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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 potential to provide an optimal operation due to its ability to accommodate abnormal traffic conditions such as incidents, special events, and holiday traffic. TRPS mode can also reduce the need for frequent redesign/updates to signal timing plans. To date, there have not been any formal guidelines for selection of robust and optimal TRPS system parameters and thresholds. Consequently, traffic engineers usually revert to the TOD mode of operation for its ease of setup.

This report provides a new methodology for robust and optimal selection of TRPS parameters and thresholds. The report presents an innovative framework of TRPS system setup following a comprehensive approach that incorporates a multi-objective evolutionary algorithm and a supervised discriminant analysis. The developed guidelines are presented in simplified tables to facilitate their implementation. Guidelines were verified by using hardware-in-the-loop simulations.

Compared to just the worst possible solutions encountered during the optimization, the final solution provided a concurrent savings of 53 percent in delay and 19 percent in stops.

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GUIDELINES FOR DETERMINATION OF OPTIMAL TRAFFIC RESPONSIVE PLAN SELECTION CONTROL PARAMETERS

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CHAPTER 1: INTRODUCTION

OVERVIEW

Closed-loop traffic control systems can be operated in 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 optimal operation due to its ability to accommodate abnormal traffic conditions such as incidents, special events, and holiday traffic. Most importantly, TRPS mode can reduce the need for frequent redesign/updates to signal timing plans. Although TRPS mode can provide a more optimal and snappier operation than 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 a methodology for selection of TRPS parameters and thresholds based on a scientific procedure. In addition, the research was also to produce simplified guidelines to facilitate the implementation of the methodology.

RESEARCH OBJECTIVES

The objective of this research was to develop a methodology and 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 the form of charts or tables 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. 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 for engineers is to implement these sets of timing plans and TRPS parameters in closed-loop systems. If the engineers have excess time and they prefer to have a more customized implementation for each closed-loop system (for instance, to improve optimality from 80 percent to 95 percent), they can conduct a detailed study following the steps detailed in this report. Otherwise, engineers can still feel "comfortable" that the closed-loop system operates with a reasonably good performance.

The proposed approach, while not claiming to achieve 100 percent system optimality, 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.

CHAPTER 2: TRPS CONTROL AND STATE OF THE PRACTICE

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 dial-up 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 requires that timing plans be varied in a timely manner as the traffic conditions change.

CLOSED-LOOP SYSTEMS MODES OF OPERATION

Closed-loop systems can operate under four modes:

- The “free” mode. In this mode, each intersection runs 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 operates 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 repetitive traffic patterns. 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 with predictable traffic patterns, 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 operation 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 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.

ADVANTAGES OF TRPS

Timing plans are typically developed on the basis of historical vehicle demand data. In reality, the actual demands 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 times that drivers arrive at intersections along their routes. 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 changes timing plans in response to changes in traffic demands. The objective is to enable the signal controller to implement optimal timing plans 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 latter statement stems from the fact that the TRPS system automatically switches plans in response to changes in traffic patterns.

A recent study conducted in the 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, 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 period 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 simulation 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 the 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. Consequently, the study reported that TRPS frequently resulted in unexpected time plan changes, reducing the overall system performance *(9)*.

CHALLENGES OF TRPS SETUP

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 is the numerous factors and parameters that need 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 (occupancy and counts) collected from system detectors to measure the traffic conditions in the closed-loop system network. The occupancy and count information is aggregated into certain TRPS parameters (e.g., cycle level, 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 master controller continuously compares the control parameters 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 serves 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, the detectors 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, the detectors 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 split level and, therefore, the detectors should be placed on the side streets.

The general guidelines require location of the system detectors relatively far from the traffic signal to eliminate the effects of signal timings 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)*.

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. Equation 1 shows how the new value is calculated:

$$\bar{x}_{new} = \bar{x}_{old} + k(x_{new} - \bar{x}_{old}) \tag{1}$$

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, resulting 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. 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.

Weighting Factors

Each system detector is assigned a weighting factor by which its data are 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.

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 pre-defined by the controller manufacturer.

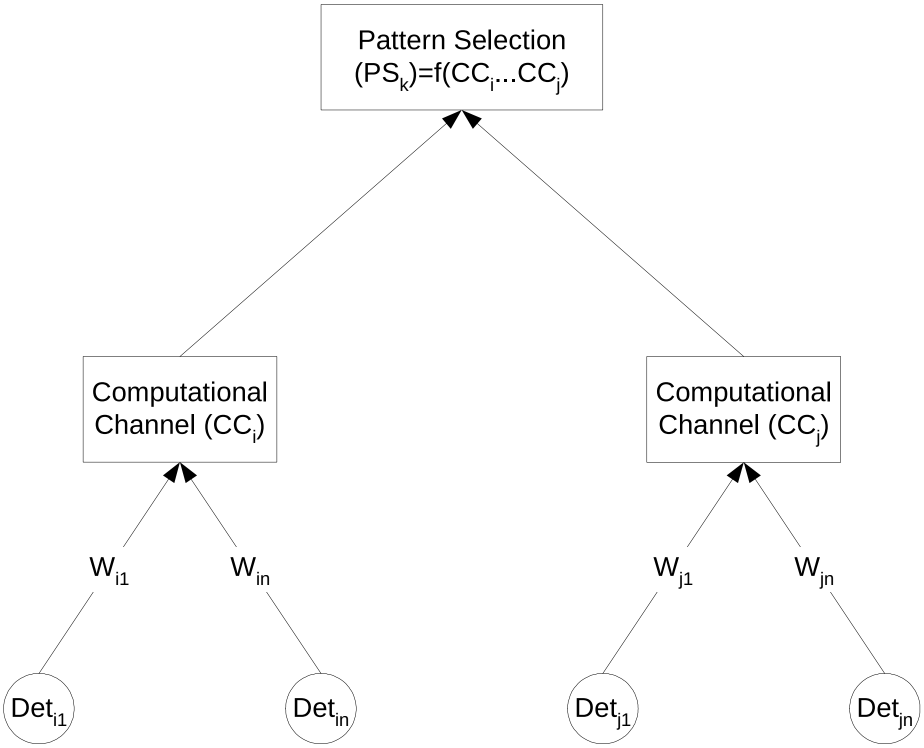


Figure 1. General TRPS Mechanism.

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 look-up procedure. The look-up 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 look-up 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).

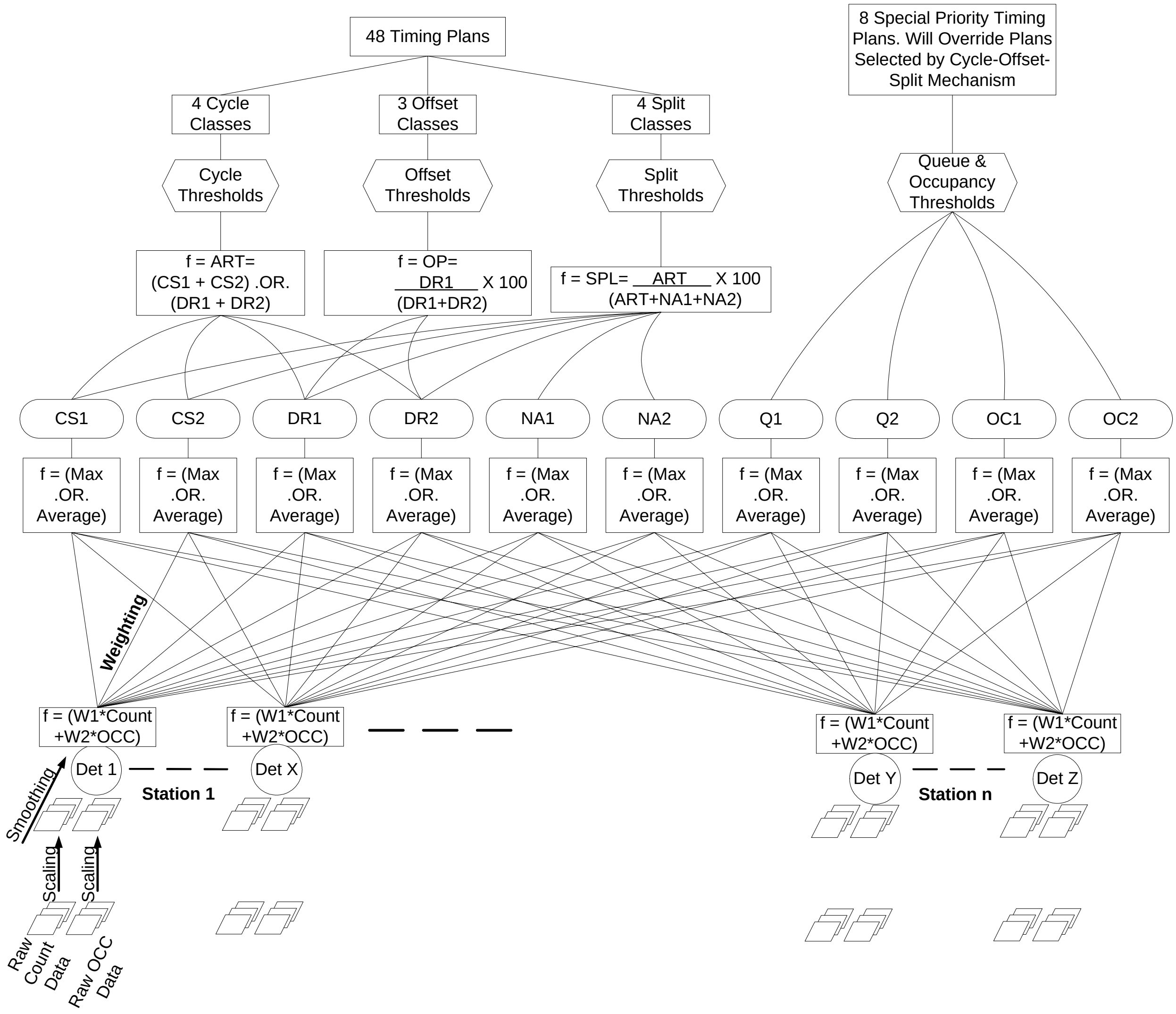


Figure 2. Eagle TRPS Parameters and Mechanism.

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 look-up 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.

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 *(15)*. Therefore, there is a need for theoretically sound guidelines on how TRPS parameters and thresholds can be selected such that TRPS results in an optimal and stable system operation.

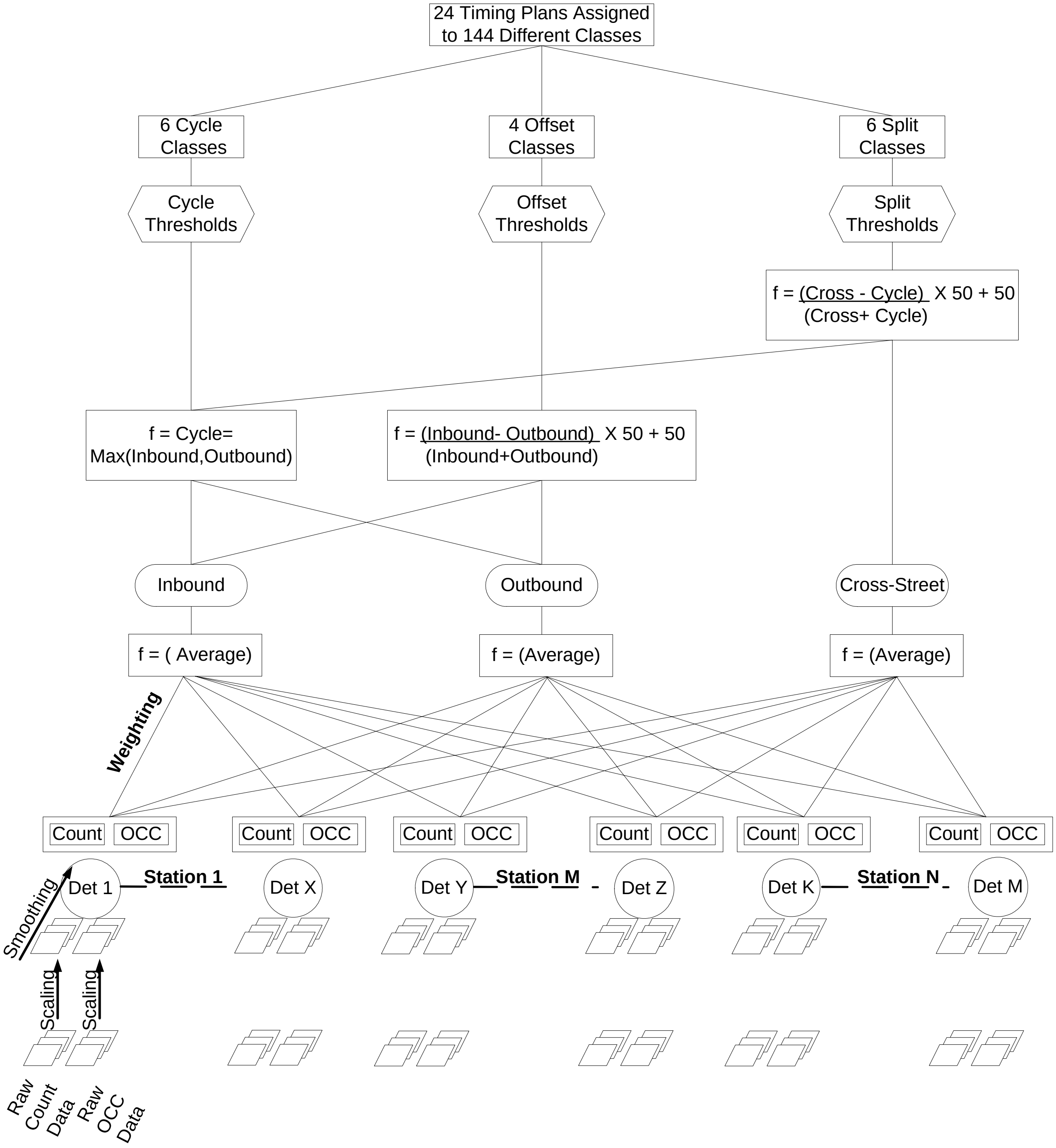


Figure 3. Naztec TRPS Parameters and Mechanism.

STATE OF THE PRACTICE ON TRPS CONTROL

State of the practice in setting up a TRPS mode was assessed through communication with in- and out-of-state engineers and technicians. Information was sought about the problems experienced with the TRPS mode and closed-loop systems. Information obtained during the interviews suggested that there is limited experience with operation of closed-loop systems with the TRPS mode in general. Some engineers used a “fine-tuning” process for TRPS setup. 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 *(16)*.

Several engineers and technicians 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 also show 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’s instability resulting in too frequent changes between timing plans that would eventually lead to an increase in overall system delays. Some engineers 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.

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 set-up time the TRPS requires such that it operates in an efficient and stable manner *(16)*.

CHAPTER 3: GENERALIZED DESIGN FOR OPTIMAL TRPS CONTROL

OVERVIEW

As previously discussed, TRPS provides a mechanism by which the traffic signal system changes timing plans in response to changes in traffic conditions. The objective is to enable the signal controller to implement optimal timing plans 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 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 will be addressed in the next chapter.

SCOPE OF STUDY

The scope of this research is limited to closed-loop systems on arterial networks. The guidelines developed in this research are targeting the sites with the following characteristics:

- urban/suburban arterials with moderate-to-high volumes (normal-to-congested conditions);
- systems consisting of three to five intersections;
- intersections with typical geometry (two lanes, four-leg intersections, etc.);
- systems that do not include interchanges; and

- closed-loop systems that have working system detectors. System detectors can be either inductive loops or possibly video-based detectors installed right above the system detector location.

This research does not address oversaturated conditions or lane blockage of left turn lanes by through lanes, and vice versa (i.e., left turn bays are assumed to be long enough to handle vehicular demands). The guidelines developed in this research are developed for typical closed-loop systems. Sites with special geometrical considerations (e.g., arterial's left turns that cannot be run together) will impose extra constraints on the system that might or might not reduce system performance. Special situations such as high pedestrian demands, proximity to diamond interchanges, and/or grid networks are beyond the scope of this research.

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 closed-loop systems. The proposed approach, while not claiming to achieve 100 percent system optimality, provides a "blanket" of good performance that serves several purposes, including:

- encouraging traffic engineers to implement TRPS systems that will achieve good performance (for instance, 80 percent optimality) rather than a possible poor performance due to outdated TOD plans (for instance, 50 percent optimality);
- saving engineers and technicians valuable time that is otherwise required to develop timing plans for each TOD traffic pattern; and
- reducing the effects of timing plans "aging" through the implementation of traffic responsive mode.

