systems. If the engineers have excess time and they prefer to implement a more customized setup for each closed-loop system (to improve efficiency from 80 percent to 95 percent, for example), they can conduct a detailed study following the steps detailed in this report. Otherwise, they can still feel "comfortable" that the closed-loop system is operated with a reasonably good performance.

A GLOBAL LOOK INTO TRAFFIC RESPONSIVE CONTROL

Due to the large number of traffic pattern levels and conditions, it is imperative to group similar traffic conditions together and address them with one solution (one timing plan). This approach is similar to what traffic engineers currently do when they design a limited number of timing plans, one for each period, and apply one timing plan to a certain period of time (e.g., am-peak plan that extends from 7:00 a.m. until 10:00 a.m., off-peak from 10:00 a.m. to 4:00 p.m., and pm-peak from 4:00 p.m. to 6:00 p.m.). For example, in Figure 11, the engineer made the decision to apply a timing plan that was designed for the 8:00 a.m. to 9:00 a.m. volume to the whole period from 7:00 a.m. to 10:00 a.m. assuming that the traffic conditions are relatively comparable during this period.

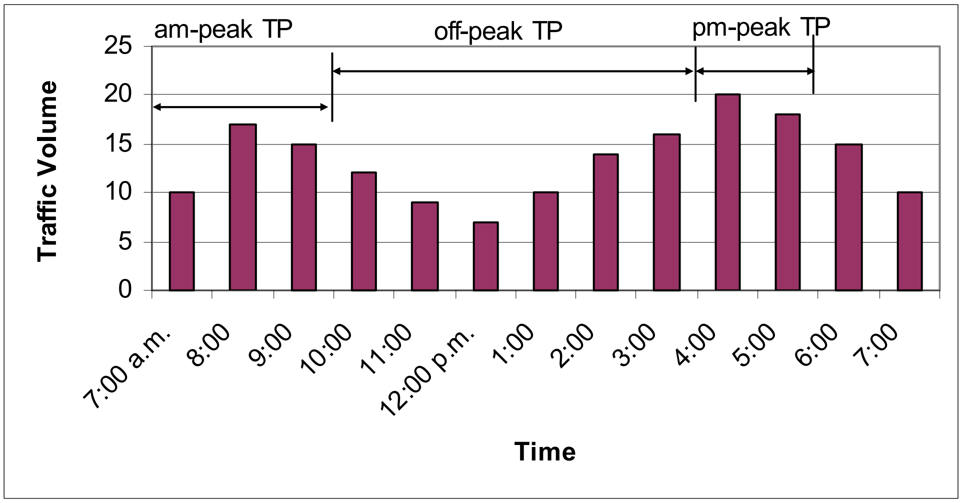


Figure 11. Illustration of Current Plan Selection Practice.

Selection of the representative timing plans in this research follows a similar approach by grouping similar traffic conditions together into a smaller number of groups and applying one suitable timing plan to each group. The major difference is that the procedure is not limited to grouping traffic patterns that are temporarily adjacent.

The State-Timing Plan Space

The problem of traffic responsive operation can be represented by two variables: states (S) and timing plans (P). The state variable describes the existing traffic pattern at all approaches at a certain point in time. The timing plan variable identifies the optimum timing plan for the current state. In addition, there is a detection filter (D) that represents the "perceived" condition as represented by the occupancy and counts from system detectors. The main challenges of a TRPS setup are:

1. to select the optimal subset of the P space to be included in the limited memory of the traffic controllers,
2. to determine the optimal plan from the available P space that should be applied to the existing sample of the S space, and

3. to be able to specify a function that can differentiate between different states (S) as represented by the detection filter (D).

These challenges can be more appreciated when one realizes that filter D is not only dependent on S, but on P as well. For example, consider a state S1 that is associated with optimum plan P1. If plan P2 is implemented instead, queues may back up 200 feet upstream of the traffic signal 20 percent of the time causing certain occupancy values at a detector located at that location; if plan P3 is implemented for the same state S1, queues may back up 200 feet upstream of the signal 40 percent of the time causing different occupancy values. Therefore, it can be recognized that for a complete representation and evaluation of the studied system, all state-plan combinations have to be considered. This recognition, with the realization of the vast number of state values, begs the question of "how many states should we consider?" The answer to which must follow the path of answering another question: "What is a significant difference between two successive states?"

The Timing Plan as a Grouping Criterion

One plausible answer to the above questions is to use the optimal timing plan associated with a given state as a grouping criterion. If two states, S1 and S2, have "similar" timing plans, then it can be argued that there is no significant difference between the two states as far as the TRPS setup is concerned. For all practical purposes, S1 and S2 can be considered as one state, Si. It is worth noting that this reasoning might only apply to states that share the same traffic characteristics (e.g., over-saturated or under-saturated conditions). It should also be noted that different optimization programs (i.e., PASSER *[21]* versus SYNCHRO) might produce different timing plans for the same given state since they use different objective functions. However, it is likely that two states identified by one optimization program as having "similar" timing plans will also be recognized as such by the other program, basically because optimization programs apply systematic procedures to develop their recommended timing plans. The range of recommended timing plans by each program, however, might be different. The final guidelines developed based on different optimization programs might therefore be different. In addition, guidelines developed using SYNCHRO are likely to produce less delay; where those developed using PASSER are likely to produce better through-phase progression. Timing plans were needed for grouping purposes only; no Measures of Effectiveness (MOEs) produced by the optimization programs were used. The System Control Delay (SCD), used as a MOE, was rather obtained by simulating the S-P space using CORSIM. This step was important to obtain the SCD for all combinations in the S-P space, especially because the actuated signal logic is not fully represented in the optimization packages.

Developing Alternate Analysis Scenarios for PASSER V Runs

Researchers developed alternative analysis scenarios based on traffic counts performed at the Bastrop site. The counts consisted of hourly turning-movement counts at five intersections on Texas State Highway (SH) 71 over a 24-hour period under normal weekday traffic conditions, and a four-hour period from 2:45 p.m. to 6:45 p.m. on the Memorial Day and Labor Day weekends.

Traffic origins and destinations on the network were identified and numbered as shown in Figure 12.

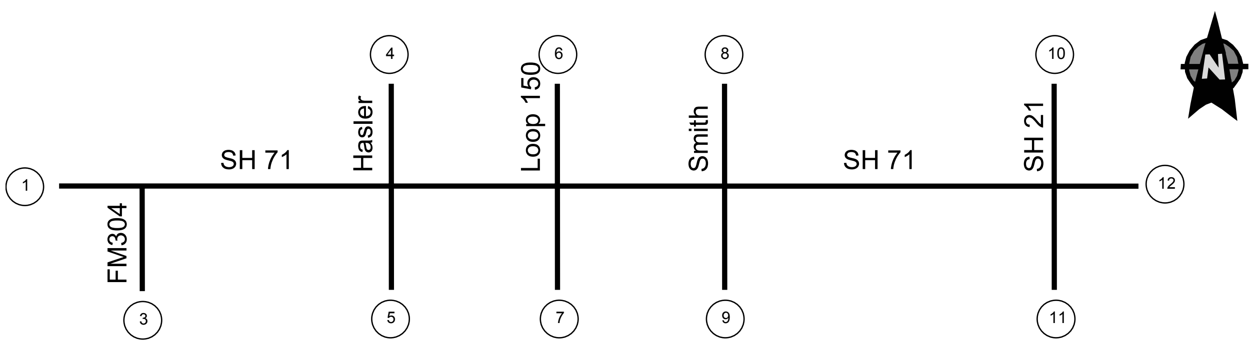


Figure 12. Origin-Destination Codes on Bastrop Closed-Loop System.

For each of the 28 one-hour counts, an origin-destination (O-D) matrix was estimated from the turning-movement volumes. To estimate this, the cells of the O-D matrix were divided into three types:

- Cells with contents that could be determined directly from the traffic counts. For example, origin-destination pair 4-5 in Figure 12, which corresponds to the southbound through movement on Hasler Blvd.

- Cells corresponding to zero demand. These include the diagonal cells of the O-D matrix which represent U-turn demand on the external approaches to the network. Demand between minor O-D pairs in the network was also assumed to be zero for the purposes of this research. Major traffic movements on the network take place between origins and destinations 1, 3, 10, and 12. The remainder of movements O-D pairs, for example between O-D pair 5-6, was assumed to be very low and set to zero.
- Cells with unknown, but assumed to be non-zero, contents. This type includes all the cells not included in the first two types.

For each one-hour counting period, the unknown (type 3) cell's O-D matrix was estimated using Microsoft® Excel's "Solver" function. The Solver function performs non-linear optimization, which allows it to determine the value in each unknown cell that would yield the least error between observed and estimated traffic volumes.

The next step was to generate a "random" O-D matrix that represents some traffic distribution state in the network. This step was achieved by using the Box-Muller method (*22*) to generate a normally distributed random variable from the mean and standard deviation for each cell in the matrix. The "Recalculate" function in Excel allowed the entire O-D matrix to be recalculated with new random cell values. Since the sum of the random cell values originating from each origin was not equal to one, the random matrix was rescaled to yield unit origin flows.

Based on the observed turning-movement counts, various volume levels were defined for each of the origins. Five volume levels were defined for the major origins (origins 1, 3, 10, and 12 in Figure 12), while three volume levels were defined for the remaining minor origins. Table 9 shows the actual volume for each volume level. Realistic volume level combinations were obtained for each of the two adjacent major origins to produce 13 combinations for each of the North-East and South-West bounds as shown in Table 10. This scheme resulted in a total of 169 (13 X 13) combinations for the overall network. These scenarios were repeated for three levels of minor street movements. For each of these 507 scenarios (169 X 3), a random, unity-scaled O-D matrix was generated as described above. This matrix was then scaled up to represent the volume level in the scenario by multiplying each cell in a row with the volume of the corresponding origin.

Table 9. Volumes Used to Generate Flow Scenarios.