This chapter describes a comprehensive approach for selecting optimal timing plans for TRPS control. The approach discussed here proposes that only a few timing plans are needed for all traffic networks that share the same characteristics. Once the timing plans for certain network characteristics have been chosen, TRPS parameters need to be selected such that the most suitable plans in the controllers' databases are selected to match the existing traffic conditions. This approach, and making sure that controllers store plans for handling extreme conditions, will reduce the effects of plan "aging."

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 time period (TP), 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 4, 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.

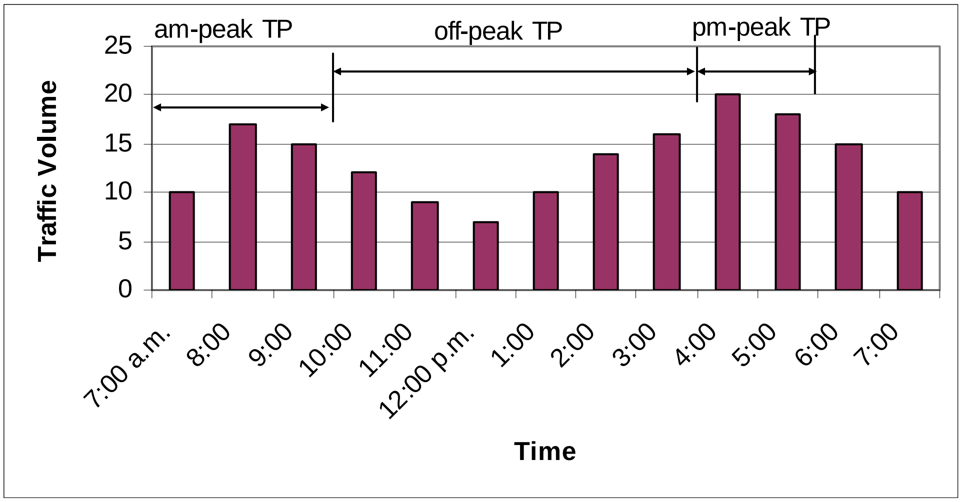


Figure 4. Illustration of Current Plan Selection Practice.

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 temporally adjacent.

The State-Timing Plan Space

The problem of selecting timing plans for traffic responsive operation can be represented by two variables: state (S) and timing plan (P). The state variable describes the existing traffic pattern for all approaches at a certain point in time. The timing plan variable identifies the timing plan active at the same point in time. 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 to: 1) select the optimal subset of the P space to be included in the limited memory of the traffic controllers and 2) determine the optimal plan from the available P space that should be applied to the existing sample of the S space. It can, therefore, be recognized that for a complete representation and evaluation of the studied system, all state-plan combinations have to be considered and evaluated.

Traffic States Clustering

In TRPS control, once timing plans are selected and associated with traffic states, the TRPS system parameters are configured to activate a timing plan when recognizing one of its associated states. The activation mechanism is implemented through a threshold system, where timing plans are activated when certain traffic volumes and/or occupancy exceed or fall below these thresholds. As such, timing plans should preferably be associated with adjacent traffic states. Otherwise, the TRPS threshold mechanism might either fail to activate the timing plan or bounce between different plans. It is, therefore, required to cluster the traffic states into groups with common characteristics. In other words, the adjacent states clustered together need to be homogeneous in their measures of effectiveness (MOEs) with regard to their associated timing plan.

Some of the previous research used K-means clustering of traffic states *(16)*. The K-means procedure considers each observation as an object in an *n*-dimensional space. The procedure groups traffic states that are closer in their attributes (eastbound [EB] volume, northbound [NB] volume, etc.) together. However, the K-means clustering procedure does not take into account the delay or number of stops associated with assigning a timing plan to different states. Therefore, applying a K-means clustering merely results in forming *n* number of homogeneous states in terms of traffic volume itself, but without any regard to homogeneity in terms of the MOEs when applying a timing plan to those states.

Previous research also looked into clustering traffic patterns by using genetic algorithms to optimize the time span between TOD break points *(17)*. While this approach could potentially be used to solve the problem of determining a threshold in volume to when the timing plans need to be switched, it does not address higher states' dimensionality. It should be noted at this point that every critical movement in a state is a dimension in the state space. State space can, therefore, have at least three dimensions considering the inbound, outbound, and cross-street volumes.

PROPOSED APPROACH

The proposed approach consists of the following steps:

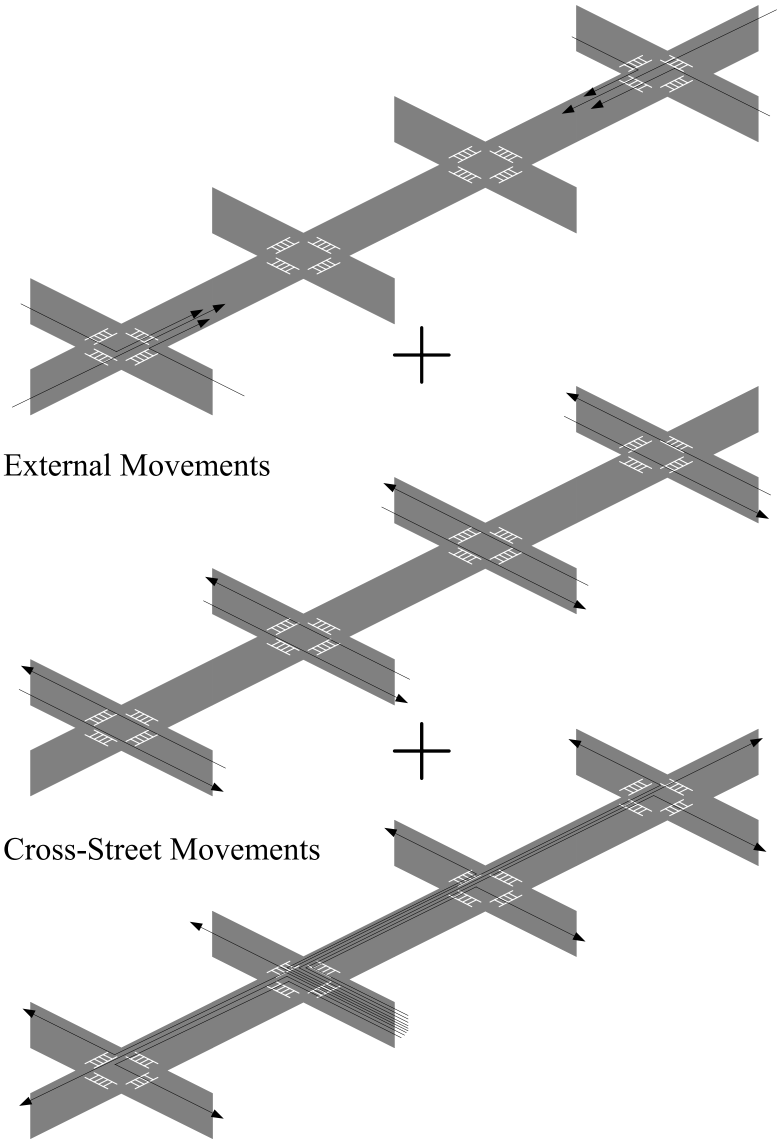
1. Design timing plans for all significant levels of state conditions. In this context, significant level increase is an increase in the number of vehicles that could result in more than 2 seconds difference in phase duration as obtained from a signal optimization program (such as PASSER V *[18]*). Actual levels used in the analysis will be described later.
2. Run each timing plan with all traffic states in a batch mode to obtain MOEs if the traffic state was to be associated with that timing plan. This step was performed using the PASSER V optimization package.
3. In addition to the traditional MOEs (stops and delay), define a new MOE known as the degree of detachment (DOD). The DOD measures the degree by which traffic states are detached from adjacent states. In this context, detachment occurs when the adjacent state (state that is one level below or one level above the current state's level) is associated with a different timing plan.
4. Conduct multi-objective optimization for delay, stops, and DOD using a non-dominated sorting genetic algorithm. The algorithm produces *n* number of timing plans and a traffic state-timing plan association that results in the least delay and least number of stops, while maintaining that timing plans are assigned to mostly adjacent states. This makes it easier to define thresholds based on volume to switch to another timing plan.

Network Geometry and Timing Plan Generation

In order to cover all reasonable traffic states in this analysis, a global perspective was used to look at all possible traffic states. The global perspective classifies arterial volume into three main movements as shown in Figure 5: 1) major external movement to the arterial, 2) additional cross-street movement, and 3) internal or local movements. Preliminary PASSER runs were conducted to find the realistic limit of each movement in the system so that the intersections are not oversaturated. The global perspective network consisted of four intersections with traffic control using a standard eight-phase ring structure with protected left turns only. No geometric constraints were applied to the network (i.e., left turns on the arterial can follow any pattern, lead-lead, lead-lag, etc.). The global perspective network was selected as described above since it provides a general case. Actual constraints in the field can be made to the guidelines developed for this network as will be described later. Table 1 shows the levels for each external movement. Table 2 shows levels and resulting interior turning volumes.

Table 1. Volume Levels for Arterial External Movements.

Level	External Movement Volume (vph)					
	EB-Thru	SB-Left	NB-Right	WB-Thru	NB-Left	SB-Right
1	400	0	0	400	0	0
2	800	200	200	800	200	200
3	1200	300	300	1200	300	300
4	1600	--	--	1600	--	--



1) External Movements

2) Cross-Street Movements

3) Internal Movements

Figure 5. Generalized Arterial Volume Distribution.

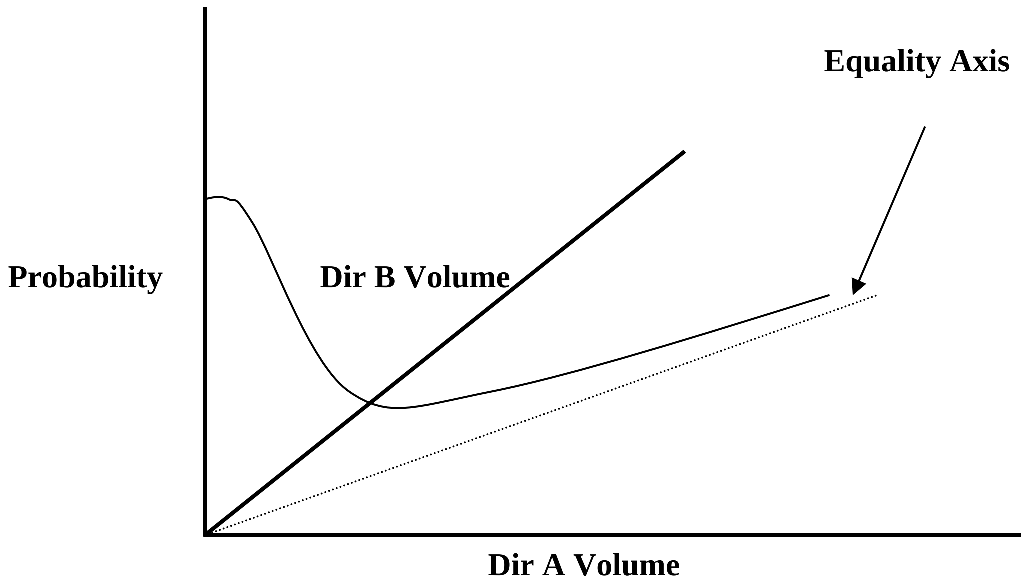
Table 2. Volume Levels for Internal Local Movements.

Cross-Street Level	Volume (vph)	Inter-section	Volume on Each Approach (vph)											
			EB			WB			NB			SB		
			L	T	R	L	T	R	L	T	R	L	T	R
1	150	1	21	127	21	134	113	134	131	19	19	19	19	131
		2	59	272	59	96	267	96	94	19	56	56	19	94
		3	96	267	96	59	272	59	56	19	94	94	19	56
		4	134	113	134	21	127	21	19	19	131	131	19	19
2	300	1	42	253	42	267	225	267	263	38	38	38	38	263
		2	117	544	117	192	534	192	188	38	113	113	38	188
		3	192	534	192	117	544	117	113	38	188	188	38	113
		4	267	225	267	42	253	42	38	38	263	263	38	38
3	300 +100	1	42	253	42	267	225	267	263	138	38	38	138	263
		2	117	544	117	192	534	192	188	138	113	113	138	188
		3	192	534	192	117	544	117	113	138	188	188	138	113
		4	267	225	267	42	253	42	38	138	263	263	138	38

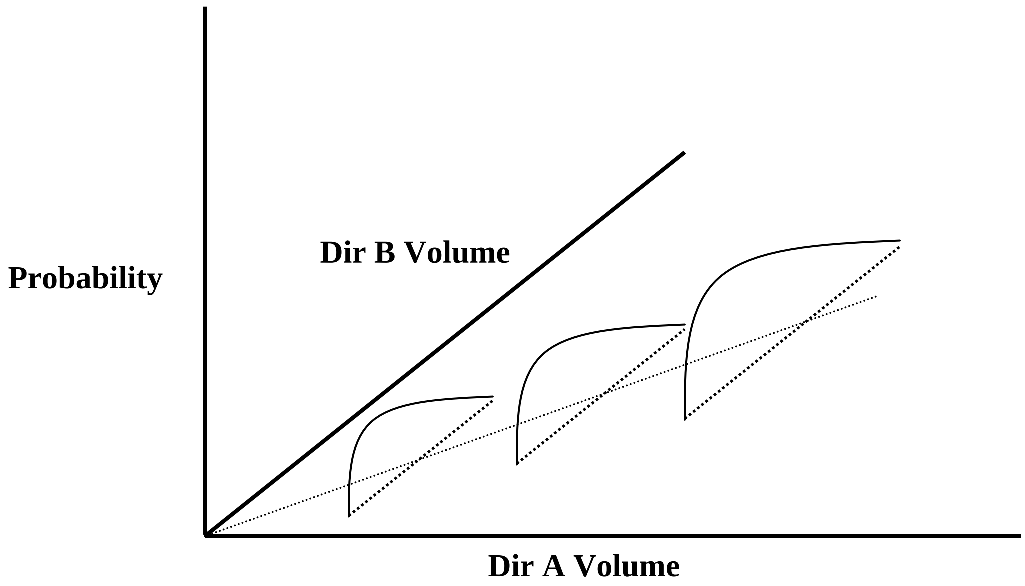
EB: Eastbound, WB: Westbound, NB: Northbound, SB: Southbound, L: Left Turn, T: Thru, R: Right Turn

Traffic State Probability

In order to design an optimal selection of timing plans, there is a need to know the probability of occurrence of each traffic state. A state that occurs more frequently would obviously be favored by the algorithm when selecting the timing plans. The probability of any particular state was determined based on the average occurrence of that state as observed in data from four sites in Texas. The probability of a state was determined in two steps: 1) determine the probability of occurrence of traffic volume in a major arterial direction and 2) given a major arterial direction, determine the probability of all other volumes in the other direction. Figure 6 shows the concept of major and minor axis state probabilities in an arterial system. The final state probability was determined as the product of the two probabilities.



a) Major Probability Distribution



b) Minor Probability Distribution

Figure 6. State Probability Distributions.

Based on the data collected from Odem, Lampasas, and Brownwood closed-loop systems in Texas, distribution fits were conducted to obtain a general state probability distribution. Figure 7 shows the major probability distribution fitted to field data.

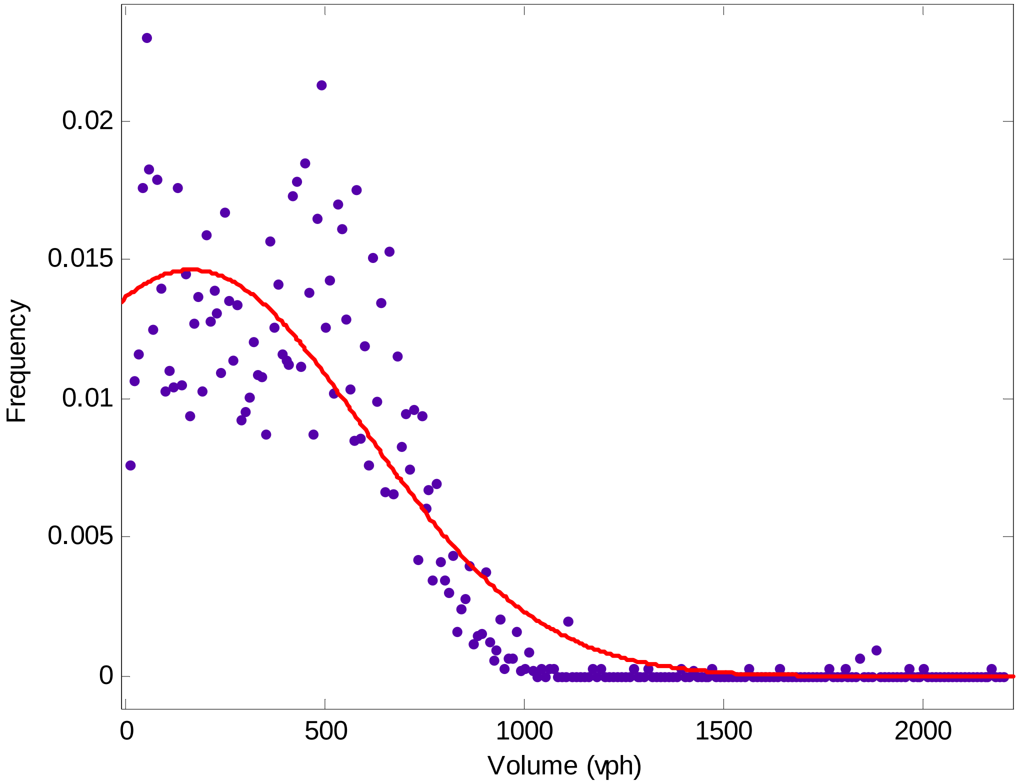


Figure 7. Fitted Probability Distribution.

The major volume distribution was found to follow a general Gaussian model of the following form with R square of 0.85:

$$Y = ae^{-\left(\frac{(x-b)}{c}\right)^2} \qquad \textbf{(2)}$$

Where:

Y = probability of occurrence,

X = traffic volume,

a = 0.01464,

b = 164.8, and

c = 615.5.

For the minor probability, normal distributions were fitted. The mean was input as the major level. The best fit for each minor axis resulted in the determination of the standard deviation for various minor axis volumes. The standard deviations are shown in Table 3.

Table 3. Standard Deviations for Minor Axis Volumes.

Volume (vph)	Standard Deviation	Volume (vph)	Standard Deviation	Volume (vph)	Standard Deviation
100	55.99	900	503.91	1700	951.83
200	111.98	1000	559.90	1800	1007.82
300	167.97	1100	615.89	1900	1063.81
400	223.96	1200	671.88	2000	1119.80
500	279.95	1300	727.87	2100	1175.79
600	335.94	1400	783.86	2200	1231.78
700	391.93	1500	839.85	2300	1287.77
800	447.92	1600	895.84		

Genetic Algorithms

Genetic algorithms (GAs) were used to perform the optimization step. GAs are optimization techniques based on the process of natural selection and genetics *(19)*. The GAs start by randomly selecting *n* timing plans that constitute the initial chromosomes. Through natural selection and the genetic operators, crossover and mutation, chromosomes (sets of plans) with better fitness (lower MOEs) 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 MOEs) than their parents. The crossover operator emphasizes the exploitation of the solution surface, while the mutation operator allows new areas of the response surface to be explored and prevents the solution from being trapped at local minima.

While GAs were widely used to solve traffic signal problems *(20)*, most of the previous research concentrated on either the optimization of one objective, or the optimization of several criteria by eventually integrating them into one objective.

Non-dominated Sorting Genetic Algorithm

Non-dominated sorting genetic algorithm (NSGA II) was developed by Dep et al. *(21)*. The algorithm belongs to a set of multi-objective algorithms that strive to find the Pareto front (the front of compromised solutions) of all objectives rather than integrating all objectives together. Solutions lying above the Pareto front are non-optimal solutions, while those lying below the Pareto front are infeasible solutions. All solutions on the Pareto front are optimal with regard to at least one objective. The shape of the Pareto front itself provides very valuable information to the analyst. One would know, looking at the Pareto front shape, how much other objective functions would be compromised if a selected objective function is to be favored.

The NSGA II is similar to simple GAs in the use of the selection, crossover, and mutation operators. However, prior to the selection step, the algorithm ranks the whole population based on all objectives. All individuals in the population that are non-dominated (i.e., there does not exist an individual that is better than this individual in all objectives) are given a rank of 1. The individuals with rank 1 are removed from consideration, and all other individuals are ranked again and are assigned a rank of 2. The process continues until all individuals are assigned a rank. After the process is completed, a crowding distance is calculated for all individuals. The crowding distance is used to diversify the population by assigning a higher value to individuals with larger cuboids formed by the individual and its neighboring individuals. The selection operator is then applied while assigning higher fitness to individuals with higher ranks and crowding distances. The algorithm ensures elitism by combining the parent population with the children population before applying the crossover and mutation operators.

Plan Selection Optimization

The methods by which GA operators are applied would normally produce random individual values. However, in applying GAs to the selection of plans, it was necessary to satisfy two constraints: 1) each individual solution must contain only integer numbers within the range of the total number of plans and 2) the integer numbers must be unique within any individual. 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 1 and the total number of plans (n). Restricting the plans to be coded as a set of consecutive integer numbers, the routine randomly picks the first plan 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 Figure 8 illustrates. Crossover and mutation were conducted in a similar fashion to ensure the production of valid chromosomes.

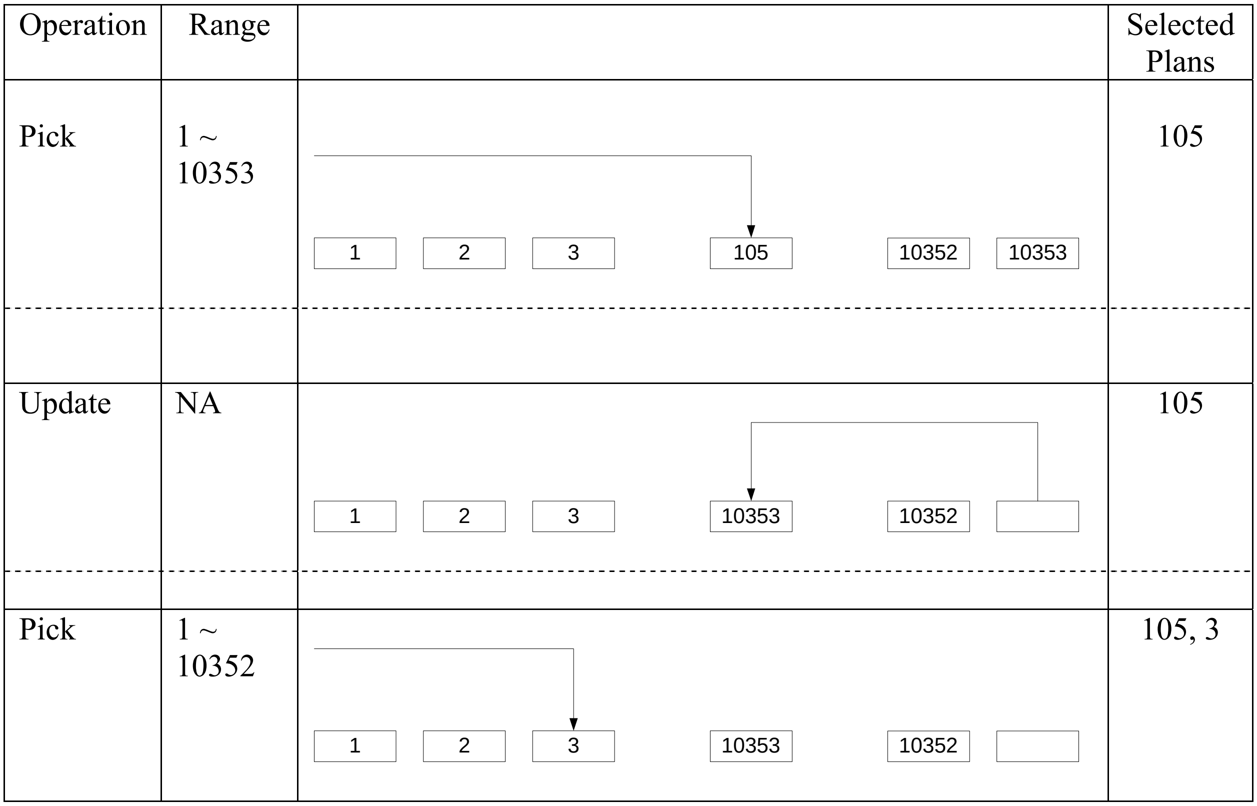


Figure 8. Genetic Algorithm Selection of Timing Plans.

Degree of Detachment

The authors defined a new MOE for the purpose of clustering traffic states for this problem. The DOD measures the degree by which a traffic state is detached from adjacent states. In this context, detachment occurs when associating the adjacent state (state that has a level one below or one above the current state's level) with a different timing plan. Recall from Table 1 and Table 2 that any traffic state is basically represented by a seven-element vector (three EB external movement levels, three WB external movement levels, and one cross-street movement level). As such, there are 14 DOD degrees of freedom for any given state (seven upper levels and seven lower levels). Figure 9 shows the DOD value for three levels in the state representation vector.

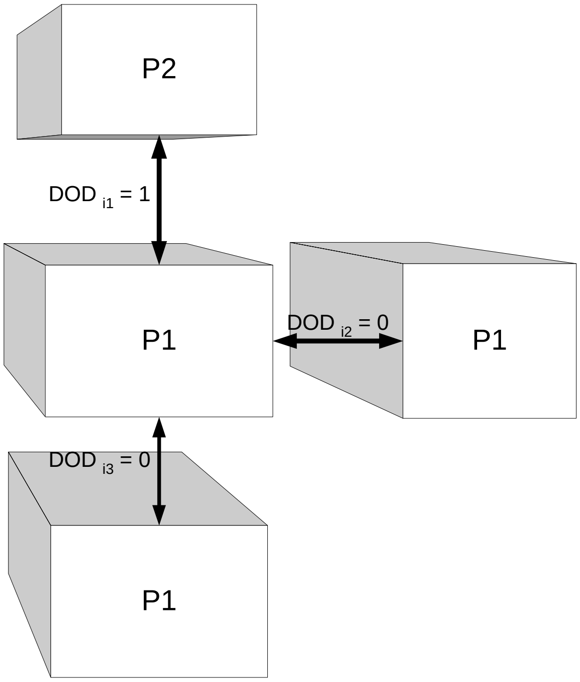
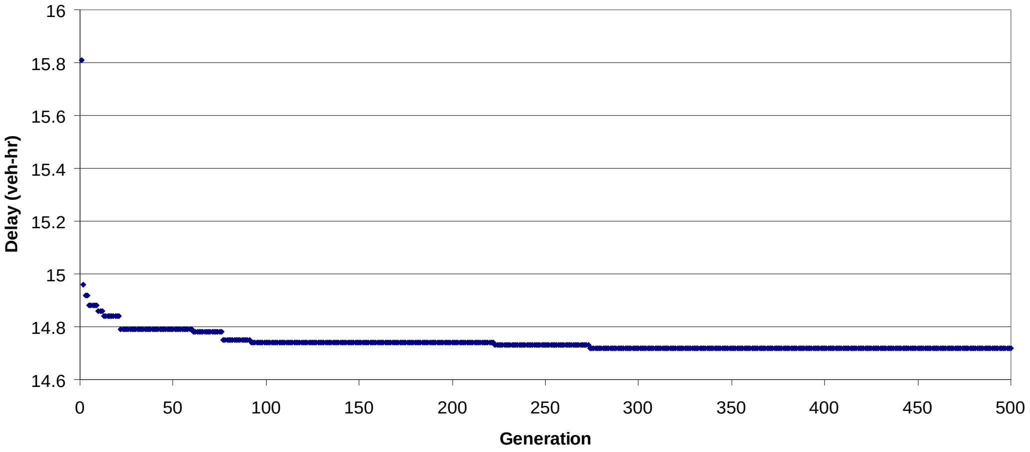


Figure 9. DOD Concept.

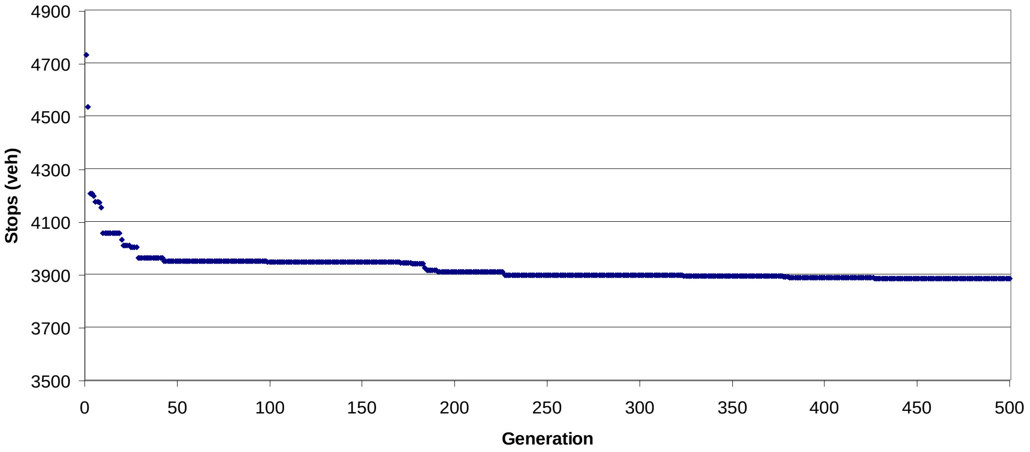
MULTI-OBJECTIVE OPTIMIZATION RESULTS

NSGA II Runs

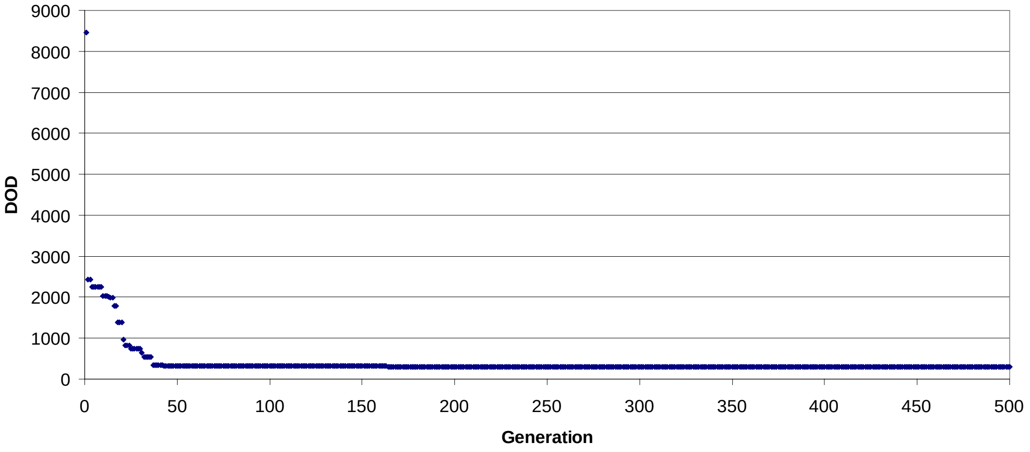
The NSGA II algorithm was run to optimize the three objectives: delay, stops, and DOD. Different GA parameters were tried to investigate the shape of the Pareto front. Crossover probabilities tried were 0.8 and 0.9. Population sizes tried were 80, 200, and 500. The mutation probabilities tried were 0.02 and 0.1. Most of the combinations produced similar Pareto fronts. Figure 10 shows the evolution of the solutions for delay, stops, and DOD, respectively. It can be deduced from Figure 10 that the solution converges around the 200th generation.



a) Delay Evolution



b) Stops Evolution



c) DOD Evolution

Figure 10. 4 GA Evolution.