Origin	Maximum Observed Volume (vph)	Volume (vph) at Volume Level				
		1	2	3	4	5
1	2186	224	632	1162	1789	2500
3	896	98	278	511	787	1100
4	398	96	272	500	-	-
5	273	67	191	350	-	-
6	492	115	327	600	-	-
7	212	48	136	250	-	-
8	42	19	54	100	-	-
9	40	19	54	100	-	-
10	1627	179	506	930	1431	2000
11	122	28	79	145	-	-
12	1396	161	455	837	1288	1800

Table 10. Different Major Movement Combinations on Bastrop Closed-Loop System (North and East Bounds Example).

Index	Volume Level at Origin	
	1	3
1	1	1
2	1	2
3	2	1
4	2	2
5	2	3
6	3	2
7	3	3
8	3	4
9	4	3
10	4	4
11	4	5
12	5	4
13	5	5

By adding various combinations of cells in the scaled-up O-D matrix for each scenario, the turning-movement volumes corresponding to the scenario could then be generated. Finally, a PASSER V input file containing these turning-movement volumes was generated.

Clustering Analysis

As previously discussed, timing plans can be used to group similar states together. This grouping is meant to satisfy two objectives:

1. to reduce the number of states that need to be studied, and
2. to add statistical robustness to the state representation.

The first objective is important since every state identified will need to be simulated and evaluated with all timing plans associated with all states. For example, if 200 states are being considered, 40,000 simulation runs will need to be conducted (200 states X 200 plans). The second objective is important because states will be grouped according to a *statistical criterion*. The criteria used to distinguish between states will lessen the need to exhaust lower resolutions of state levels (i.e., be able to consider volume increment of 500 vph on main through approach instead of 200 vph). The MATLAB *(23)* k-means clustering procedure was used to form groups such that the differences *between* groups are maximized; while the differences *within* groups are minimized. In our analysis, we made sure that volume levels are increased in reasonable increments such that no large areas in the S-P space are "omitted."

The k-means procedure considers each observation (timing plan) as an object in an n-dimensional space. In the case of a timing plan, each dimension is one of the phases' duration at an intersection. One of the important decisions to make was selecting the number of clusters in the data set as an input to the k-means procedure. Increasing the number of clusters means a better representation of each cluster to its group. However, increasing the number of clusters also dictates that a larger number of cases needs to be simulated. The k-means procedure provides evaluation criteria for measuring homogeneity of observations within each cluster. One of these criteria is the summation of distances (sum dist.) from each observation to the centroid of its cluster. Another criterion is the silhouette value of each observation. The silhouette value of an observation ranges from 1, indicating that the observation is very distant from other clusters, to -1, indicating that the observation is probably assigned to the wrong cluster.

Figure 13 shows a plot of the sum dist. and silhouette mean value associated with different numbers of k-means clusters. A subjective call was made to select 100 clusters as it seemed to be the point of diminishing return and also provided a relatively reasonable silhouette value.

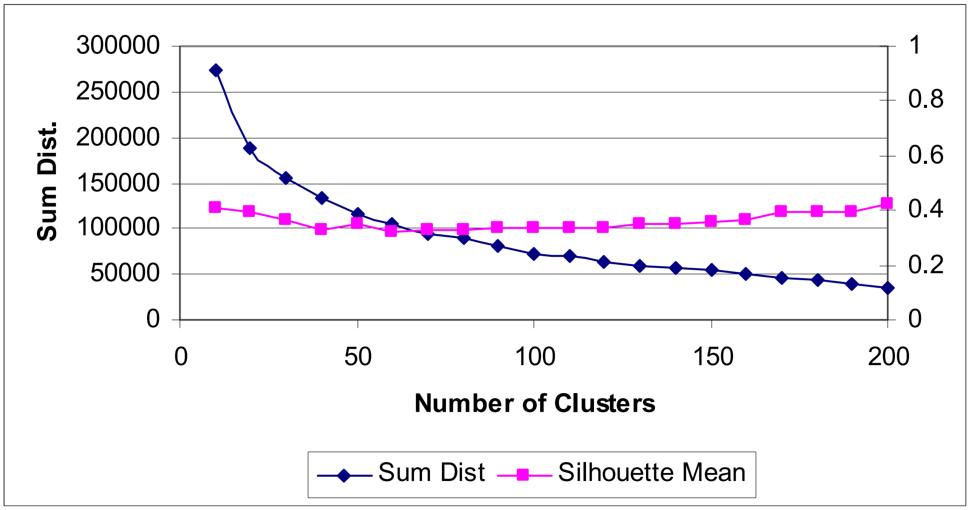


Figure 13. Selection of Number of Clusters for S-P Space Representation.

Clustering the traffic conditions into 100 clusters basically suggests that if a range of traffic conditions falls into the same cluster, then it can be addressed by one timing plan. It also proposes that all the traffic conditions in a given cluster can be represented by one of its group. For example, Figure 14 shows a contour of 30 timing plans that were obtained using SYNCHRO for illustration purposes. Areas within each contour are basically similar traffic conditions as far as the TRPS system is concerned (they need to be addressed by the same timing plan). As can be observed in the figure, some timing plans can cover a wide range of traffic conditions (timing plan Y) while other timing plans are only suitable to a limited range of conditions (timing plan X). It should, however, be noted that this contour does not account for the actuated operation effect (i.e., the actuated effect is very likely to allow a particular timing plan to cover an even wider range of traffic conditions).

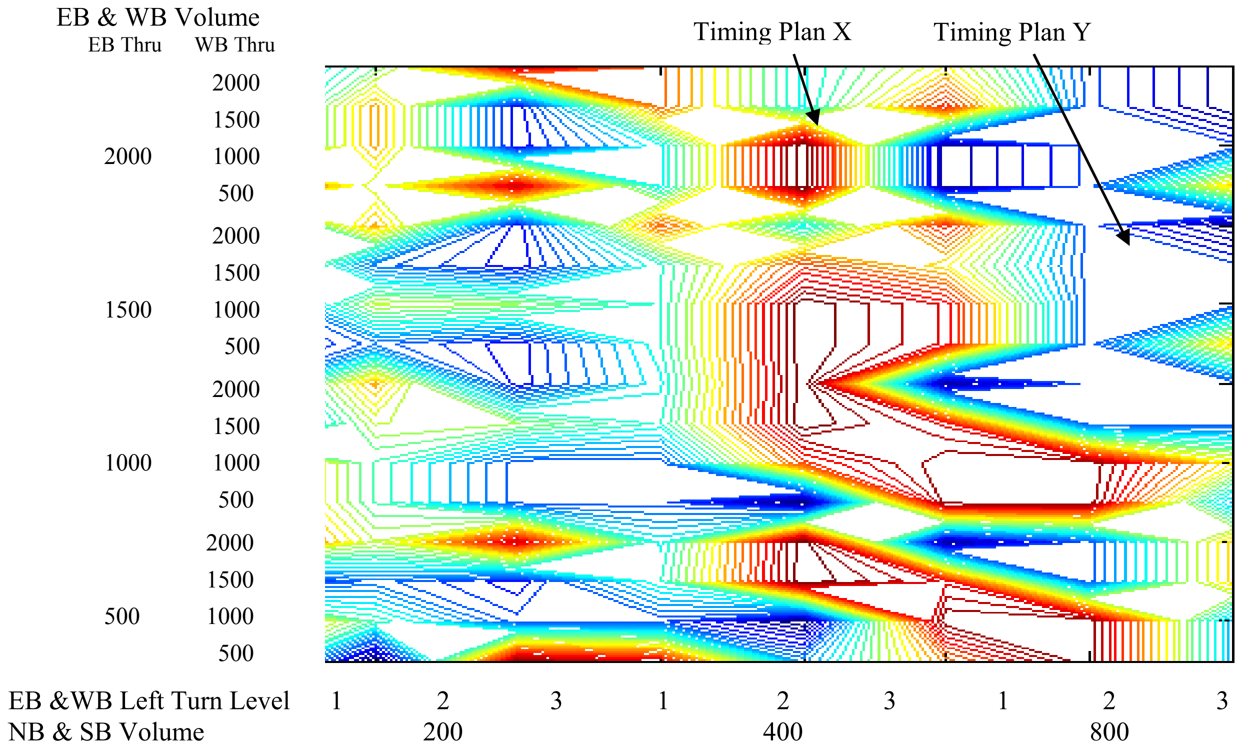
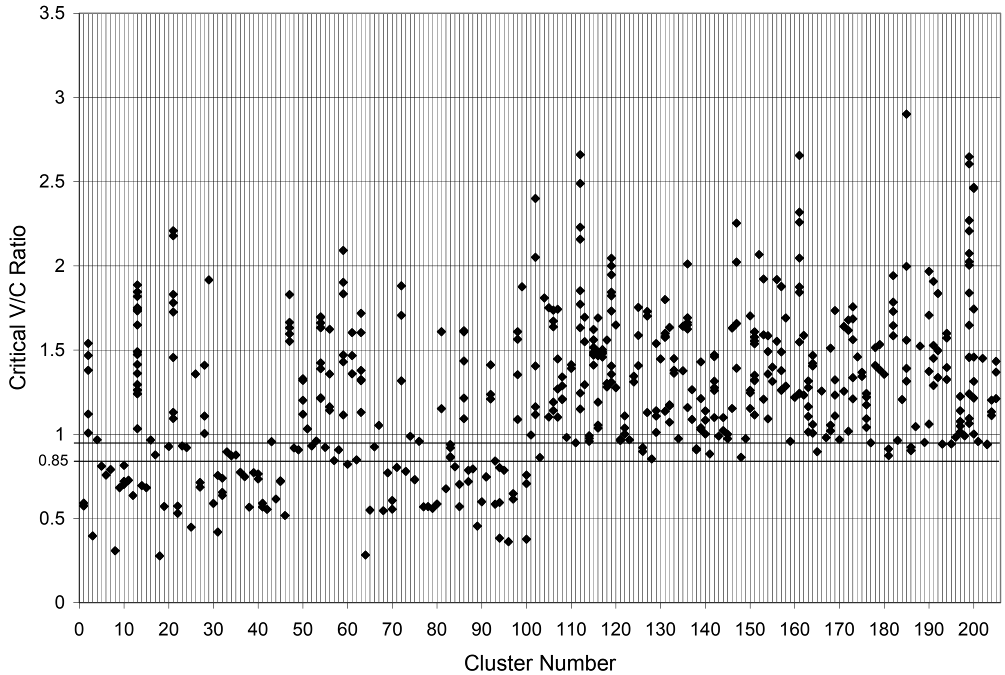
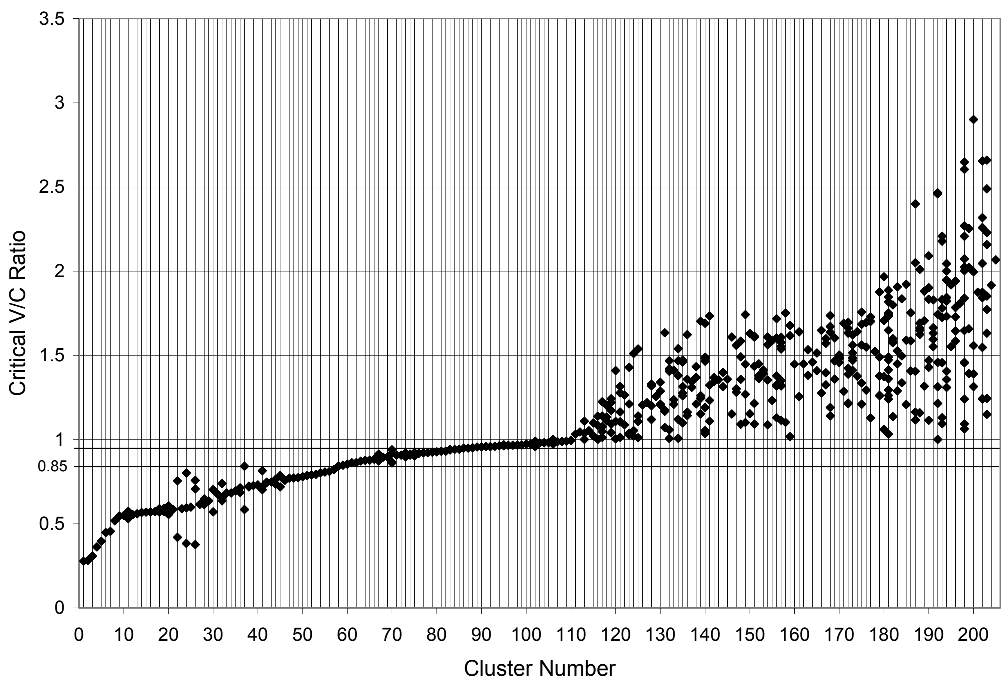