The Pareto Front

Figure 11 shows the Pareto front obtained from the NSGA II run. The figure clearly shows the trade-offs between different objectives. In order to simplify the selection of final solution, the Pareto front is projected into three two-axis figures as shown in Figure 12**.**

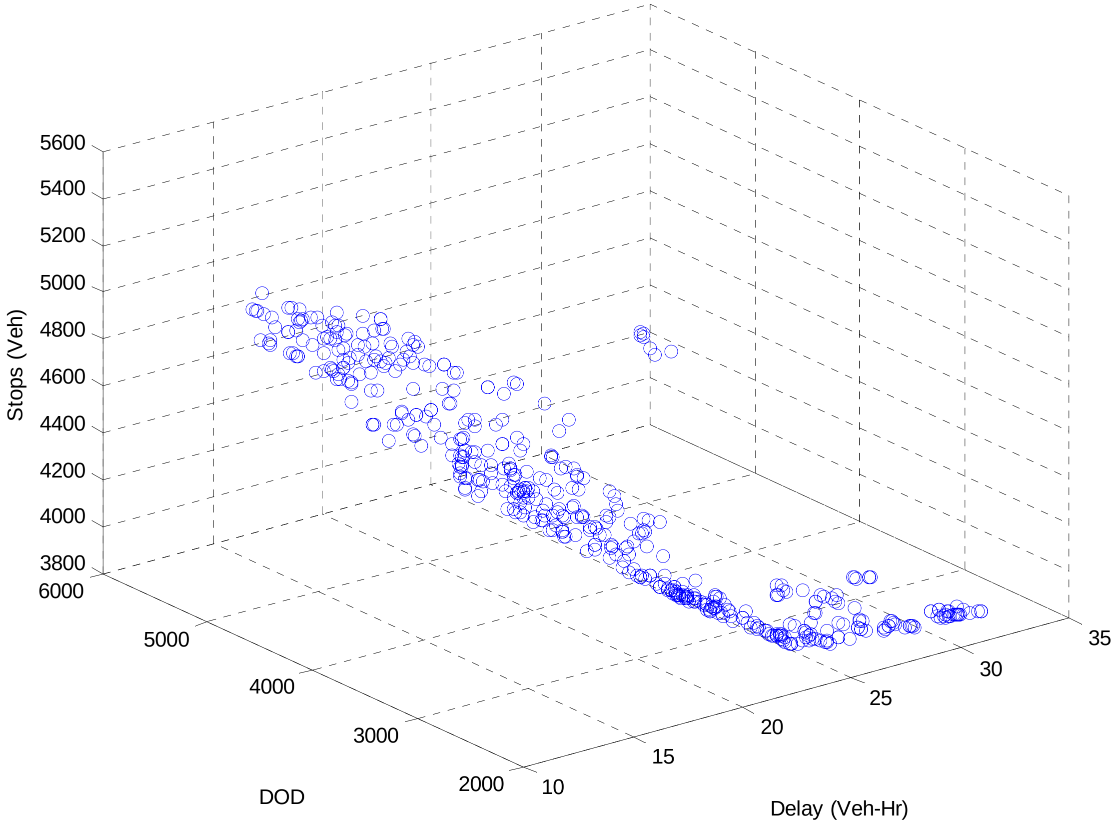
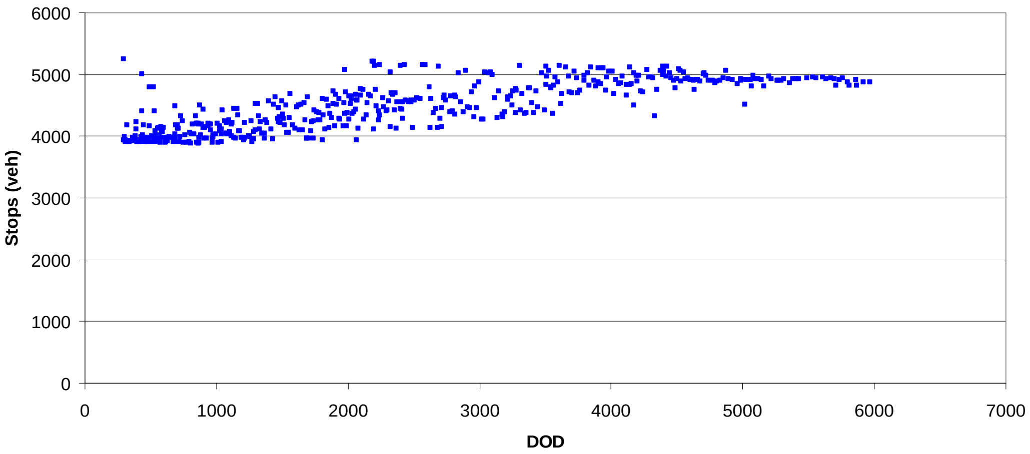
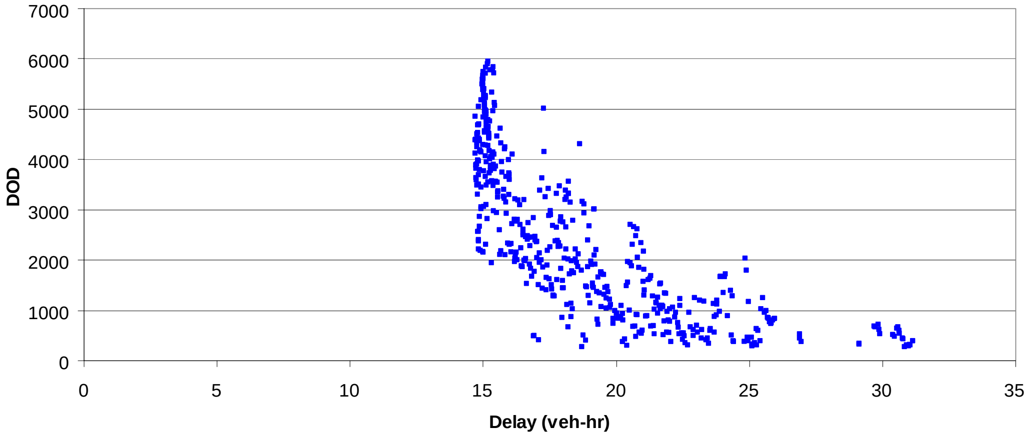


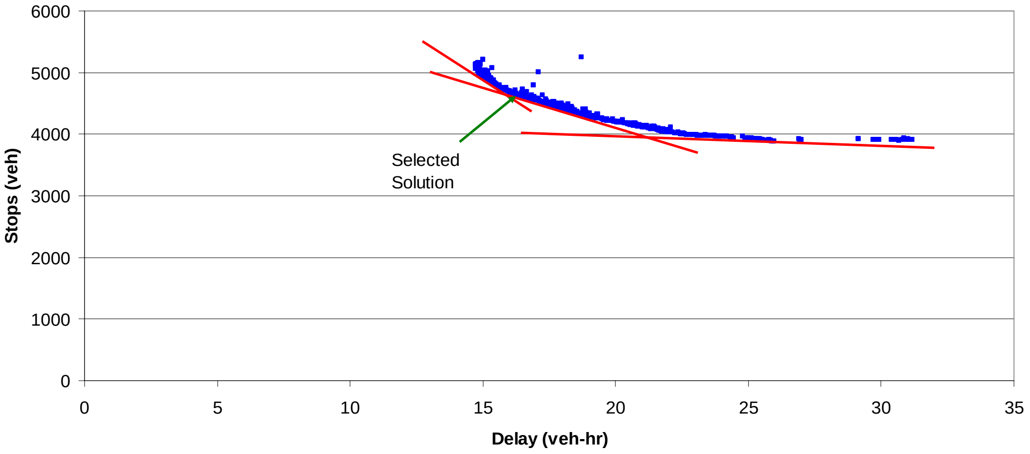
Figure 11. The Pareto Front.



a) Stops and DOD Axes



b) Delay and DOD Axes



c) Delay and Stops Axes

Figure 12. Projections of the Pareto Front into Two-Objective Axes.

It was clear from Figure 12a and 12b that solutions with low DOD values can be selected without much adverse effect on the delay and stops. Figure 12c shows the effect of reducing the number of stopped vehicles on the overall delay on the system. The three lines show three different trends or "preferences." The uppermost line would be the region entertained by an analyst who is mainly pro-delay reduction and does not value the objective of minimizing vehicular stops. The lower line would be the preferred region for an analyst interested mainly in minimizing vehicular stops without much regard for the huge delay incurred as a result of saving a small number of stops. The line in the middle is the region for the conservatives. In this report, the selected solution shown in Figure 12c was chosen because it provided low DOD and the least delay within the second region.

State-Plan Association

Figure 13 shows the final clustering of states and their association with the selected timing plans. It can be seen in the figure that adjacent states are mostly assigned to the same timing plans. Table 4 shows the final timing plans selected. Even though 24 was input as the desired number of final plans, traffic states were associated with only 14 timing plans, with a resulting total average delay of 16.2 veh-hr and total average stops of 4656 vehicles. Compared to just the worst possible solutions of 34.22 veh-hr and 5722 stops encountered during the optimization, the final solution provided a concurrent savings of 52.7 percent in delay and 18.6 percent in stops.

Timing Plan Generalization

As discussed earlier, the global perspective network consisted of four intersections with traffic control using a standard eight-phase ring structure with protected left turns only. It was speculated that other network and control constraints, such as protected-permitted operation, can be accommodated within the selected setup. Adding the permitted portion for the left turn operation, in the field, preserves or enhances the capacity provided by the protected only operation. As such, the timing plans produced for the analysis network are conservative. Other network constraints, such as dual left turns, are assumed to produce the same operation given that they were designed properly. An additional left turn lane that was added to reduce the left turn demand to capacity ratio below saturation practically reduces the actual field network to the hypothetical network. There are, however, some constraints that are very site specific and need to be handled at the site. For example, if the arterial lefts cannot be run simultaneously due to geometrical constraints, a lead-lead or lag-lag recommended phase sequence will not be feasible. If an alternative phase sequence was available in the guidelines, it should be used. Otherwise, such constraints might reduce optimality. Offset and phase sequence for such networks should be fine-tuned in the field.

One constraint that needed to be addressed separately is the split-phase operation on the side streets. Split-phase operation on side streets requires that phase timing be allocated differently. Minimum green requirements on the side street might significantly affect the green allocation to all phases. To address this issue, PASSER V was rerun for all of the 14 selected timing plans but with split-phase operation on the side streets. The resulting new phase allocations are shown in Table 5. These phase allocations should be used for networks with split phasing on side streets. Original phase durations can be used for intersections in the network that are not using split phasing.

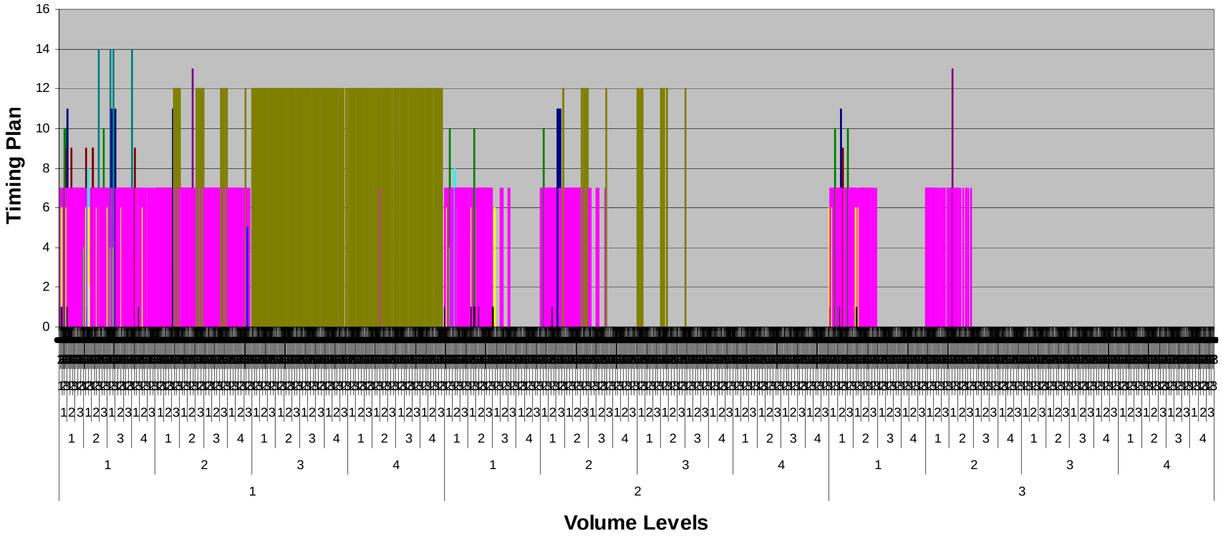


Figure 13. Final Clustering of Traffic States.

Table 4. Recommended Timing Plans.

Timing Plan	Inter-section	Cycle	Phase								Sequence	Offset
			1	2	3	4	5	6	7	8		
1	1	60	10	28	10	12	10	28	12	10	Lead-Lead	0
	2	60	10	30	10	10	10	30	10	10	Lag-Lead	25
	3	60	10	30	10	10	10	30	10	10	Lead-Lag	37
	4	60	10	26	11	13	13	23	11	13	Lag-Lead	59
2	1	100	17	29	24	30	10	36	21	33	Lead-Lead	0
	2	100	13	59	13	15	11	61	12	16	Lag-Lead	25
	3	100	10	61	13	16	14	57	13	16	Lag-Lead	38
	4	100	10	50	30	10	22	38	18	22	Lead-Lag	44
3	1	60	11	26	11	12	10	27	13	10	Lead-Lead	0
	2	60	10	30	10	10	10	30	10	10	Lag-Lead	25
	3	60	10	30	10	10	10	30	10	10	Lead-Lag	36
	4	60	10	26	14	10	13	23	11	13	Lead-Lead	59
4	1	60	10	24	12	14	10	24	12	14	Lead-Lead	0
	2	60	10	30	10	10	10	30	10	10	Lag-Lead	25
	3	60	10	30	10	10	10	30	10	10	Lead-Lag	33
	4	60	10	26	10	14	10	26	11	13	Lead-Lead	59
5	1	75	11	39	12	13	10	40	15	10	Lead-Lead	0
	2	75	10	45	10	10	10	45	10	10	Lead-Lead	37
	3	75	10	45	10	10	10	45	10	10	Lead-Lag	43
	4	75	10	36	14	15	11	35	13	16	Lag-Lead	71
6	1	60	10	30	10	10	10	30	10	10	Lead-Lead	0
	2	60	10	30	10	10	10	30	10	10	Lag-Lead	25
	3	60	10	30	10	10	10	30	10	10	Lead-Lag	35
	4	60	10	29	11	10	10	29	10	11	Lag-Lead	57
7	1	90	22	38	14	16	10	50	10	20	Lead-Lead	0
	2	90	14	55	10	11	10	59	10	11	Lag-Lead	29
	3	90	10	59	10	11	10	59	10	11	Lead-Lag	41
	4	90	10	55	10	15	12	53	12	13	Lead-Lag	29
8	1	90	22	39	13	16	10	51	19	10	Lead-Lead	0
	2	90	14	55	10	11	10	59	10	11	Lag-Lead	29
	3	90	10	59	10	11	10	59	10	11	Lead-Lag	41
	4	90	10	55	10	15	12	53	12	13	Lead-Lag	29
9	1	75	11	37	12	15	10	38	13	14	Lead-Lead	0
	2	75	10	45	10	10	10	45	10	10	Lag-Lead	25
	3	75	10	45	10	10	10	45	10	10	Lead-Lag	41
	4	75	10	40	10	15	10	40	12	13	Lag-Lead	70
10	1	90	12	54	11	13	10	56	14	10	Lead-Lead	0
	2	90	10	60	10	10	10	60	10	10	Lead-Lag	2
	3	90	10	60	10	10	10	60	10	10	Lag-Lead	33
	4	90	10	53	17	10	12	51	12	15	Lead-Lead	46

Table 4. Recommended Timing Plans (Cont.).

Timing Plan	Inter-section	Cycle	Phase								Sequence	Offset
			1	2	3	4	5	6	7	8		
11	1	90	18	32	18	22	10	40	10	30	Lead-Lead	0
	2	90	14	46	14	16	12	48	13	17	Lag-Lead	25
	3	90	10	50	13	17	16	44	14	16	Lag-Lead	25
	4	90	10	41	10	29	23	28	18	21	Lead-Lag	43
12	1	75	15	27	15	18	10	32	15	18	Lead-Lead	0
	2	75	11	39	11	14	10	40	11	14	Lead-Lead	26
	3	75	10	40	11	14	13	37	11	14	Lead-Lag	29
	4	75	10	33	10	22	20	23	15	17	Lag-Lead	60
13	1	75	15	26	16	18	10	31	18	16	Lead-Lead	0
	2	75	11	40	11	13	10	41	11	13	Lead-Lead	26
	3	75	10	40	11	14	13	37	11	14	Lead-Lag	28
	4	75	10	33	17	15	20	23	15	17	Lag-Lead	60
14	1	90	19	23	19	29	10	32	19	29	Lead-Lead	0
	2	90	14	41	14	21	12	43	12	23	Lag-Lead	25
	3	90	10	44	13	23	17	37	14	22	Lag-Lead	23
	4	90	10	35	11	34	20	25	18	27	Lead-Lag	42

Table 5. Recommended Timing Plans with Side Street Split Phasing.

Timing Plan	Inter-section	Cycle	Phase								Sequence	Offset
			1	2	3	4	5	6	7	8		
1	1	60	10	26	10	14	10	26	14	10	Lead-Lead	0
	2	60	10	30	10	10	10	30	10	10	Lag-Lead	25
	3	60	10	30	10	10	10	30	10	10	Lead-Lag	37
	4	60	10	26	11	13	13	23	13	11	Lead-Lead	59
2	1	100	17	29	33	21	10	36	21	33	Lead-Lead	0
	2	100	13	59	13	15	11	61	15	13	Lag-Lead	25
	3	100	10	61	16	13	14	57	13	16	Lag-Lead	38
	4	100	10	45	30	15	20	35	15	30	Lead-Lag	44
3	1	60	10	26	10	14	10	26	14	10	Lead-Lead	0
	2	60	10	30	10	10	10	30	10	10	Lag-Lead	25
	3	60	10	30	10	10	10	30	10	10	Lead-Lag	35
	4	60	10	24	16	10	13	21	10	16	Lead-Lead	59
4	1	60	10	24	14	12	10	24	12	14	Lead-Lead	0
	2	60	10	30	10	10	10	30	10	10	Lag-Lead	19
	3	60	10	30	10	10	10	30	10	10	Lead-Lag	33
	4	60	10	23	10	17	10	23	17	10	Lead-Lead	0
5	1	75	11	36	10	18	10	37	18	10	Lead-Lead	0
	2	75	10	45	10	10	10	45	10	10	Lead-Lead	36
	3	75	10	45	10	10	10	45	10	10	Lead-Lag	43
	4	75	10	36	14	15	11	35	15	14	Lag-Lead	70
6	1	60	10	27	13	10	10	27	10	13	Lead-Lead	0
	2	60	10	30	10	10	10	30	10	10	Lag-Lead	22
	3	60	10	30	10	10	10	30	10	10	Lead-Lag	33
	4	60	10	26	14	10	10	26	10	14	Lag-Lead	55

Table 5. Recommended Timing Plans with Side Street Split Phasing (Cont.).

Timing Plan	Inter-section	Cycle	Phase								Sequence	Offset
			1	2	3	4	5	6	7	8		
7	1	90	20	34	23	13	10	44	13	23	Lead-Lead	0
	2	90	14	55	10	11	10	59	11	10	Lag-Lead	30
	3	90	10	59	11	10	10	59	10	11	Lead-Lag	41
	4	90	10	55	13	12	12	53	12	13	Lead-Lag	31
8	1	90	21	37	11	21	10	48	21	11	Lead-Lead	0
	2	90	14	55	10	11	10	59	11	10	Lag-Lead	30
	3	90	10	59	11	10	10	59	10	11	Lead-Lag	41
	4	90	10	55	13	12	12	53	12	13	Lead-Lag	30
9	1	75	11	37	14	13	10	38	13	14	Lead-Lead	0
	2	75	10	45	10	10	10	45	10	10	Lead-Lead	38
	3	75	10	45	10	10	10	45	10	10	Lead-Lag	43
	4	75	10	36	10	19	10	36	19	10	Lag-Lead	72
10	1	90	12	52	11	15	10	54	15	11	Lead-Lead	0
	2	90	10	60	10	10	10	60	10	10	Lead-Lag	1
	3	90	10	60	10	10	10	60	10	10	Lag-Lead	31
	4	90	10	49	20	11	11	48	11	20	Lead-Lead	46
11	1	90	17	29	24	20	10	36	20	24	Lead-Lead	0
	2	90	14	46	14	16	12	48	16	14	Lag-Lead	25
	3	90	10	50	16	14	16	44	14	16	Lag-Lead	26
	4	90	10	40	21	19	23	27	19	21	Lead-Lag	44
12	1	75	15	26	16	18	10	31	18	16	Lead-Lead	0
	2	75	11	39	11	14	10	40	14	11	Lead-Lead	27
	3	75	10	40	14	11	13	37	11	14	Lead-Lag	29
	4	75	10	30	16	19	18	22	19	16	Lag-Lead	61
13	1	75	15	26	16	18	10	31	18	16	Lead-Lead	0
	2	75	11	40	11	13	10	41	13	11	Lead-Lead	26
	3	75	10	40	14	11	13	37	11	14	Lead-Lag	28
	4	75	10	33	17	15	20	23	15	17	Lag-Lead	60
14	1	90	18	21	25	26	10	29	26	25	Lead-Lead	0
	2	90	13	39	17	21	12	40	21	17	Lag-Lead	25
	3	90	10	42	21	17	16	36	17	21	Lag-Lead	25
	4	90	10	35	27	18	20	25	18	27	Lead-Lag	40

SUMMARY

This chapter introduced a new 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 range of traffic conditions to one of the few available timing plans while maintaining the clustering of traffic states together. The methodology maintained a global perspective of looking at traffic states and used the NSGA II algorithm, with a newly defined MOE, to achieve its optimization objectives. Fourteen timing plans were identified to provide optimal control of the traffic system with an average savings of at least 53 percent in delay and 19 percent in the number of vehicle stops.

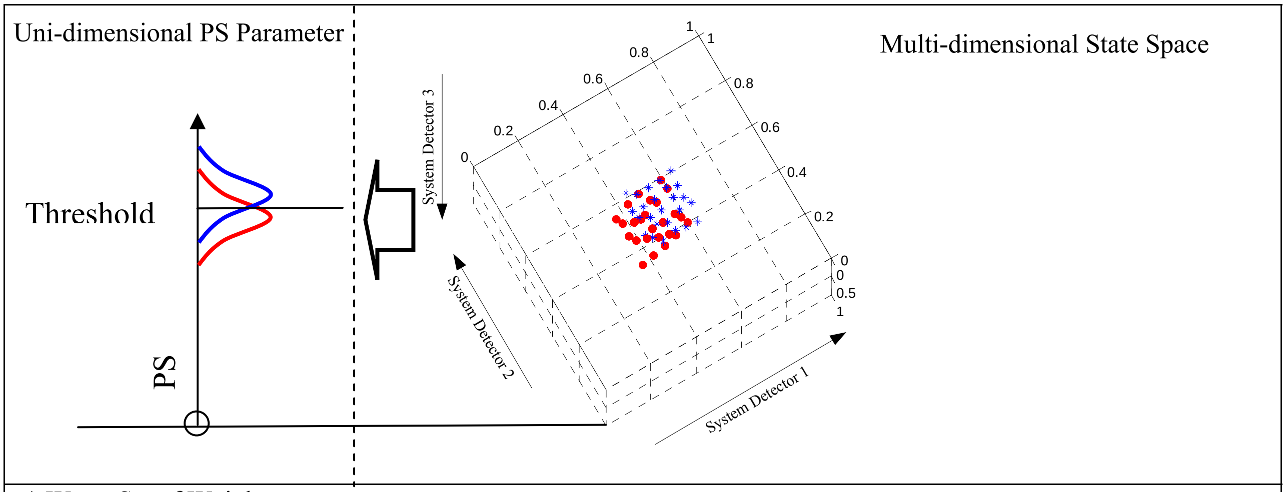
CHAPTER 4: ROBUST CONFIGURATION OF TRPS PARAMETERS

INTRODUCTION

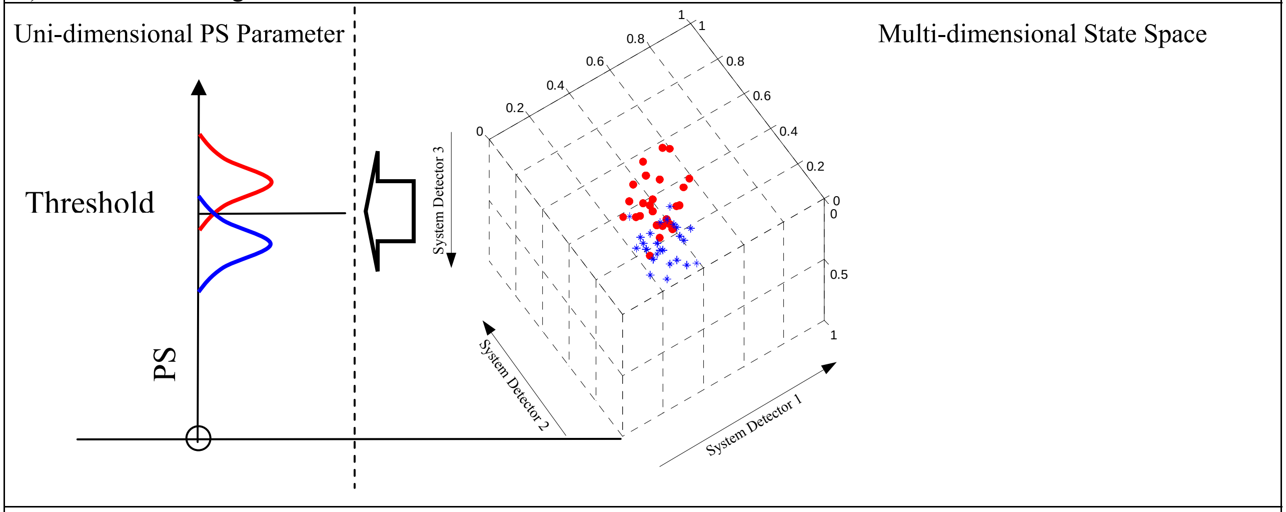
This chapter addresses the most important challenge in setting up a TRPS mode: robust and optimal selection of TRPS parameters and thresholds. These selections include weighting factors for each system detector as well as the thresholds corresponding to each selection level (cycle, offset, and split 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.

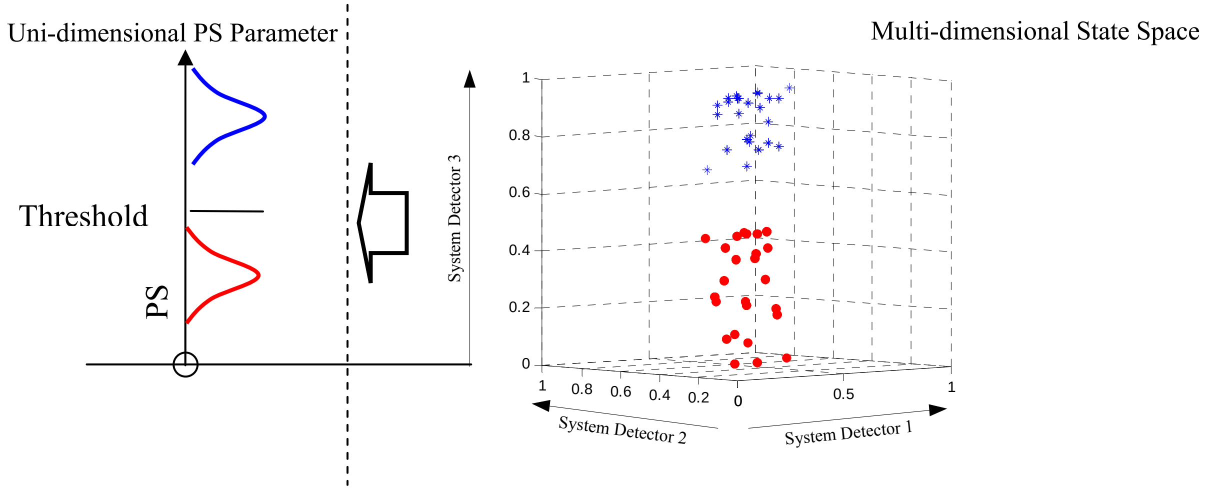
Figure 14 illustrates this concept. Figure 14 is a simplified three-dimensional space that shows samples from two different state distributions. The reader can think of these two states as low- and high-volume cases, respectively. The three-dimensional sample points from these two states correspond to occupancy data from three system detectors placed at three different approaches. Parts a, b, and c of Figure 14 correspond to three different sets of detector weights. Figure 14a shows a set of weights that provides poor separation of the two state distributions. Figure 14b shows a different set of weights that provides a better separation. Figure 14c shows the best set of weights that provides total separation of the two state distributions.



a) Worst Set of Weights



b) Better Set of Weights



c) Best Set of Weights

Figure 14. Effects of Detector Weights on the TRPS State Space.

The following sections discuss the use of an evolutionary algorithm with supervised discriminant analysis to determine system detector weights such that the best possible recognition of different states can be achieved.

Parameter Thresholds and Plan Selection

In TRPS mode, actual traffic conditions are monitored by gathering system detector outputs (i.e., volume and occupancy data) at regular time intervals (5 minutes for this study). The traffic detector outputs from all system detectors are continuously processed and aggregated into three plan selection parameters. Thus, actual traffic conditions are expressed in terms of these three parameters, the cycle, split, and offset indexes.

The optimum timing plan for the traffic conditions for each 5-minute time period can also be determined. In the present study these plans were calculated using the PASSER V signal optimization package. Knowing the plan selection parameters and corresponding optimum timing plans for a wide range of traffic conditions (i.e., from data collected over a large number of 5-minute intervals) provides a training set that can be used to derive timing plan selection rules. The rules applicable to available system controllers have the following structure:

$$P = P_k \quad if\ (x1_{Lk} \le x1 < x1_{Uk}) \bigcap (x2_{Lk} \le x2 < x2_{Uk}) \bigcap (x3_{Lk} \le x3 < x3_{Uk}), \quad k = 1,..,K \qquad \mathbf{(3)}$$

Where:

P = selected timing plan;

P_k = k-th available timing plan in the controller;

K = maximum number of timing plans that can be implemented in TRPS mode;

$x1$, $x2$, and $x3$ = the three plan selection parameters (i.e., cycle, split, and offset indexes); and

subscripts L and U = the lower and upper boundaries of the plan selection parameters for which the optimum timing plan is P_k .

The maximum number of timing plans K is controller specific. For controller manufacturers approved by TxDOT it is limited to 48 (4 cycles × 4 splits × 3 offsets).

The plan selection rules can be derived by determining the $x1_{Lk}$, $x2_{Lk}$, $x3_{Lk}$ lower thresholds and $x1_{Uk}$, $x2_{Uk}$, $x3_{Uk}$ upper thresholds for all k (i.e., all available timing plans). Each observed traffic situation (from 5-minute detector outputs) can be represented by a point in the three-dimensional coordinate system of the three plan selection parameters, and an optimum timing plan is assigned to each of these points. Therefore, determining the appropriate thresholds for these parameters is a three-dimensional classification problem. The task is to find the best separation of observed data points into K groups in terms of their corresponding optimum timing plan. The best separation is the one that minimizes the within-group differences and maximizes the between-group differences. Groups (i.e., observed data points from the same state) generally have nonlinear boundaries, and several groups may even overlap each other. Therefore, in most cases, nonlinear decision (separation) boundaries could achieve the best classification.

There are several techniques, such as principal components, discriminant functions, artificial neural networks, decision-tree classifiers, and various forms of nearest neighbor classification methods, that can be used for data classification. However, the present classification problem has certain constraints that make most available techniques impractical and very difficult to use. These constraints stem from the controllers' operational logic in TRPS mode. In TRPS mode, signal timing plans are selected from a look-up table based on real-time values of the three plan selection parameters. The look-up table consists of $K = 48$ cells in a three-dimensional $4 \times 4 \times 3$ grid. Although the 48 cells can be divided among the three plan selection parameters in many different ways, the $4 \times 4 \times 3$ arrangement, illustrated in Figure 15, is consistent with most controllers approved by TxDOT, and therefore it was the cell arrangement used in the present project.

A look-up table can be imagined as a wardrobe cabinet with drawers, in which clothes are arranged according to certain rules. For example: (1) clothes for everyday use are in the left column of drawers, and clothes for special occasions are in the right column; and (2) winter clothes are in the bottom, and summer clothes are in the top drawers. Based on these rules one can easily pick the right outfit for any occasion and weather conditions. Similarly, look-up tables for the timing plan selection are used according to specific rules such as the one shown in equation (3). It is important to note that the thresholds (i.e., lower and upper boundaries) in the rules are constant scalars (i.e., they cannot be functions of either plan selection parameters). Each cell in the look-up table corresponds to a given interval of plan selection parameters, where the parameter intervals are defined by appropriate thresholds.