Figure 14. Example of Timing Plans Contour.

However, as mentioned above, it was important to make sure that the same timing plan was not chosen for a different reason. This is important to consider given that the same timing plan could be chosen by the optimization software to handle an oversaturated condition and an undersaturated condition. Obviously, in such a case not all traffic conditions within the cluster are representative of each other. To make sure this issue was addressed, critical Volume by Capacity (V/C) ratios for each observation in all clusters were plotted (Figure 15a). Each cluster was then subgrouped into undersaturated (V/C <0.85), moderately saturated (V/C = 0.85-0.95), saturated (0.95-1.0), and oversaturated (>1.0). Figure 15b shows the resulting 205 clusters.



a. Critical V/C Ration for Original 100 Clusters



b. Final 205 Clusters Sorted by V/C Ratios

Figure 15. System Representative States.

System Control Delay Matrix and State Probability

CORSIM was used to simulate all 42,025 pairs of S-P clustering combinations (205 states X 205 plans). SCD was calculated for each combination, and a matrix of 205 rows X 205 columns representing the simplified S-P space was prepared for the system optimization analysis.

In addition, volume counts for representative normal and congested conditions were used to obtain the probabilities of occurrence of particular representative states.

The traffic conditions occurring in field (actual state) were classified into the representative states using a volume difference index (VDI), as shown in equation (1). First, the volume weighted difference between the actual state and the calculated state in each direction was obtained. VDI was obtained by adding all the differences in each direction for each state. The state giving the minimum value of VDI was selected as the representative state for a particular traffic condition. This analysis was done for normal and congested day conditions. The proportional distribution of representative state instances, in the available data, was used to calculate the probabilities of each state occurrence.

$$VDI_{Statei} = \sum_{alldirection} \frac{StateVolumeInDirectionj - ActualVolumeInDirectionj}{\max(StateVolumeInDirectionj)} \qquad (1)$$

Figure 16 shows examples of field volumes and their representative states. The figure shows that each field condition was mapped to a higher level representative state. The number of representative states in the whole sample was multiplied by the number of days the sample represented in the year to obtain the probability of each state occurring over the year. The input to the overall optimization process was the probability of the state occurring during the year and the SCD expected of that state with each of the 205 analyzed plans.

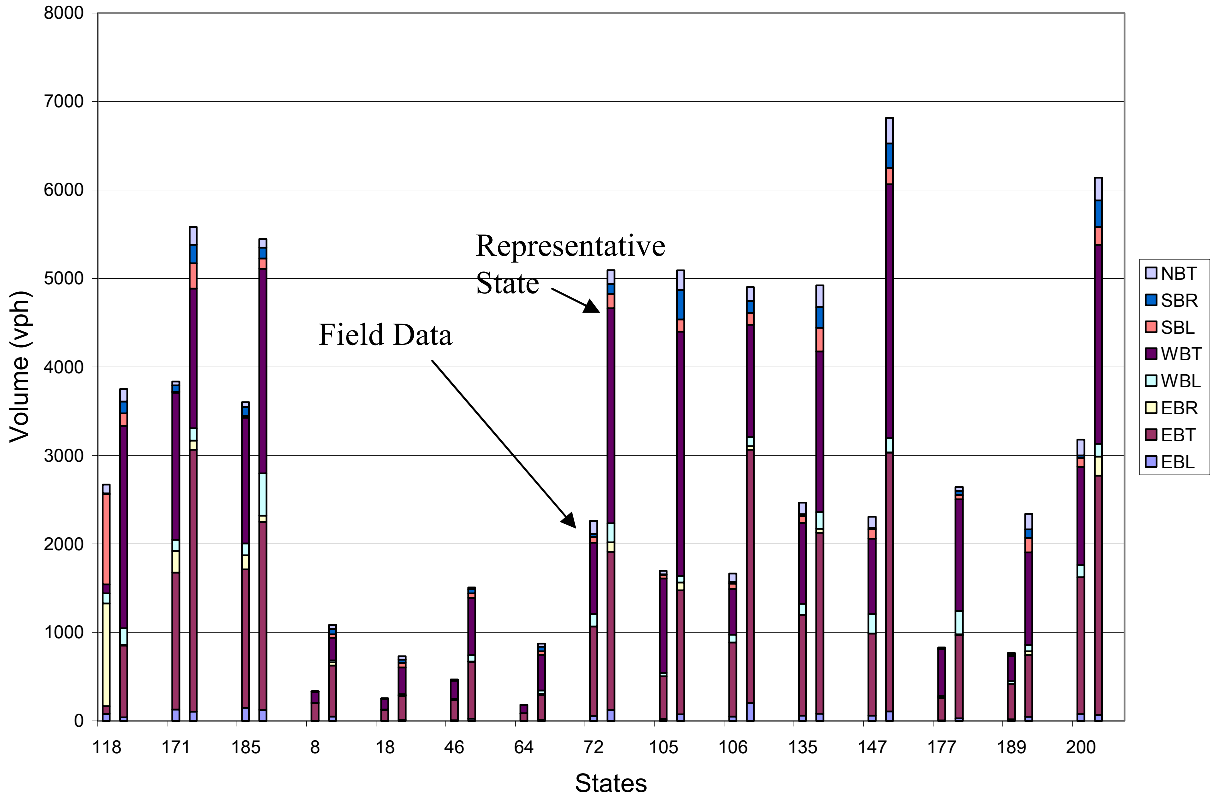


Figure 16. Assignment of Field Volume to Representative States.

Genetic Algorithm's Selection of Optimal Timing Plans

Why Genetic Algorithms?

Since 205 different timing plans were identified while only a limited number of timing plans (e.g., a maximum of 24 for Naztec controllers) can be stored in controller's database, it was necessary to conduct an optimization process to select a final set of timing plans. Genetic algorithms (GAs) are optimization techniques based on the process of natural selection and genetics *(24)* that can produce a near-global optimum solution for a given problem, especially in large solution spaces as is the case here. The GAs start by producing a group of random candidate selection of *n* number of timing plans that constitute the initial set of chromosomes. Through natural selection and the genetic operators, crossover and mutation, chromosomes (sets of plans) with a better fitness (lower SCD) are found. This natural selection process guarantees that chromosomes with the best fitness will propagate in future populations. The crossover operator mates genes (individual plans) from two parent chromosomes (sets of plans) to form two new children chromosomes (new sets of plans) that have a high probability of having better fitness (lower SCD) than their parents. The mutation operator allows new areas of the response surface to be explored and prevents the solution from being trapped at local optima. The methods by which these operations are applied are normally completely random with a certain probability of occurrence. However, in applying a GA to the selection of plans, it was necessary to satisfy two constraints: 1) the population (collections of plans) must contain only integer numbers within the range of the total number of clusters, and 2) the integer numbers must be unique within any chromosome. These two conditions had to be considered during the initialization of populations and the crossover and mutation operations.

In order to satisfy these requirements and uniquely select each chromosome gene (plan number), the selection routine in the GA program used a consecutive integer array, r(), initially having values ranging between one and the total number of plans, (n). Restricting the plans to be coded as a set of consecutive integer numbers, the routine picks the first plan randomly by picking an integer number, i, between 1 and n and selecting the location that is in r(i) position. The r() array is then updated by setting the value of r(i) to r(n+1-j), where j is the number of plans selected up to the moment. The routine then chooses the second plan location by randomly picking an integer number within the range of 1 to n-j as illustrated in Figure 17. Crossover and mutation were conducted in similar fashion in order to ensure the production of valid chromosomes.