According to this operational logic, the decision boundaries separating different groups (i.e., traffic conditions with common optimum timing plan) can either be parallel or orthogonal to each other, as Figure 15 indicates. Each decision boundary is a plane parallel to one of the x_1-x_2, x_1-x_3, or x_2-x_3 planes in the x_1-x_2-x_3 coordinate system. The task is to determine the location of these decision boundaries (i.e., horizontal and vertical planes) that provide the best separation of the 48 cells. To perform the classification subject to these constraints a supervised linear discriminant analysis (SLDA) technique was developed. The method is described in the following sections.

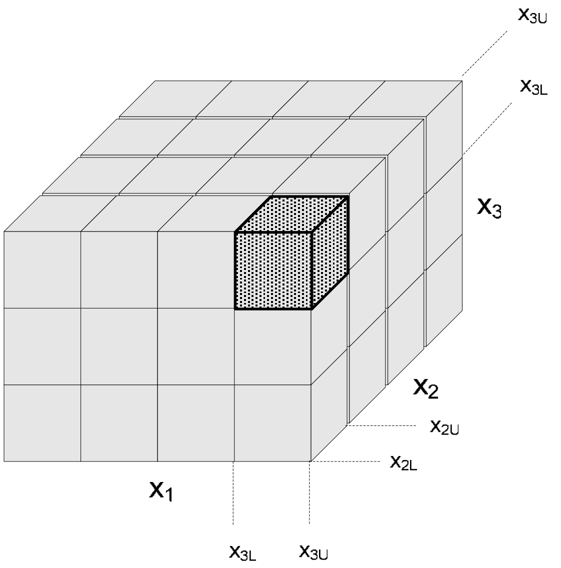


Figure 15. Structure of Look-Up Table for Plan Selection Rule.

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 *(22)*.

SLDA to Find Parameter Thresholds

Let $\boldsymbol{X} = \{x_{ij} : i = 1,..,N; j = 1,..,3\}$ be a matrix containing the plan selection parameters for N observations so that cycle indexes (***x1***) are in the first column, split indexes (***x2***) are in the second column, and offset indexes (***x3***) are in the third column of matrix $\boldsymbol{X}$. Also, let $\boldsymbol{g} = \{g_i : \mathrm{i} = 1,..,N\}$ be the vector containing pointers to the original traffic state corresponding to the time selection parameter observations in matrix $\boldsymbol{X}$.

The goal is to determine rules for assigning timing plans for future observations of pattern selection parameters. Using matrix $\boldsymbol{X}$ and vector $\boldsymbol{g}$ as a training set, the rules can be derived by finding the parameter thresholds which best separate the observation points corresponding to different traffic states (groups). Then based on these thresholds an optimum timing plan can be assigned to each of the 48 cells, and thereby a look-up table created. The main steps of the procedure are summarized in Figure 16 and discussed in the following sections.

Group Centers

In the first step, the group centers are determined to be able to measure the relative displacement of each group. The three group center coordinates $\{\mu_{kj} : j = 1,..,3\}$ are calculated for all groups ($k = 1,..,K$) from the observation points $\{x_{ij} : i = 1,..,N, j = 1,..,3\}$:

$$\mu_{kj} = E(x_{ij} \mid g_i = k) \qquad \forall i, \forall j, \forall k \tag{4}$$

Initial Thresholds

To be able to separate the observation points into 4 × 4 × 3 groups according to the three plan selection parameters x_1, x_2, and x_3, initial thresholds are determined first. The initial thresholds are placed between those group centers which are the farthest from each other. For this purpose groups are ordered according to the corresponding group center coordinates. Note that instead of Euclidian distances, the differences in group center coordinates $\{\Delta_{kj} : j = 1,..,3\}$ are determined between ordered groups:

$$\Delta_{kj} = \mu_{(k+1)j} - \mu_{kj} \qquad (k = 1,..,K-1), \quad (j = 1,..,3) \tag{5}$$

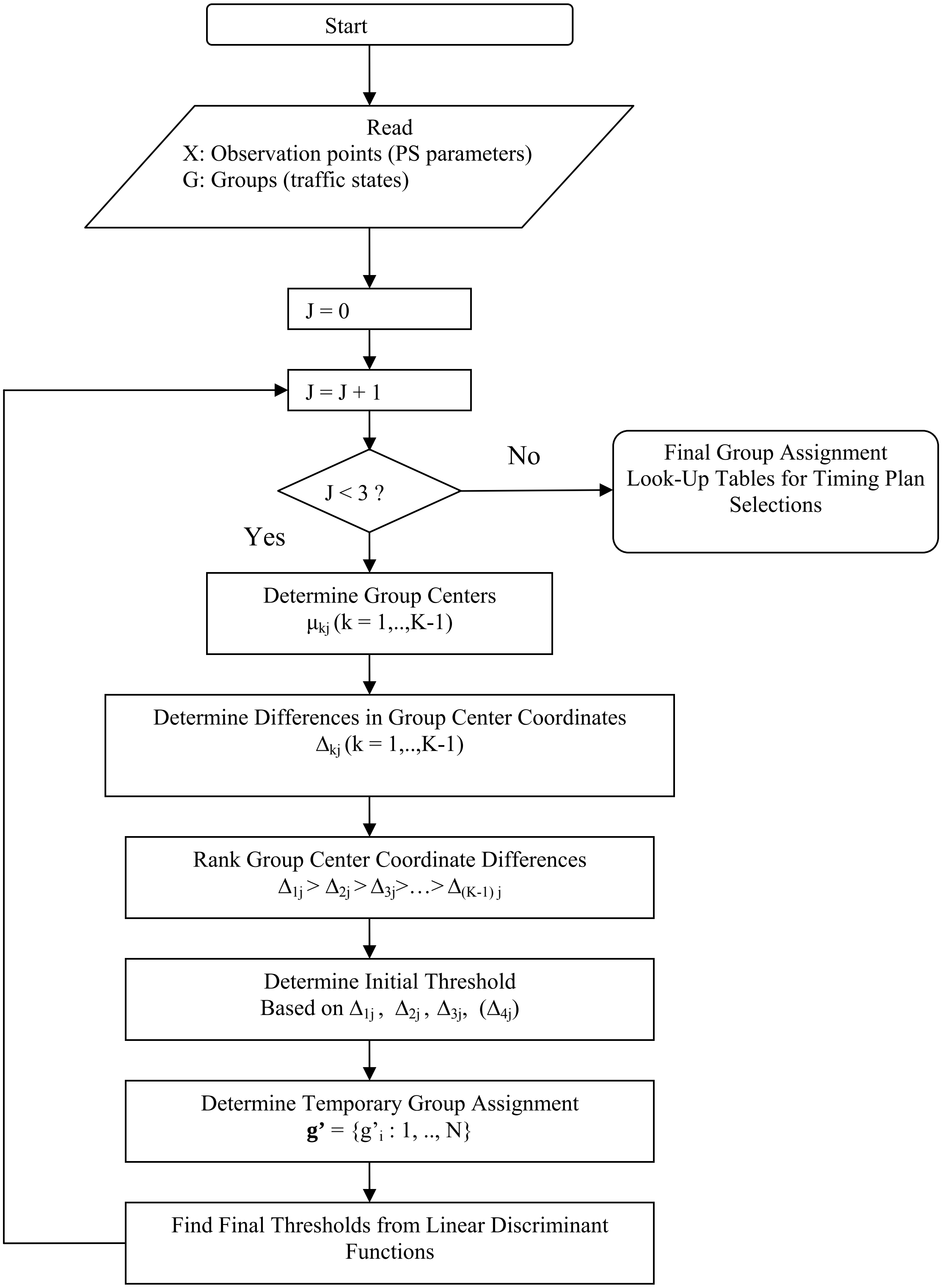


Figure 16. SLDA Procedure to Set Up Look-Up Table for Timing Plan Selection.

Then the coordinate differences are ranked into decreasing order, and thresholds, 3 for x_1 and x_2, and 2 for x_3, are defined between the group centers with the first 3 (2) largest differences. Thus, the first threshold τ_{j1} for the j-th plan selection parameter can be defined as:

$$\tau_{j1} = (\mu_{(k+1)j} + \mu_{(k-1)j})/2 \quad | \quad \Delta_j = \underset{\forall k}{MAX}\{\Delta_{kj}\} \qquad \textbf{(6)}$$

Temporary New Group Assignment

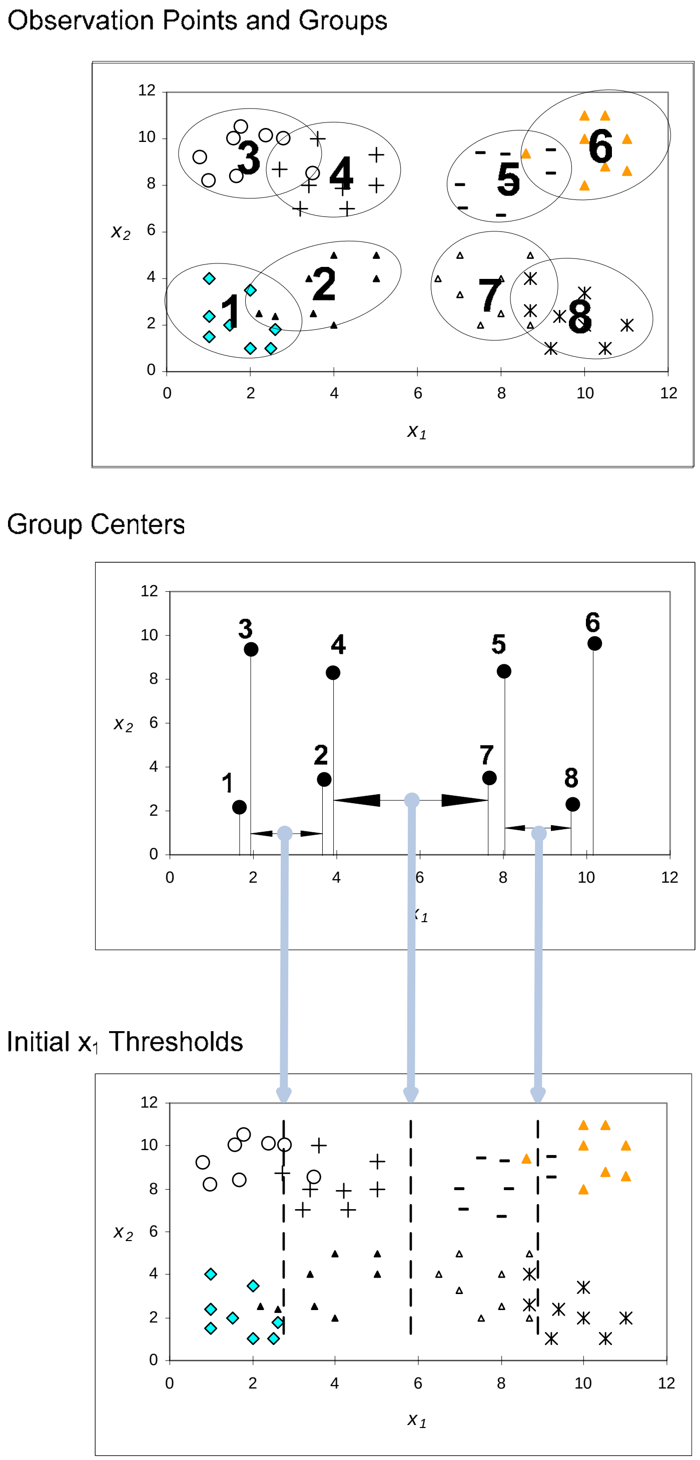
Once the initial thresholds have been defined, new groups 1, 2, 3, and 4 are assigned to each observation point. Four groups are assigned for the cycle and split PS parameters, and three groups for the offset PS parameter. The new group assignments are stored in vector $\boldsymbol{g}' = \{g'_i : i = 1,..,N\}$. The rules for the new group assignments are:

$$g'_i = \begin{cases} 1 & if\ (\qquad \mu_{g_i\ j} \leq \tau_{j1}) \\ 2 & if\ (\tau_{j1} < \mu_{g_i\ j} \leq \tau_{j2}) \\ 2 & if\ (\tau_{j2} < \mu_{g_i\ j} \leq \tau_{j3}) \\ 4 & if\ (\tau_{j3} < \mu_{g_i\ j} \qquad) \end{cases} \qquad (j = 1,..,3)\ , \quad \forall i \qquad \textbf{(7)}$$

The procedure is illustrated in Figure 17.

Final Thresholds from SLDA

Based on the new group assignment $\boldsymbol{g}'$, a linear discriminant analysis is performed to find the best separation of the observation points according to the four new groups. Figure 18 plotted the linear discriminant functions (LDF) for the same data set used in the previous sections. The points where the LDFs intersect determine the thresholds that provide the best separation of the four groups. Figure 19 shows the final thresholds for both plan selection parameters.

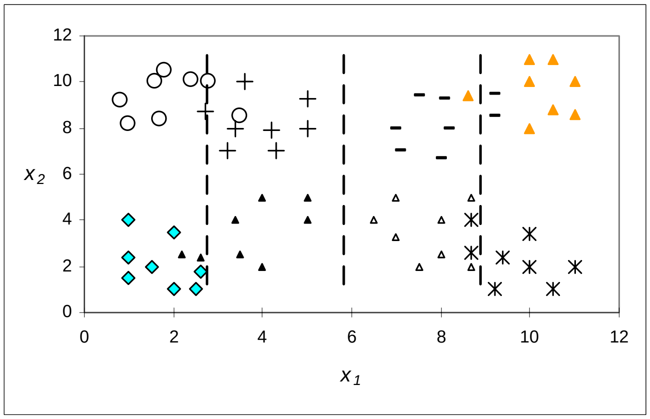

Observation Points and Groups

Group Centers

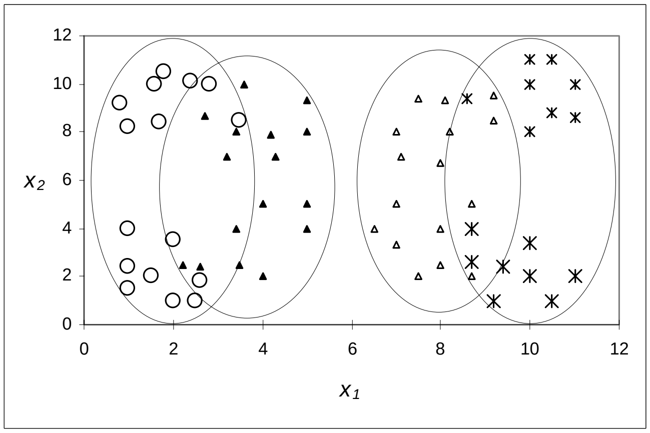
Initial x_1 Thresholds

Figure 17. Initial Thresholds from Differences in Group Center Coordinates.

Initial x_1 Thresholds



Temporary New Group Assignment



Linear Discriminant Functions and Thresholds

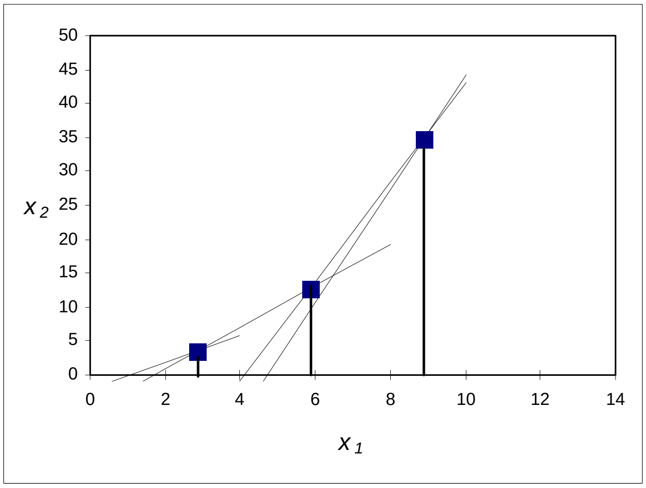


Figure 18. Temporary New Group Assignment Based on Initial Thresholds.