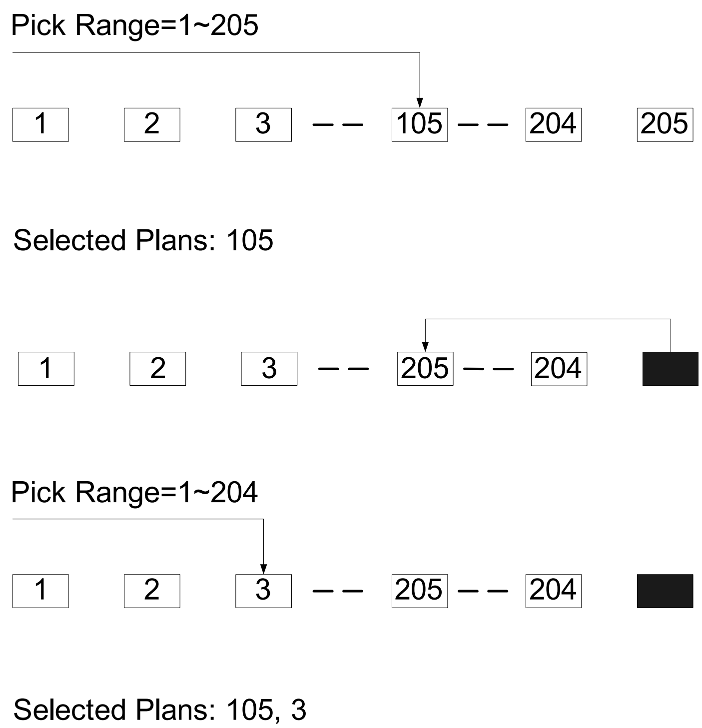


Figure 17. Genetic Algorithm's Coding of State-Plan Representation.

State-Plan Association

The SCD matrix listing the effect of running a timing plan Pi with a state Sj was input to the GA program to select the optimal set of timing plans to be implemented in the system. Each state was associated with the most suitable available timing plans in the selected set. The overall SCD was calculated as the accumulation of control delay of each state with its most suitable timing plans in the selected set multiplied by its probability of occurrence.

The delay incurred by including plan P1 in the selection depends on what other timing plans are included in the selection. For example, in Figure 18a, the system delays are those incurred due to P1 with states S1-S6 plus P7 with states S7-S8. In Figure 18b, the system delays are those due to P1 and states S1-S3 plus P4 with S4-S5 plus P6 with states S6-S8 (each state multiplied by its probability of occurrence). For illustration purposes, Figure 18 shows states that are numbered in order by their association to timing plans. In reality and due to actuated operation of each intersection, the program associates each state to the most suitable plan in the available selection (the plan that produces the least SCD).

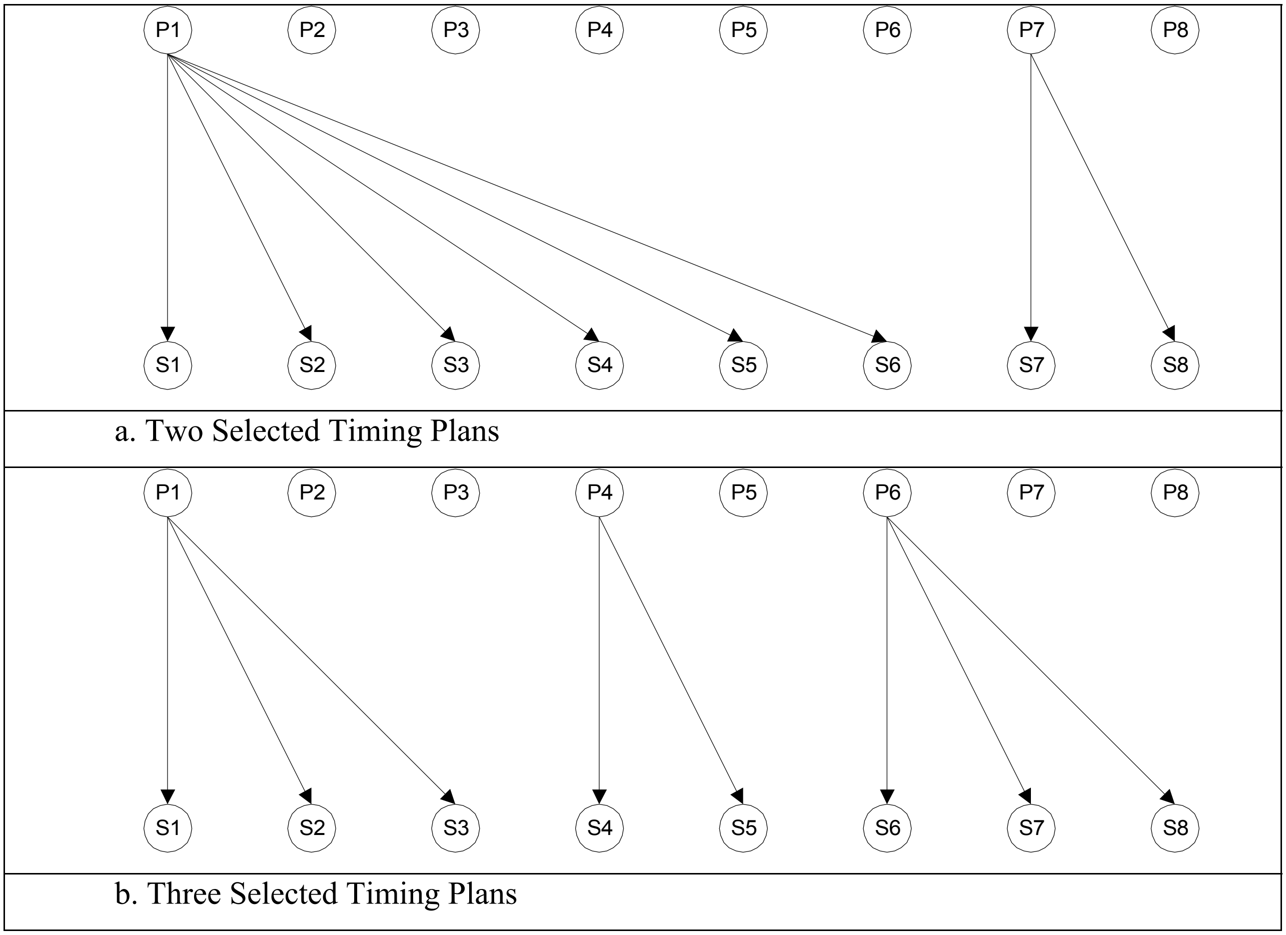


Figure 18. Example of Optimal Timing Plans and Associated States.

System Optimization and Determination of Final Timing Plans

The last decision to be made was how many plans are to be selected. The GA program was run, and the SCD was recorded for different target numbers of system plans. Figure 19 shows a plot of SCD versus the number of selected plans. It is very important to realize that including more plans into the final selection will reduce the SCD. However, this will be asking more from the system parameters required to be able to distinguish among occasions to bring those plans. The more plans included the more possible a misclassification error might be introduced into the system. The final decision was made to select 10 plans as the return in SCD is diminishing at that point with a value of 16,350 vehicle-minutes/hour. Table 11 lists the final selected plans.

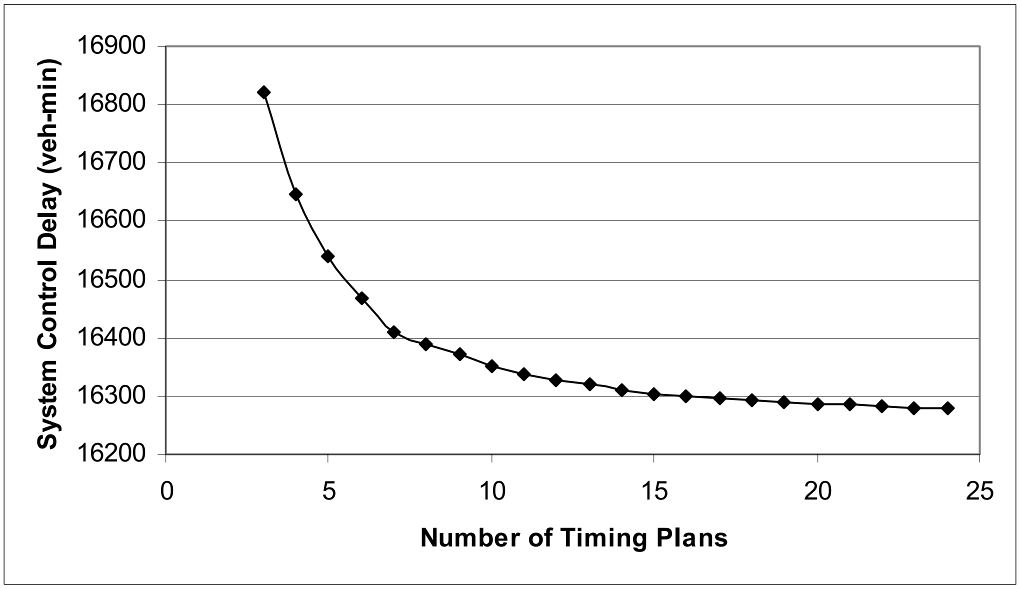


Figure 19. System Control Delay versus Number of Timing Plans.

Table 11. Final Selection of Timing Plans.

Plan Number	Intersection with SH 71	Cycle	Phase								Offset
			1	2	4	3	6	5	7	8	
	FM 304	120	40	57	23	--	85	12	23	--	0
	Hasler	120	32	62	12	14	82	12	12	14	53
	Loop 150	120	22	71	15	12	13	80	15	12	88
	Smith	120	25	71	12	12	80	16	12	12	105
11	SH 21	120	12	50	46	12	41	21	46	12	52
	FM 304	115	21	42	52	--	51	12	52	--	0
	Hasler	115	13	63	18	21	64	12	18	21	44
	Loop 150	115	13	62	25	15	19	56	25	15	88
	Smith	115	12	79	12	12	65	26	12	12	105
21	SH 21	115	12	58	33	12	29	41	33	12	57
	FM 304	70	12	42	16	--	42	12	16	--	0
	Hasler	70	12	24	16	18	24	12	16	18	15
	Loop 150	70	12	22	23	13	12	22	23	13	38
	Smith	70	12	34	12	12	29	17	12	12	43
22	SH 21	70	12	34	12	12	23	23	12	12	47
	FM 304	115	12	60	43	--	60	12	43	--	
	Hasler	115	12	79	12	12	70	21	12	12	50
	Loop 150	115	12	79	12	12	37	54	12	12	69
	Smith	115	12	79	12	12	40	51	12	12	106
52	SH 21	115	12	79	12	12	23	68	12	12	58
	FM 304	160	45	90	25	--	123	12	25	--	0
	Hasler	160	12	120	13	15	119	13	13	15	65
	Loop 150	160	38	95	15	12	18	115	15	12	66
	Smith	160	48	88	12	12	117	19	12	12	105
55	SH 21	160	12	78	58	12	65	25	58	12	12
	FM 304	70	15	24	31	--	27	12	31	--	0
	Hasler	70	12	30	14	14	30	12	14	14	68
	Loop 150	70	12	31	15	12	12	31	15	12	21
	Smith	70	12	34	12	12	34	12	12	12	28
62	SH 21	70	12	27	19	12	23	16	19	12	35
	FM 304	105	12	36	57	--	36	12	57	--	0
	Hasler	105	12	69	12	12	64	17	12	12	40
	Loop 150	105	12	69	12	12	35	46	12	12	75
	Smith	105	12	69	12	12	39	42	12	12	0
123	SH 21	105	12	69	12	12	22	59	12	12	38

Table 11. Final Selection of Timing Plans (cont.).

Plan Number	Intersection with SH 71	Cycle	Phase								Offset
	FM 304	125	67	22	36	--	77	12	36	--	0
	Hasler	125	59	42	12	12	89	12	12	12	52
	Loop 150	125	48	53	12	12	12	89	12	12	83
	Smith	125	50	51	12	12	89	12	12	12	91
137	SH 21	125	15	52	46	12	52	15	46	12	26
	FM 304	115	38	60	17	--	86	12	17	--	0
	Hasler	115	28	49	18	20	65	12	18	20	76
	Loop 150	115	23	53	24	15	12	64	24	15	109
	Smith	115	27	64	12	12	77	14	12	12	3
159	SH 21	115	12	50	41	12	45	17	41	12	68
	FM 304	180	39	56	85	--	83	12	85	--	0
	Hasler	180	33	98	25	24	119	12	25	24	65
	Loop 150	180	28	104	29	19	22	110	29	19	40
	Smith	180	37	119	12	12	129	27	12	12	42
188	SH 21	180	12	95	61	12	62	45	61	12	172

Discriminant Analysis and TRPS Setup

Once the system timing plans have been selected, discriminant analysis was carried out similar to the previous chapter to determine the TRPS system parameters and thresholds. Stepwise discriminant analysis was used to select the group of eight system detectors that has the most correlation with the changes in state variable. Figure 20 shows all the system detectors in the Bastrop network. The selected detectors are listed in the next section with their associated weights.

One-Level Discriminant Analysis

Discriminant analysis was conducted to determine the TRPS system parameters and thresholds. Figure 21 shows a plot of the discriminant functions for each assigned plan versus the canonical value. Figure 22 shows the classification accuracy for each assigned plan arranged by the canonical value. Figure 22 shows that due to the high variability in state representation in the Bastrop system, there was a relatively high misclassification rate at the one-level discriminant analysis.

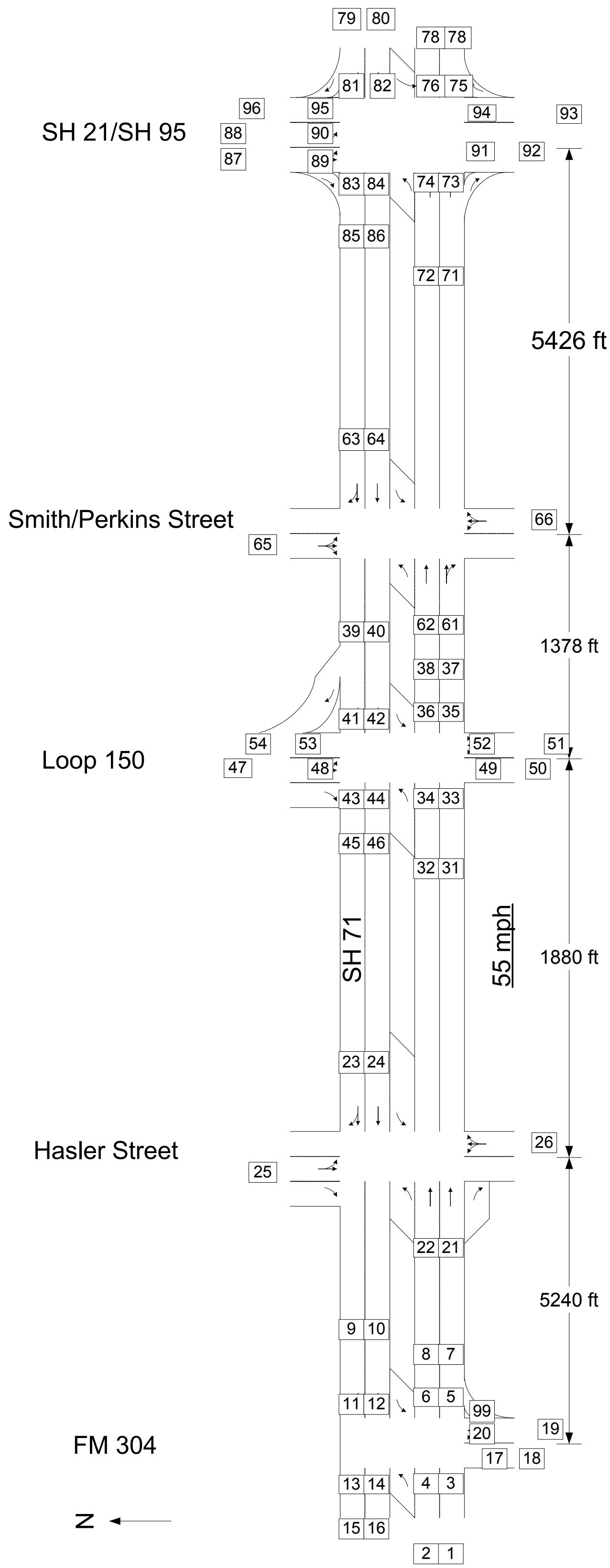


Figure 20. System Detectors in the Bastrop Closed-Loop System.

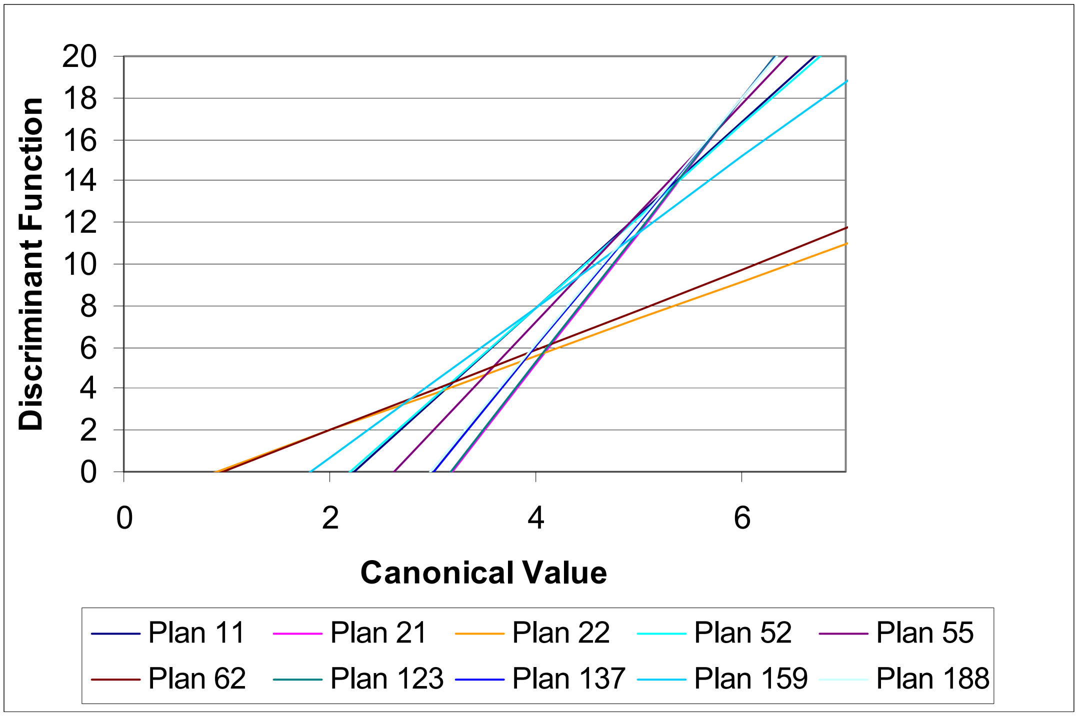


Figure 21. Discriminant Functions for Assigned Plans.