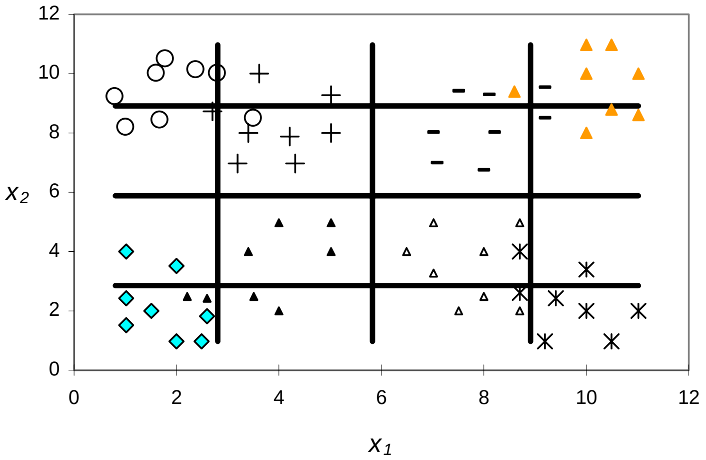


Figure 19. Final Thresholds.

Timing Plan Assignment

After the thresholds have been determined, timing plans can be assigned to all 48 cells in the look-up table. Classification accuracy is determined according to the following logic:

1. Apply the selection rules defined by equation (7) to all observations. The result will be a vector C containing pointers to one of the 48 cells corresponding to each observation.
2. Assign one of the 14 timing plans to each of the 48 cells. This information is stored in vector C′.
3. Define a vector T that contains pointers to the timing plan associated with each observation based on steps 1 and 2 above.
4. For each state group, determine the plan that is associated with most of the state observations and assign the plan to the state. This information is stored in vector S. Then, for each observation, determine the associated plan based on vectors g and S. This information is stored in vector P.

The next section explains how the SLDA is integrated with the multi-objective optimization process.

MULTI-OBJECTIVE OPTIMIZATION

The major step in the TRPS configuration is the multi-objective optimization involved in the configuration process. Only a limited number of timing plans can be assigned to several traffic states. The assignment should be done to minimize delay (and stops) as well as the misclassification error. The objective functions used in the analysis are shown below.

Minimize $Z_1 = \sum_{\forall i} d(g_i, T_i)$

Where:

d (S, P) = delay associated with operating state S with plan P.

The second objective function is:

Minimize $Z_2 = \sum_{\forall i} C_i$

Where:

$$C_i = \begin{cases} 1 \text{ if } T_i \neq P_i \\ 0 \text{ otherwise} \end{cases}$$

In order to perform the multi-objective optimization, the GA optimizer was integrated with the supervised discriminant analysis algorithm. Input data were obtained from CORSIM *(23)* simulations where each of the 14 selected timing plans was run with all 1479 traffic states. CORSIM simulation was necessary to obtain detector actuations that correspond to running a timing plan with any particular state. The actuations obtained from the simulation replicated realistic conditions, such as occasional queuing of vehicles over system detectors, to help the algorithm select appropriate timing plans. The algorithm is shown in Figure 20.

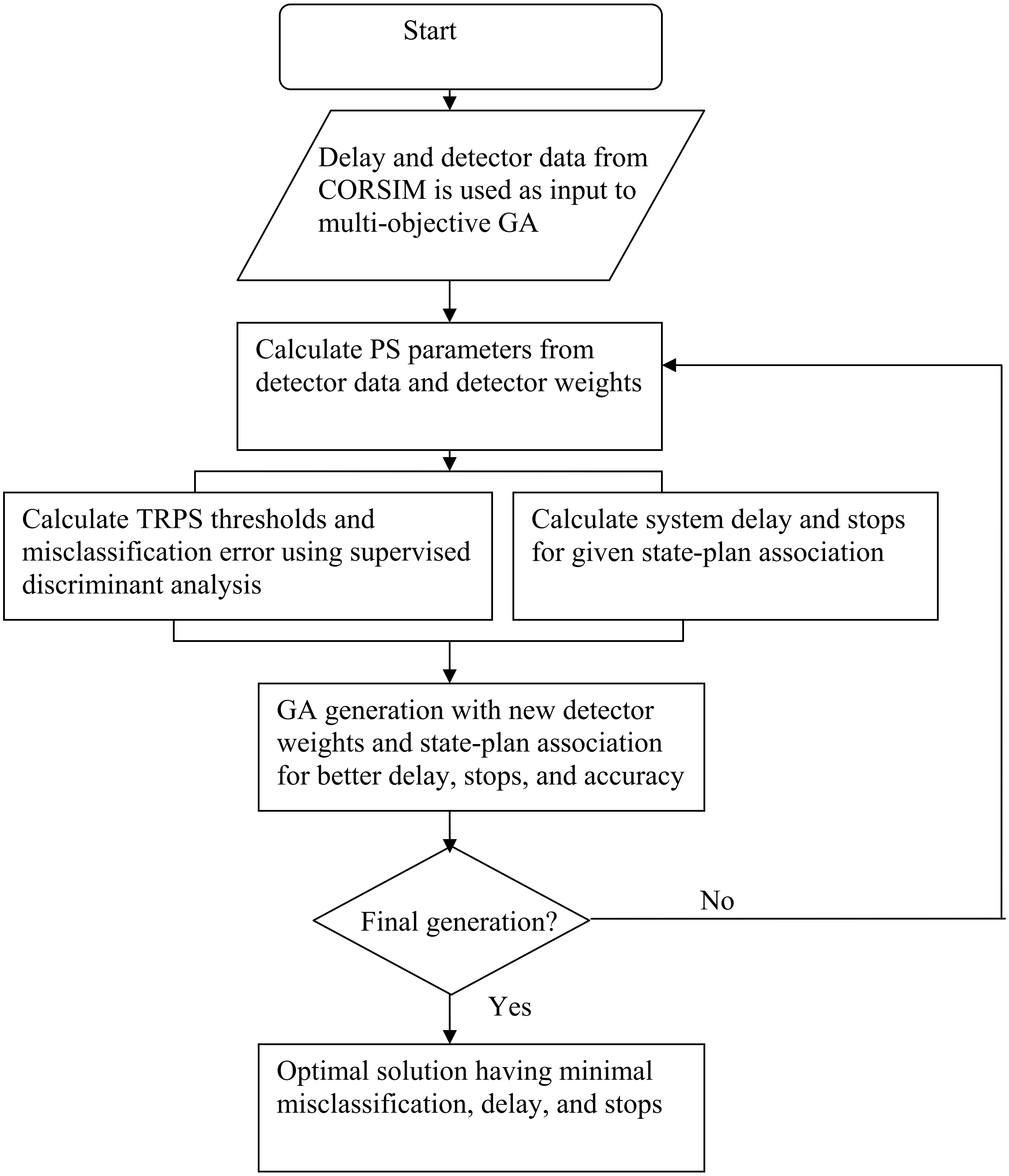


Figure 20. Multi-objective TRPS Configuration Algorithm.

System Detector Locations

The first-year report used stepwise discriminant analysis to determine critical detector locations *(16)*. The best system detector locations were determined to be 400 feet upstream of the traffic signal in the inside lane; except for detectors 3, 6, 10, and 12, located 300 feet upstream of the left turn approach. System detectors are shown in Figure 21. The recommended locations achieved highest discriminant power and were able to effectively distinguish between different traffic states. These locations were therefore used in the subsequent analysis. Averaging/sampling time used in the analysis was 5 minutes.

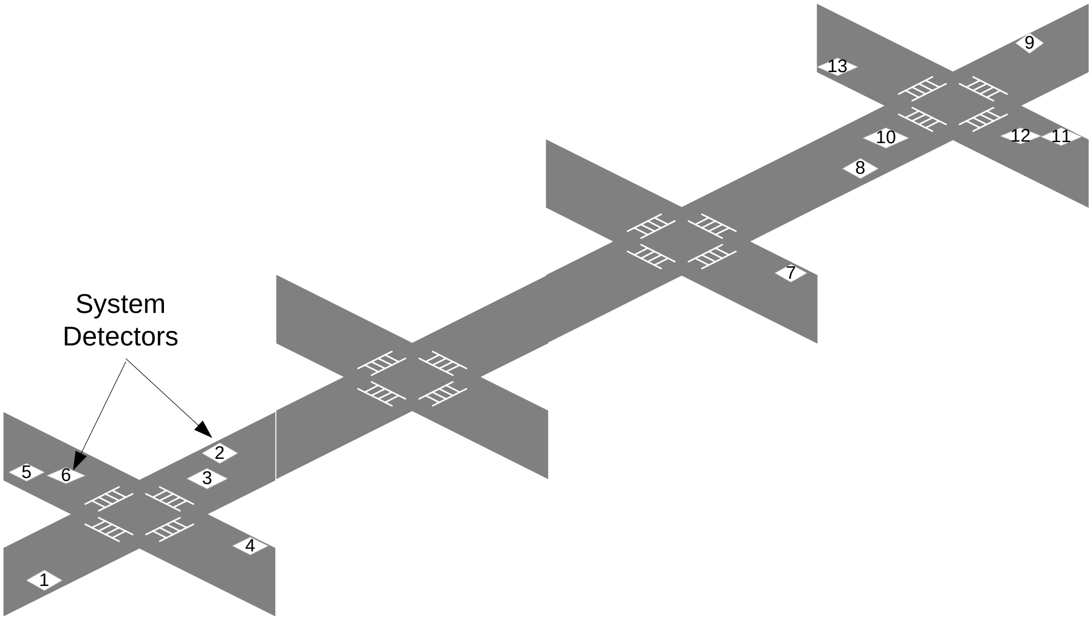


Figure 21. System Detector Locations.

Count and Occupancy Correction Factors

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 a 5-minute sampling rate and the controller converts the raw volume back to a volume per minute, the maximum approach capacity should be entered as 20 (100/5) vehicles per minute (1200 vehicles per hour). 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-minute sampling period was 30 percent, the controller will divide that by the maximum occupancy rate to arrive at 30/100 = 30 percent.

Naztec Controller Guidelines

Out of the 14 possible timing plans shown in Table 4, the multi-objective GA selected only 9 plans for the Naztec configuration. Indexes of the 9 selected plans are shown in Table 6.

Table 6. Final Selection of Timing Plans for Naztec Controller.

Timing Plan Index	1	2	3	4	5	6	7	8	9
Timing Plan Number	1	4	5	6	9	10	11	12	13

The latest version of the Naztec master allows the assignment of each of the 48 system detectors to any of the three pattern-selection parameters (inbound, outbound, and cross-street). This arrangement allows the assignment of up to 16 system detectors to each pattern-selection parameter. The guidelines developed in this research, however, require the assignment of only 13 system detectors to each of the pattern-selection parameters. Table 7 shows the detector weights assigned to each of the system detectors for each of the three pattern selection parameters. In locations where TxDOT is using old master versions where only 10 detectors can be specified, detectors 3, 5, 10, and 11 should be dropped.

The associated thresholds are listed in Table 8. Note that the TRPS mechanism allows the user to enter both entering and exiting thresholds. The entering thresholds should be configured per Table 8. The initial value for an exiting threshold should be set equal to that of the corresponding entering threshold. This value may need to be fine-tuned in the field. The plan table look-up entries are listed in Table 9.

Table 7. Naztec Controller Detector Weights.

Direction	Actuation	Detector												
		1	2	3	4	5	6	7	8	9	10	11	12	13
Inbound	Count	13	83	27	14	92	76	1	12	59	77	92	65	85
	Occupancy	12	21	75	9	10	52	16	52	21	25	5	26	13
Outbound	Count	98	52	22	63	91	5	1	99	44	4	6	61	1
	Occupancy	86	68	45	10	63	38	34	38	60	13	5	43	27
Cross	Count	3	53	15	79	33	1	74	10	90	10	95	79	91
	Occupancy	52	12	34	72	29	22	14	22	11	56	12	15	25

Table 8. Naztec Controller TRPS Thresholds.

Level	Cycle	Offset	Split
1	11	59	34
2	12	65	41
3	19	66	

Table 9. Naztec Controller TRPS Plan Look-Up Table Entries.

Cycle	Offset	Split		
		1	2	3
1	1	4	4	6
1	2	4	4	6
1	3	7	7	7
1	4	3	9	6
2	1	5	7	1
2	2	7	7	4
2	3	9	4	4
2	4	9	7	5
3	1	4	9	2
3	2	8	8	7
3	3	8	8	2
3	4	4	1	7
4	1	7	2	2
4	2	4	2	2
4	3	3	3	4
4	4	3	5	4

Eagle Controller Guidelines

The multi-objective GA selected only five plans for the Eagle configuration. The indexes of the five selected plans are shown in Table 10.

Table 10. Final Selection of Timing Plans for Eagle Controller.

Timing Plan Index	1	2	3	4	5
Timing Plan Number	2	3	5	9	11

The Eagle master allows up to eight system detectors per computational channel (DR1, DR2, CS1, CS2, etc.). However, the pattern-selection parameters (cycle select, offset select, and split select) can combine similar computational channels (e.g., CS1 and CS2) to provide up to 16 system detectors per pattern-selection parameter. The cycle-selection and split-selection parameters in this research are associated with both CS1 and CS2 channels (but not DR1 and DR2). The detector weights are listed in Table 11. Since the Eagle master does not have a pattern table, duplicate plans will need to be entered in each controller. The user can do this using the "Coordination Copy" feature in the Eagle controller.

Since the CS1 and CS2 channels are aggregated by the controller, it is not critical which system detector is assigned to which channel. As such, detectors 1 through 8 could be assigned to CS1, while detectors 9 through 13 could be assigned to CS2. Similarly, detectors 1 through 8 could be assigned to NA1, and detectors 9 through 13 could be assigned to NA2. The DR1 and DR2 are used by the offset-selection parameter. Since the offset-selection parameter uses the ratio of DR1 to the sum of DR1 and DR2 in its calculations, the detectors assigned to the DR1 and DR2 channels, and their weights, are listed separately.

Note that unlike the Naztec master, the Eagle master does not allow the specification of different detector weights for each occupancy and count. It was therefore necessary to account for this constraint in the optimization process. The appropriate weights are listed in Table 11.

The entering thresholds are listed in Table 12. The initial value for an exiting threshold should be set equal to that of the corresponding entering threshold, until fine-tuned in the field. Table 13 lists the plan look-up entries for the Eagle master. Since the Eagle master does not have a pattern table, duplicate plans will need to be entered in each controller. The user can do this using the “Coordination Copy” feature in the Eagle controller.

It should also be noted that the Eagle controller allows practitioners to use the offset index to activate different offsets for the same timing plans previously selected by the cycle and split indexes, but not to activate different timing plans. This usage does not conform to the methodology used in this research. The offset index is therefore not used in this setup. Users, however, can define their own usage for the offset index during the customization of the guidelines to their specific sites.

Table 11. Eagle Controller Detector Weights.

Direction	Detector												
	1	2	3	4	5	6	7	8	9	10	11	12	13
ART (CS1 &CS2)	94	44	6	62	80	59	43	63	83	62	9	22	95
NART	40	56	0	10	81	80	59	38	59	53	29	83	88

Table 12. Eagle Controller TRPS Thresholds.

Level	Cycle	Split	Offset
1	18	56	--
2	21	59	--
3	32	60	

Table 13. Eagle Controller TRPS Plan Look-Up Table Entries.

Cycle	Split	Plan Index
1	1	5
1	2	5
1	3	5
1	4	5
2	1	1
2	2	2
2	3	2
2	4	2
3	1	2
3	2	2
3	3	5
3	4	5
4	1	2
4	2	2
4	3	5
4	4	3

OFFSET AND PHASE SEQUENCE CALCULATIONS

Implementation of a TRPS system requires a set of pre-determined timing plans capable of handling most, if not all, possible traffic conditions that may arise. The impracticality of developing one timing plan for each possible traffic condition and the limits placed by vendors dictate that this set contains a relatively small number of timing plans. The earlier chapters of this report describe details of research conducted to develop such a set of timing plans capable of handling all possible combinations of demand levels and origin-destination patterns expected on typical arterials maintained by TxDOT. This set contains 14 timing plans. To facilitate the development of these timing plans, researchers used the geometry of an arterial from Brownwood, Texas. The cycle length and splits for these timing plans can be utilized for any other arterial because they have the capacity to handle a wide variety of traffic conditions. However, since link speeds and distances will most likely be different for other arterials, new optimal offsets and phase sequences will have to be determined for each of these timing plans before using these plans at a new implementation site. These parameters should be selected such that each plan provides the best progression on the selected arterial. One approach for achieving the desired results would be to use an optimization program (i.e., PASSER IV [*24*] or PASSER V) to determine these two sets of parameters. However, a more practical and simpler approach is to provide easy-to-use figures and charts that can be used to select appropriate phase sequences and offsets for any new implementation site. This section describes research conducted to achieve this objective.