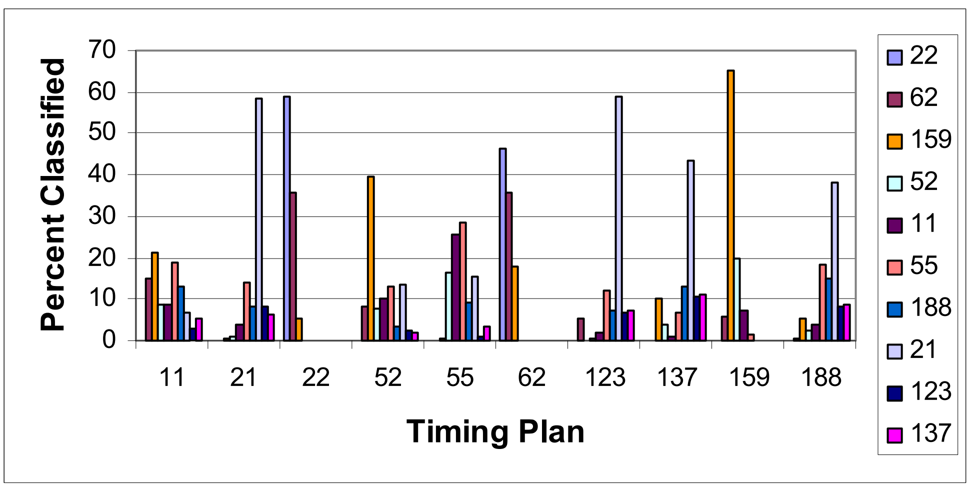


Figure 22. Classification Accuracy by Assigned Plan.

Three-Level Discriminant Analysis (Cycle, Split, and Offset Levels)

Since one-level classification was not deemed accurate enough, Figure 22 was used to decide on grouping plans that had high cross-misclassification together such that they can be distinguished from each other later using the split and offset levels. Table 12 shows the subgroups of assigned plans along with the level at which they are to be distinguished.

Table 12. Subgroups of Assigned Plans and Their Associated Levels.

Subgroup	Classification Level
(22, 62, 159), 55, (21, 123, 137, 188)	Cycle
22, 62, 159	Split
21, 123, 137, 188	Offset
11, 52	Reassigned

The discriminant analysis was re-run with the regrouped plans. Figure 23 and Figure 24 show the classification accuracy at the cycle level and a plot of the discriminant functions, respectively. From Figure 24, the thresholds were calculated as 3.6 and 5.7, respectively.

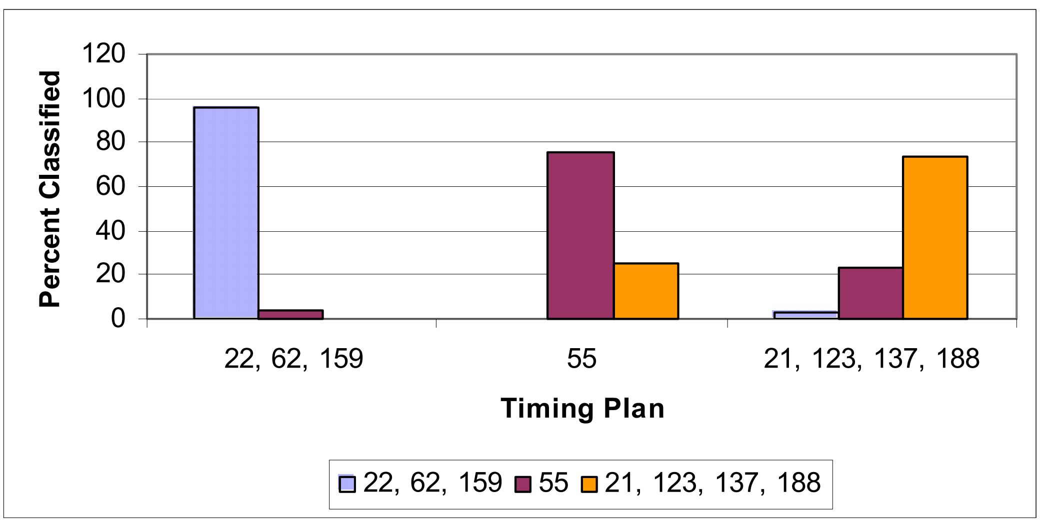


Figure 23. Classification Accuracy at the Cycle Level.

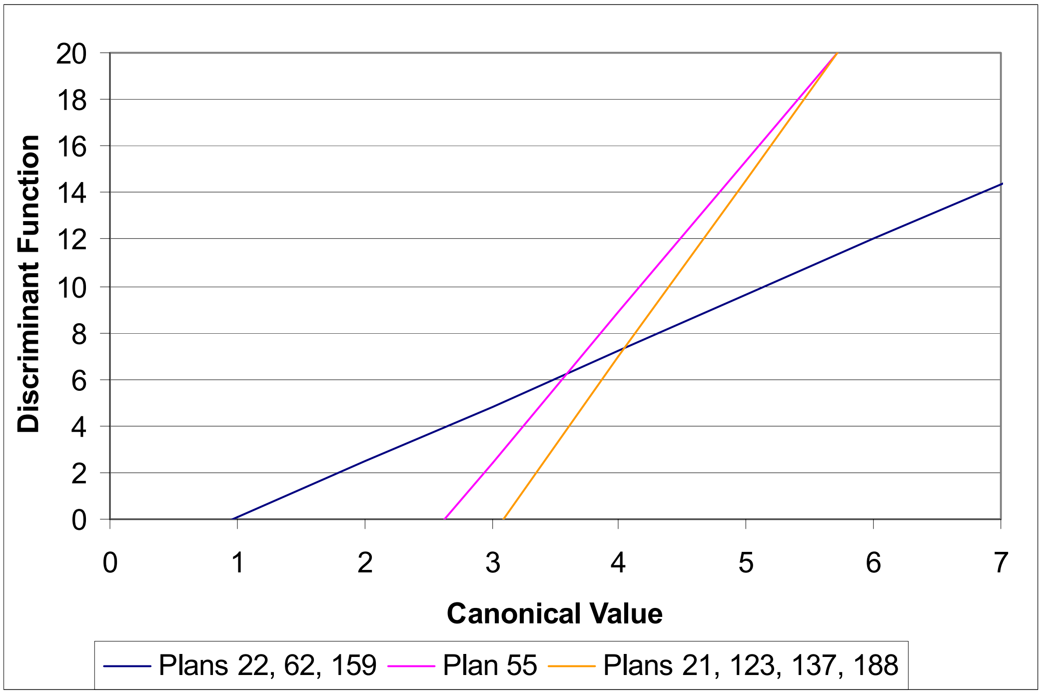


Figure 24. Discriminant Functions at the Cycle Level.

The classification accuracy and discriminant functions for the plans to be distinguished under the split level are shown in Figure 25 and Figure 26, respectively. Figure 25 shows a high rate of cross-classification between plans 22 and 62, which suggests that only one plan should represent the two plans. Plan 22 was selected since it had the total minimum delay for all states. From Figure 26, the canonical value threshold was calculated as 4.7. Due to the limitation of the TRPS control mechanism, the threshold values had to be recalculated to suit the TRPS mechanism. The split PS parameter implemented by Eagle, for example, uses the value ART/(ART+NA1+NA2)*100. The analysis used only eight system detectors for the discriminant analysis. These eight detectors can be assigned to NA1. For the activation to work correctly with the split threshold having a value between 0 and 100, the ART channel will need to be assigned to a dummy detector with a substituted fault value of 1. The split thresholds are then calculated 1/(1+4.7)*100 or 18 percent. Note that the plans will need to be assigned in reverse order; i.e., plan 22 should be implemented if the canonical value is greater than 18 percent instead of it being less than 4.7.

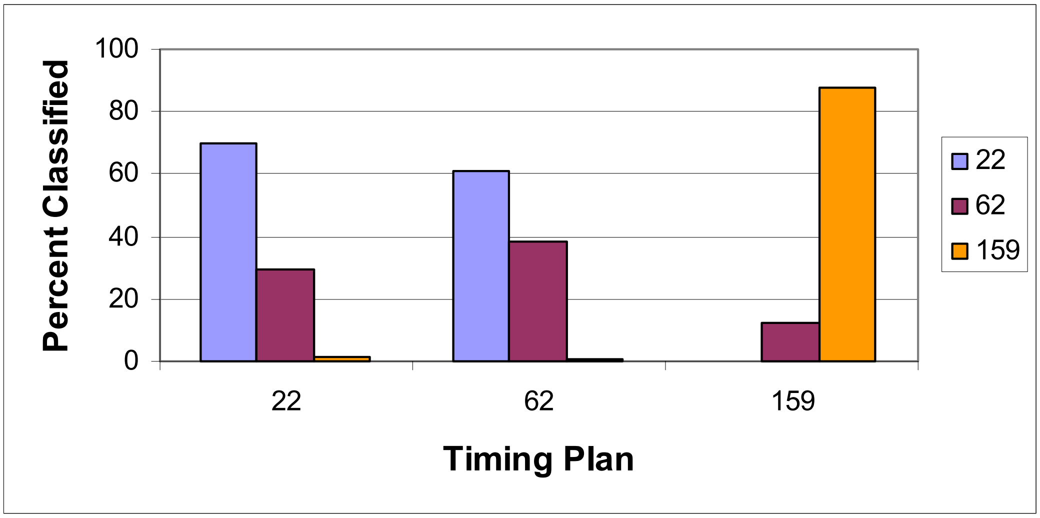


Figure 25. Classification Accuracy at the Split Level.

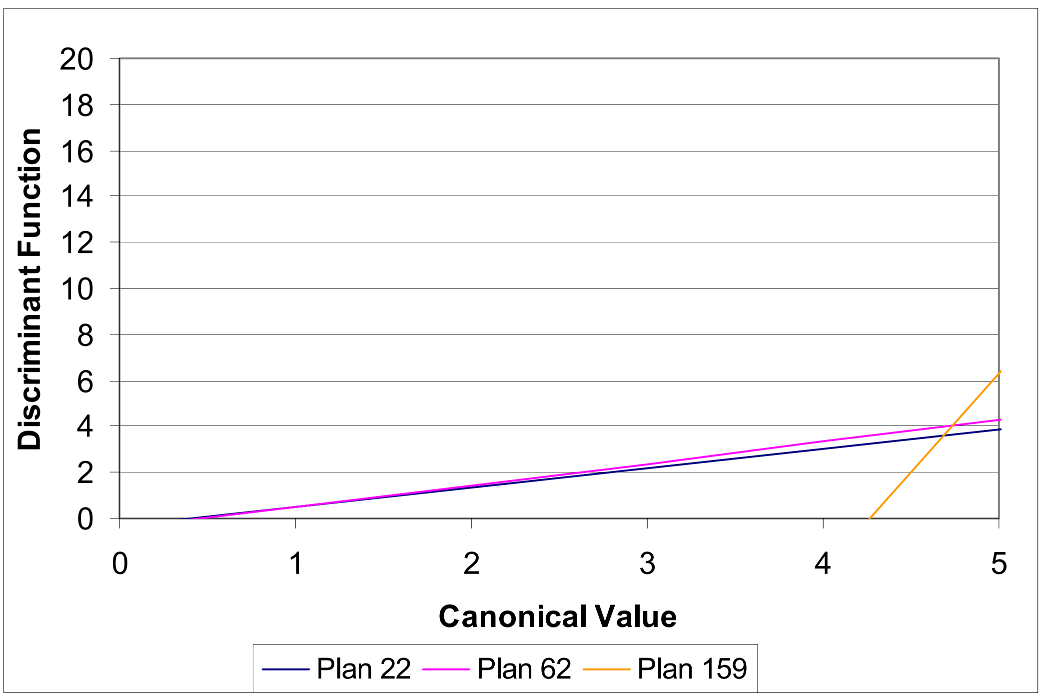


Figure 26. Discriminant Functions at the Split Level.

The classification accuracy and discriminant functions for the plans to be distinguished under the offset level are shown in Figure 27 and Figure 28, respectively. From Figure 28, the canonical value thresholds can be calculated as 2.3, 3.2, and 3.8, respectively. From Figure 27, it is clear that plans 21 and 123 should be combined and plans 137 and 188 should be combined.

The offset threshold was calculated similar to the calculation of the split thresholds as 1/(1+3.2) or 24 percent.

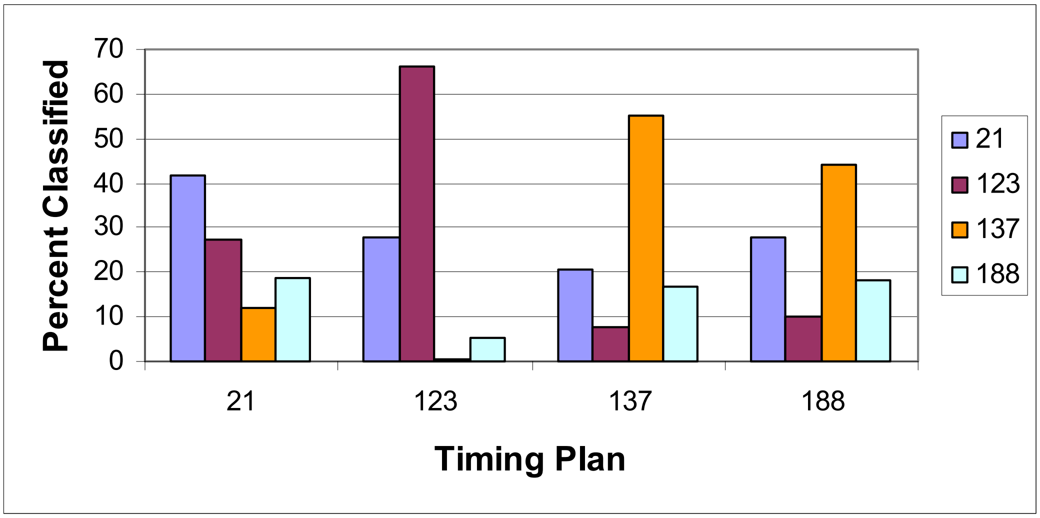


Figure 27. Classification Accuracy at the Offset Level.

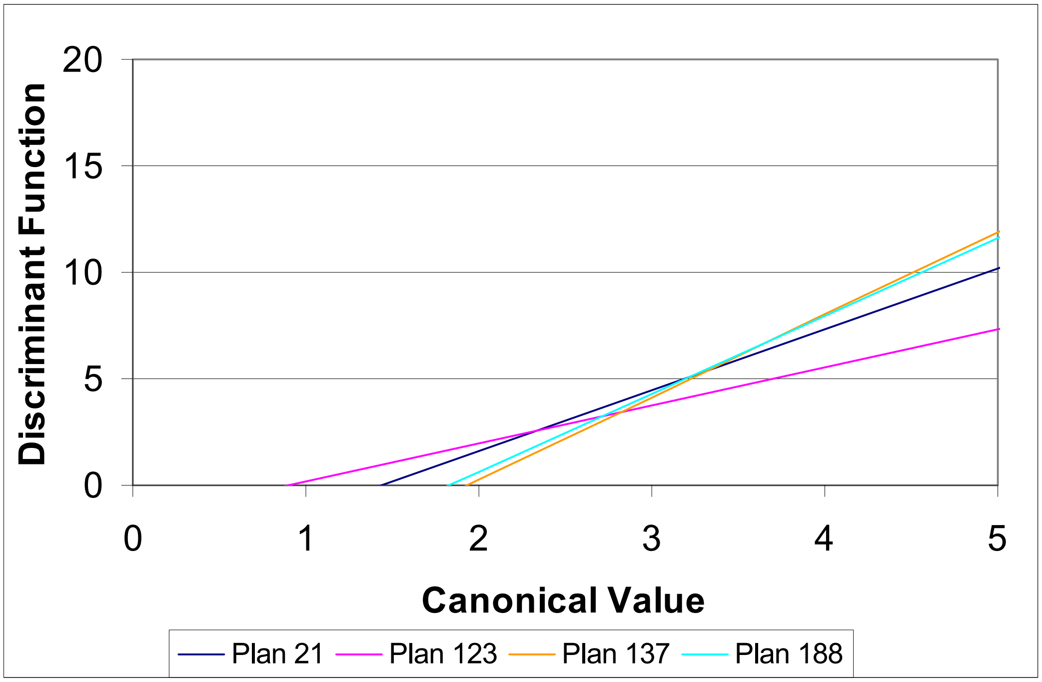


Figure 28. Discriminant Functions at the Offset Level.

Weighting and Scaling Factors

Weighting and scaling factors were calculated similar to the previous chapter. Table 13, Table 14, and Table 15 list the recommended detector weights for the cycle, split, and offset levels, respectively.

Table 13. System Detector Weights and Scaling Factors at the Cycle Level.

System Detector Number	Raw Weight		Detector Weight	
	Count	Occupancy	Count	Occupancy
2	0.015274	0.011705	2	1
19	0.024358	0.002238	2	0
87	0.002396	0.012414	0	1
93	0.06173	-0.00397	6	0
80	0.021604	0.010107	2	1
47	0.033663	0.009464	3	1

Table 14. System Detector Weights and Scaling Factors at the Split Level.

System Detector Number	Raw Weight		Detector Weight	
	Count	Occupancy	Count	Occupancy
19	0.034984	-0.15731	3	0
87	-0.00326	0.080094	0	8
93	0.105717	0.15339	11	15
80	0.00154	0.048186	0	5
47	-0.09186	0.312265	0	31

Table 15. System Detector Weights and Scaling Factors at the Offset Level.

System Detector Number	Raw Weight		Detector Weight	
	Count	Occupancy	Count	Occupancy
87	0.009652	0.004223	1	0
93	0.169401	-0.02495	17	0
80	0.04771	-0.00221	4	0
72	0.043313	-0.00375	4	0

System Benefits

There are mainly two potential sources of benefits when using the research approach for TRPS setup as compared to the TOD mode. The first source of benefits is due to the global optimization procedure that capitalizes on the fact that for a given traffic state Si, if timing plans P1 and P2 were the best and second best, respectively, P2 might perform much better than P1 for the rest of traffic states Sj. A system optimization approach is therefore crucial given that only a limited number of timing plans can be stored in the traffic controllers.

The second potential source of benefits is the fact that TRPS can bring up the most suitable timing plan for the existing traffic condition while the TOD is limited to bringing up timing plans according to a fixed time schedule regardless of the existing traffic condition.

The first source of benefit is restricted by the ability of the TRPS mechanism to recognize the traffic state correctly. If the TRPS mechanism misclassified the state as another state and brought up the wrong timing plan, the benefit would be reduced (in addition to the disadvantages associated with the transitioning effects; this issue will be addressed in the second-year report).

Table 16 shows the classification accuracy calculated for each state for the Bastrop closed-loop system. These classifications were obtained by calculating the canonical values corresponding to each of the TRPS three levels and comparing them to their corresponding thresholds. The SCD was calculated by accumulating the product of each state-plan by the proportion of state S_i classified as belonging to plan P_j multiplied by the probability of the occurrence of that particular state S_i. The average SCD due to system optimization and TRPS classification was, therefore, found to be 18,829 vehicle-minutes/hour.

Table 16. Percent Classification Accuracy on Bastrop Closed-Loop System.

State Belongs to Plan	State Classified into Plan					
	21	**22**	**55**	**159**	**188**	**Total**
11	0	18	43	15	24	100
21	56	0	20	0	23	100
22	0	99	0	1	0	100
52	10	39	43	0	9	100
55	8	0	76	0	16	100
62	0	99	0	1	0	100
123	71	5	18	0	5	100
137	27	0	25	2	46	100
159	0	9	48	43	0	100
188	27	0	33	4	36	100

To account for the second source of benefit, it was necessary to predict the total delay expected from implementing a TOD mode. Since the TOD mode cannot recognize the traffic state to bring up its most suitable plan, the delay will, therefore, range between two extremes. The best extreme will be when all states occur during the implementation of their best possible timing plan (or re-stated: if the engineer implemented the most suitable timing plan for every possible state). The worst extreme will be when all traffic states occur during the implementation of their worst timing plan. In reality, the SCD will fall somewhere in the middle of the two extremes.

To conduct a fair comparison between the TRPS and TOD, the five timing plans that were designed for the most frequent traffic states were selected. The extreme best scenario was calculated by accumulating the product of each state-best plan SCD and the state probability. The extreme worst scenario was calculated by accumulating the product of each state-worst plan SCD and the state probability.

The best and worst scenarios SCD were found to be 18,888 vehicle-minutes/hour and 29,580 vehicle-minutes/hour with an average SCD of 24,234 vehicle-minutes/hour. Using a multiplier of 2,345 to convert to dollars of annual savings [X/60 (min/hr)*24 (hrs/day)*365 (days/year)*($12.85/person-hr *[25]*)*(1.25/average persons in a car)], the potential savings in delay reduction alone can fall anywhere in the range between $138,154 to $25,211,003 per year in the Bastrop system (or $27,630 to $5,042,200 per intersection per year).

Limitation of Methodology

The methodology used consisted of optimizing the system performance with genetic algorithms, followed by the TRPS system setup using discriminant analysis. The discriminant analysis step was conducted after the system optimization step was completed, which resulted in some misclassifications that could have been prevented had the discriminant analysis provided feedback in the genetic algorithm step. This limitation needs to be addressed in order to minimize the transitioning effect and increase the lower bound of delay savings in comparison to the TOD mode.

SUMMARY

This chapter described a novel methodology for selection of optimal timing plans to be used with TRPS control. The chapter addressed two of the most important challenges in setting up a TRPS system: 1) development/selection of optimal timing plans that are suitable for a wide range of traffic conditions, and 2) mapping/association of each one of these wide ranges of traffic conditions to one of the few available timing plans that can be stored in the traffic controllers. The new procedure showed potential benefits ranging from an annual saving of $27,630 to $5,042,200 per intersection in delay reduction alone.

CHAPTER 7: CONCLUSION

OVERVIEW

Closed-loop traffic control systems can be operated by either TOD mode or TRPS mode. When properly configured, the TRPS mode has the greatest potential to provide an optimal operation due to its ability to accommodate abnormal traffic conditions such as incidents, special events, and holiday traffic. Most importantly, the TRPS mode can reduce the need for frequent redesign/updates to signal timing plans. This research was conducted to develop guidelines for selection of TRPS parameters and thresholds based on a scientific procedure. The methodology used in this research was documented in this first-year report.

RESEARCH APPROACH

This report documents a novel and comprehensive methodology for robust and optimal selection of TRPS parameters and thresholds. The approach discussed here proposes that only a few timing plans are needed for the subset of all traffic networks that share the same characteristics (arterial versus grid network, protected lefts versus permitted lefts, lead-lead versus lead-lag operation, etc.). Once the timing plans for certain network characteristics have been identified, TRPS parameters need to be selected such that the most suitable plan in the controllers' database is selected to match the existing traffic conditions. This approach, and making sure that plans for handling extreme conditions are stored in the controllers, will reduce the effect of plan "aging." The goal is to have the engineers implement these sets of timing plans and TRPS parameters in closed-loop systems. If the engineers have excess time and they prefer to implement a more customized system for each closed-loop (to improve efficiency from 80 percent to 95 percent, for example), they can conduct a detailed study following the steps detailed in the report. Otherwise, they can still feel "comfortable" that the closed-loop system is operated with a reasonably good performance.

The proposed approach is illustrated by designing the TRPS system for two closed-loop systems in Texas. One of the closed-loop systems studied consisted of three intersections in a suburban setting where traffic patterns did not exhibit a high degree of variation. The closed-loop system was used to illustrate the methodology for selecting optimal and robust TRPS parameters.

The second closed-loop system consisted of five intersections in an urban setting with highly variable traffic demand levels and patterns. The closed-loop system was used to illustrate the optimization procedure required for selecting optimal timing plans for the overall system. The task was then followed by the proposed procedure to select optimal and robust TRPS system parameters.

RESEARCH FINDINGS

The research documented in this report developed a new methodology for selection of optimal timing plans to be used with the TRPS control in addition to selection of TRPS parameters and thresholds for robust performance. For simple networks such as the Odem network, the new methodology showed a classification accuracy of 100 percent. Although the accuracy rate reduces for a more complicated system like the Bastrop network, the new procedure still shows potential benefits ranging between $27,630 to $5,042,200 annual savings per intersection in delay reduction alone.

LIMITATIONS AND FUTURE WORK

The methodology used consisted of optimizing the system performance with genetic algorithms, followed by TRPS system setup using SAS discriminant analysis procedure. The discriminant analysis step was conducted after the system optimization step was completed, which resulted in some misclassifications that could have been prevented had the discriminant analysis provided feedback in the genetic algorithm step. This limitation needs to be addressed in order to minimize the transitioning effect and increase the lower bound of delay savings in comparison to the TOD mode. In addition, the role of the smoothing factors needs to be investigated. The TRPS system parameters need to be verified and evaluated using hardware-in-the-loop simulation and/or field studies. In addition, guidelines for system detector locations need to be developed. The developed guidelines need to be presented in simple format (tables or charts) to facilitate field implementations.

CHAPTER 8: REFERENCES

1. Meyer, M. *A Toolbox for Alleviating Traffic Congestion and Enhancing Mobility*, Institute of Transportation Engineers, 1997.

2. Fambro, D., et al., *Benefits of the Texas Traffic Light Synchronization (TLS) Grant Program II*. Texas Transportation Institute, The Texas A&M University System, College Station, Texas,1995.

3. Henry, R.D., R.A. Ferlis, and J.L. Kay. *Evaluation of UTCS Control Strategies —* Technical Report. Report No. FHWA-RD-76-150. FHWA, U.S. Department of Transportation, August 1976.

4. Kay, J.L., J.C. Allen, and J.M. Bruggeman. *Evaluation of the First Generation UTCS/BPS Control Strategy.* Volume 1 – Technical Report. Report No. FHWA-RD-75-27. FHWA, U.S. Department of Transportation, February 1975.

5. Henry, R.D., R.A. Ferlis, and R.M. White. *Application of UTCS First Generation Control Software in New Orleans.* Report No. FHWA-RD-78-3. FHWA, U.S. Department of Transportation, January 1978.

6. *Highway Capacity Manual*. TRB Special Report 209, Third Edition, Transportation Research Board, District of Columbia, 1994.

7. Wilson, A. (NHTV, Breda, Netherlands). *A Traffic-Responsive Control Method for Small Networks*. Towards the New Horizon Together. Proceedings of the 5th World Congress on Intelligent Transportation Systems, Held 12-16 October 1998, Seoul, Korea. Paper No. 2020, 1998.

8. Hanbali, R. and C. Fornal. Methodology of Evaluating the Effectiveness of Traffic-Responsive System on Intersection Congestion and Traffic Safety. In *Transportation Research Record 1603*, TRB, National Research Council, Washington, D.C., 1997, pp.137-149.

9. Nelson E., M.M. Abbas, G. Shoup, and D. Bullock. *Development of Closed-Loop System Evaluation Procedures*. FHWA/IN/JTRP. Federal Highway Administration, McLean, Virginia, May 2000.

10. Kay, J., R. Henry, and S. Smith. *Locating Detectors for Advanced Traffic Control Strategies: Handbook.* Report No. FHWA-RD-75-91. FHWA, U.S. Department of Transportation, 1975.

11. Woods, D. and N. Rowan. *Detector Location for Computerized Arterial Street Sampling Detectors*. Report No. FHWA/TX-95/1392-6. Texas Transportation Institute, The Texas A&M University System, College Station, Texas, 1995.

12. *Master Controller Software.* Naztec, Inc., Sugarland, Texas, 2002.

13. *ASC/2M-1000 Zone Master Programming Manual.* Econolite Control Products, Inc., Anaheim, California, 1996.

14. *MARC 300 Series Master Controller*. Automatic Signal/Eagle Signal, Austin, Texas, 1997.

15. Balke, K.N., R.S. Keithireddipalli, and C.L. Brehmer. *Guidelines for Implementing Traffic Responsive Mode in TxDOT Closed-Loop Traffic Signal Systems*, Research Report 2929-3F, Project No. 7-2929. Texas Transportation Institute, The Texas A&M University System, College Station, Texas, August 1997.

16. Light, Janie. *Flexible Advanced Computer Traffic Signal System*. Texas State Department of Highways and Public System, Electronic Systems Section, Division of Automation, Austin, Texas, December 1989.

17. ITT Systems & Sciences Corporation. *CORSIM User's Manual*. Version 1.04. FHWA, U.S. Department of Transportation, March 1998.

18. Huberty, C. J. *Applied Discriminant Analysis*. John Wiley & Sons, Inc., New York, New York, 1994.

19. Trafficware Corporation. *SYNCHRO 5.0 Traffic Signal Timing Software User Guide.* Trafficware Corporation, Albany, California, 2000.

20. SAS Institute, Inc. *SAS/STAT User's Guide, Version 6*. SAS Institute , Cary, North Carolina, 1989.

21. Chaudhary, N., V. Kovvali, C. Chu, and S. Alam. *Software for Timing Signalized Arterials.* Research Report 4020-1. Texas Transportation Institute, The Texas A&M University System, College Station, Texas, August 2002.

22. Kloeden, P., and Platen, E. *Numerical Solution of Stochastic Differential Equations.* Springer Verlag, New York, New York,1999.

23. The Mathworks, Inc. *MATLAB 6.5*. The Mathworks, Natick, Massachusetts, 2003.

24. Goldberg, D. *Genetic Algorithms in Search, Optimization, and Machine Learning*. Addison-Wesley, Reading, Massachusetts, 1989.

25. Schrank, D. and T. Lomax. *The 2002 Urban Mobility Report*. Texas Transportation Institute, The Texas A&M University System, College Station, Texas, June 2002.