Analysis of Timing Plans

As stated previously, the 14 selected timing plans have been developed to accommodate a wide variety of traffic conditions. As such, the cycle lengths and corresponding splits for each plan can be easily transferred to any new arterial. However, the engineers will need to select phase sequences and offsets according to the link distances and prevalent speeds for the new arterial. This task would be straightforward if the engineers had charts or figures available to them for aiding in this selection. An in-depth analysis of each timing plan is needed to identify patterns for developing such charts. The following sections provide a detailed description of analysis work conducted by researchers to achieve these results.

Offset Optimization

The first step in the analysis process was to identify the characteristics of optimal offsets and phasing sequences for all possible combinations of link distances and speeds. To minimize these combinations, researchers decided to use link travel times instead of speeds and distances. Thus, the analysis for each link consisted of the evaluation of travel times between 5 seconds and the cycle length in increments of 5 seconds. Each of these travel-time values covers a large combination of speeds and distances. Furthermore, researchers decided to perform an exhaustive analysis of all possible phasing sequences for the main artery. This means that four phasing sequences (lead-lag, lag-lead, lead-lead, and lag-lag) need to be evaluated for each signal. Thus, the cycle length for a plan, number of links, and number of signals determine the total number of optimization runs required for that plan. Table 14 provides the number of combinations studied for a three-link (four-intersection) arterial.

Table 14. Optimized Combinations for Each Cycle Length.

Plan Cycle Length	Travel Times per Link	Number of Links	Phasing Sequences per Signal	Number of Signals	Total Combinations
60	12	3	4	4	442,368
75	15	3	4	4	864,000
90	18	3	4	4	1,492,992
100	20	3	4	4	2,048,000

Example: Total combinations for a 60-second cycle = $12^3 \times 4^4 = 442{,}368$

Researchers decided to use quality of progression as the sole criterion for selecting optimal values of offsets for each combination. This decision was appropriate because delay and stops had already been considered in selecting cycle lengths and splits for these 14 plans. The next step was to perform the offset optimization for each combination. It was decided to use PASSER IV for optimizing offset because it has the following strengths:

- computational efficiency,
- ability to optimize offsets when all other timing parameters are given, and
- ability to operate under an external batch process.

Next, the researchers developed an external batch processor in FORTRAN programming language. Figure 22 provides a flowchart of an offset analysis program (OAP). The data template for a timing plan contains all data needed to run PASSER IV except link distances and specific phase sequence selections for the main street. OAP calculates link distances using the current travel time and the specified link speed. This analysis uses link speeds of 35 mph.

Table 15 shows a portion of a summary file for one timing plan. The first three columns (labeled TT1–TT3) of this table show the travel time combinations for the three links. The next four columns (labeled P1–P4) show the evaluated phasing sequences at the four signals. Columns 8, 9, and 10 (labeled O2–O4) show the best offset for the three links. The last three columns show the corresponding measures of the quality of progression. These measures are: bandwidth efficiency (the percent of cycle in actual band), total band in seconds, and attainability. Attainability is a measure of bandwidth as a percent of smallest greens in both travel directions. An attainability value of 100 percent indicates achievement of the best progression solution. The phase sequence codes are as follows:

- 1: Lead-Lag (phases 2+5 start at the arterial barrier),
- 2: Lag-Lead (phases 1+6 start at the arterial barrier),
- 3: Lead-Lead (phases 1+5 start at the arterial barrier), and
- 4: Lag-Lag (phases 2+6 start at the arterial barrier).

Table 16 shows the top portion of the same summary file when the data are ordered from best to worst progression. Comparing these data with those in Table 15, the reader can observe that not all combinations of phasing sequences for a set of travel times produce the best progression. Further observation suggests that there may be a pair of different phasing sequences (i.e., sequences 2 and 4 for the fourth signal) that are compatible in that they produce the same progression with the selection of a different offset. In Table 15 and Table 16, highlighted entries point to these observations.

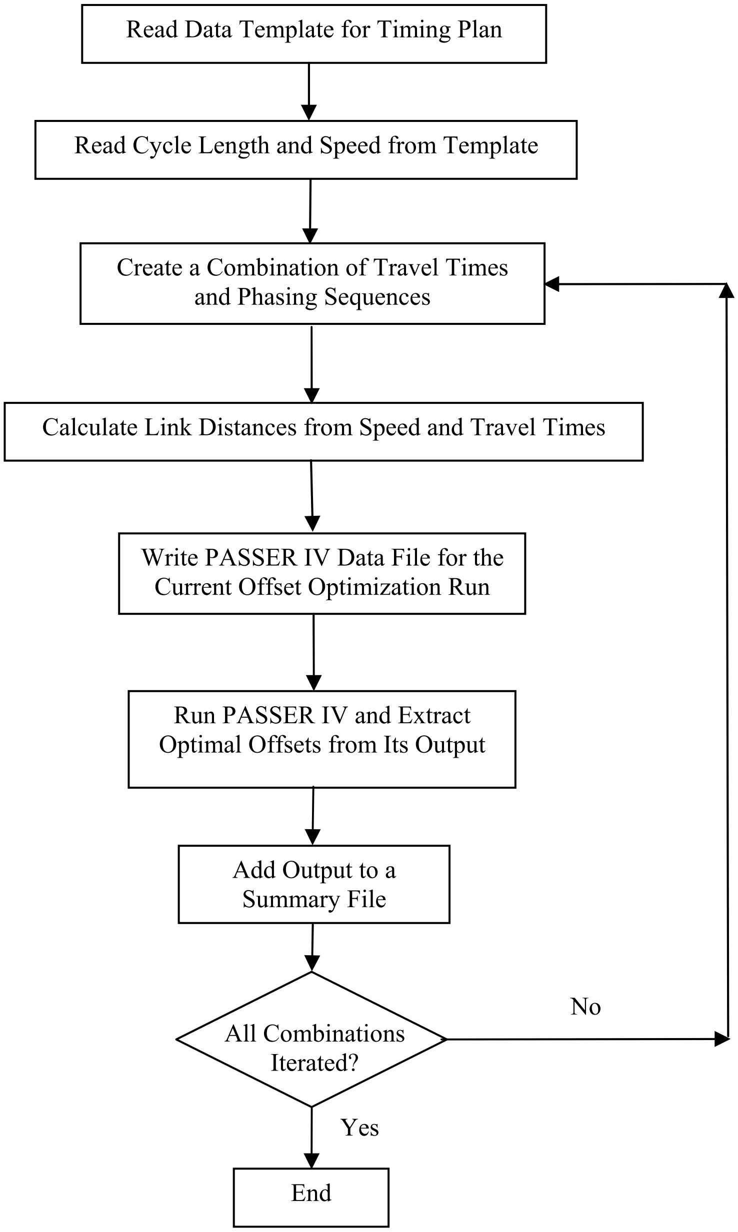


Figure 22. Flow Chart of OAP.

Table 15. Portions of Summary File from OAP.

TT1	TT2	TT3	P1	P2	P3	P4	O2	O3	O4	Efficiency	Band	Attain (%)
5	5	5	1	1	1	1	90	92	94	22.0	22.0	67.8
5	5	5	1	1	1	2	84	82	4	32.5	32.5	100.0
5	5	5	1	1	1	3	90	87	94	27.0	27.0	83.2
5	5	5	1	1	1	4	84	82	94	32.5	32.5	100.0
5	5	5	1	1	2	1	90	99	94	22.0	22.0	67.8
5	5	5	1	1	2	2	84	99	4	32.5	32.5	100.0
5	5	5	1	1	2	3	90	99	94	27.0	27.0	83.2
5	5	5	1	1	2	4	84	99	94	32.5	32.5	100.0
5	5	5	1	1	3	1	90	94	94	22.0	22.0	67.8
5	5	5	1	1	3	2	84	87	4	32.5	32.5	100.0
5	5	5	1	1	3	3	90	92	94	27.0	27.0	83.2
5	5	5	1	1	3	4	84	87	94	32.5	32.5	100.0
5	5	5	1	1	4	1	90	95	94	22.0	22.0	67.8
5	5	5	1	1	4	2	84	90	4	32.5	32.5	100.0
5	5	5	1	1	4	3	90	95	94	27.0	27.0	83.2
5	5	5	1	1	4	4	84	90	94	32.5	32.5	100.0

Table 16. Portions of Summary File When Reordered to Show Best Progression.

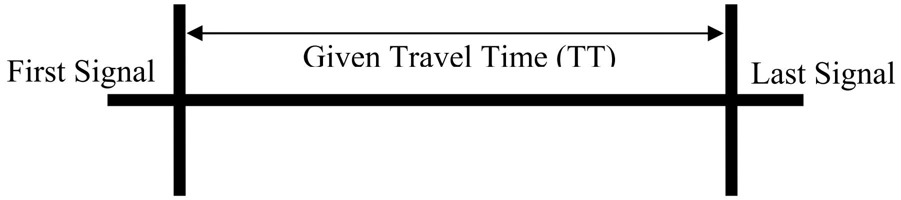
TT1	TT2	TT3	P1	P2	P3	P4	O2	O3	O4	Efficiency	Band	Attain (%)
5	5	5	1	1	1	2	84	82	4	32.5	32.5	100.0
5	5	5	1	1	1	4	84	82	94	32.5	32.5	100.0
5	5	5	1	1	2	2	84	99	4	32.5	32.5	100.0
5	5	5	1	1	2	4	84	99	94	32.5	32.5	100.0
5	5	5	1	1	3	2	84	87	4	32.5	32.5	100.0
5	5	5	1	1	3	4	84	87	94	32.5	32.5	100.0
5	5	5	1	1	4	2	84	90	4	32.5	32.5	100.0
5	5	5	1	1	4	4	84	90	94	32.5	32.5	100.0
5	5	5	1	2	1	2	99	82	4	32.5	32.5	100.0
5	5	5	1	2	1	4	99	82	94	32.5	32.5	100.0
5	5	5	1	2	2	2	99	99	4	32.5	32.5	100.0
5	5	5	1	2	2	4	99	99	94	32.5	32.5	100.0
5	5	5	1	2	3	2	99	87	4	32.5	32.5	100.0
5	5	5	1	2	3	4	99	87	94	32.5	32.5	100.0
5	5	5	1	2	4	2	99	89	4	32.5	32.5	100.0
5	5	5	1	2	4	4	99	90	94	32.5	32.5	100.0

As illustrated above, cursory observation of results from OAP indicated that there are identifiable cyclic patterns. It follows that more analysis should precisely identify these patterns.

Finding Patterns in OAP Results

Researchers conducted the analysis using Statistical Analysis Software (SAS) *(25)*. The basic assumption in doing this analysis is that once cyclic patterns have been quantified for a pair of traffic signals with a given travel time between them, an optimal set of phasing sequences can be determined using a simple equation or a look-up chart. This concept is illustrated in Figure 23.

Step 1: Determine Offset and Sequences for First and Last Signals in the System.



Step 2: One by One, Determine Offset and Sequences for Each Signal in the Middle.

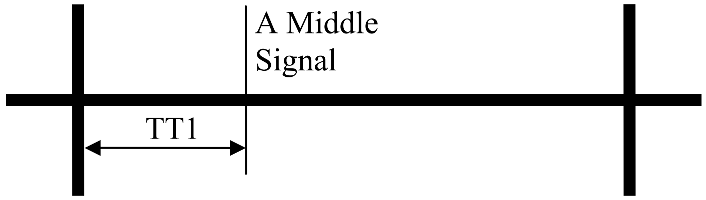


Figure 23. Optimal Selection of Offsets and Phase Sequences.

The first step was to find the optimal phase sequences for the first and last signals. The OAP results were arranged by phase sequence at the two signals. The sequence that resulted at the best efficiency is shown in Table 17. The table entries indicate the sequence at the first signal and the last signal, respectively. Multiple entries in the table indicate that several sequence combinations result in the same efficiency.

The next step in the analysis was to determine the optimal phase sequence for any intermediate intersection that would minimize the interference of that intersection with the overall band. For this step, overall efficiency was sorted for all combinations of TT, TT1, and phase sequences at the intermediate intersection. The result of the analysis was finding out which phase sequence at the intermediate intersection resulted in the highest efficiency for all combinations of TT and TT1. Careful investigation of the results showed a repetitive pattern that depends on both TT and TT1 as Table 18 shows. The offset value produced by the program was always equal to the travel time mod cycle length (since the band always started at the start of green).

Table 17. Recommended Phase Sequence at the First and Last Signals.

(Offset × 12) / Cycle	Sequence
1	13, 14, 32, 42
2	12
3	12
4	21
5	23, 24, 31, 41
6	11, 22, 33, 34, 43, 44
7	13, 14, 32, 42
8	12
9	12
10	21
11	23, 24, 31, 41
12	11, 22, 33, 34, 43, 44

Table 18. Recommended Phase Sequence at Intermediate Signals.

(External Offset × 12) / Cycle	(Internal Offset × 12) / Cycle											
	1	2	3	4	5	6	7	8	9	10	11	12
1	2	2	1	1	1	2	2	2	1	1	3	2
2	2	1	1	1	3	2	2	1	1	1	3	2
3	2	1	1	1	3	2	2	1	1	1	3	2
4	3	2	2	2	1	1	3	2	2	2	1	1
5	3	2	2	1	1	1	3	2	2	1	1	1
6	3	2	1	1	1	2	3	2	1	1	3	2
7	2	2	1	1	1	2	2	2	1	1	3	2
8	2	1	1	1	3	2	2	1	1	1	3	2
9	2	1	1	1	3	2	2	1	1	1	3	2
10	3	2	2	2	1	1	3	2	2	2	1	1
11	3	2	2	1	1	1	3	2	2	1	1	1
12	3	2	1	1	1	2	3	2	1	1	3	2

To illustrate the use of these tables, consider the case where the two external intersections are 14,300 feet apart and the design speed is 45 mph. The link travel time would be calculated as 14,300/(45 × 1.467) ≈ 217 seconds. The offset to the last intersection for a plan that has a 60 second cycle length is therefore equal to TT mod cycle = 217 mod 60 = 37 seconds (the mod function throws away all multiples of cycle lengths and leaves only the remainder). Using Table

17 to find the appropriate sequence at the last intersection requires the calculation of the look-up term "(offset × 12)/cycle." The look-up term = 37 × 12/60 = 7.4. A value of 7 in Table 17 suggests that any of the following two sequences will work at the first and last intersections, respectively: lead-lag and lead-lead, lead-lag and lag-lag, lead-lead and lag-lead, and lag-lag and lag-lead.

For an intermediate intersection 5240 feet from the first intersection, TT1 = 5240/(45 × 1.467) ≈ 79 seconds. The offset calculation for the same plan of 60 second cycle length is TT1 mod 60 = 79 mod 60 =19 seconds. From the external intersection's calculations, the first look-up factor in Table 18 = (External Offset × 12)/Cycle = 37 × 12/60 = 7.4. The second look-up factor = (Internal Offset × 12)/Cycle = 19 × 12/60 = 3.8. Using Table 18, the recommended sequence for the intermediate intersection is 1 (lead-lag).

GUIDELINES VERIFICATION WITH HARDWARE-IN-THE-LOOP SIMULATION

In order to test the guidelines developed in this project, it was necessary to simulate a case where a surge of traffic occurs within a normal traffic period. CORSIM simulation was used with hardware-in-the-loop (HITL) in order to test the performance of TRPS. HITL simulation of traffic was necessary in this case because there is a need to replicate exactly what a controller would do. In HITL simulation, the controller receives the detector information from the simulator and behaves exactly as it would in the field. The control decisions from the controller (signal indications, plan changes, etc.) are then sent back to the computer simulation.

Simulation Results

Three different traffic states of 30 minutes each were simulated. All three states are shown in Table 19. Inserting a surge of high-volume traffic into low-volume traffic simulates an event or incident where TRPS would be useful. Also, this could be looked at as a difference in traffic patterns due to some developmental changes and/or commercial activities where some high-traffic activity occurs in the middle of the day.

Table 19. Traffic States Used in HITL Simulation.

State	EB-Thru	SB-Left	NB-Right	WB-Thru	NB-Left	SB-Right	Cross Street
1	1200	0	0	400	0	0	150
2	1600	200	0	400	0	200	150
3	1200	300	200	1200	300	200	150

Figure 24 shows the three PS parameters calculated from system detectors' occupancy and count during the simulation period. The figure also shows the thresholds to switch between a PS index and the next level. Note how PS parameters change values during the simulation as the traffic state changes from one level to the next. Figure 25 shows the index and the plan assigned to the look-up table entry. TRPS was found to bring up the most appropriate timing plan in a stable and timely fashion.

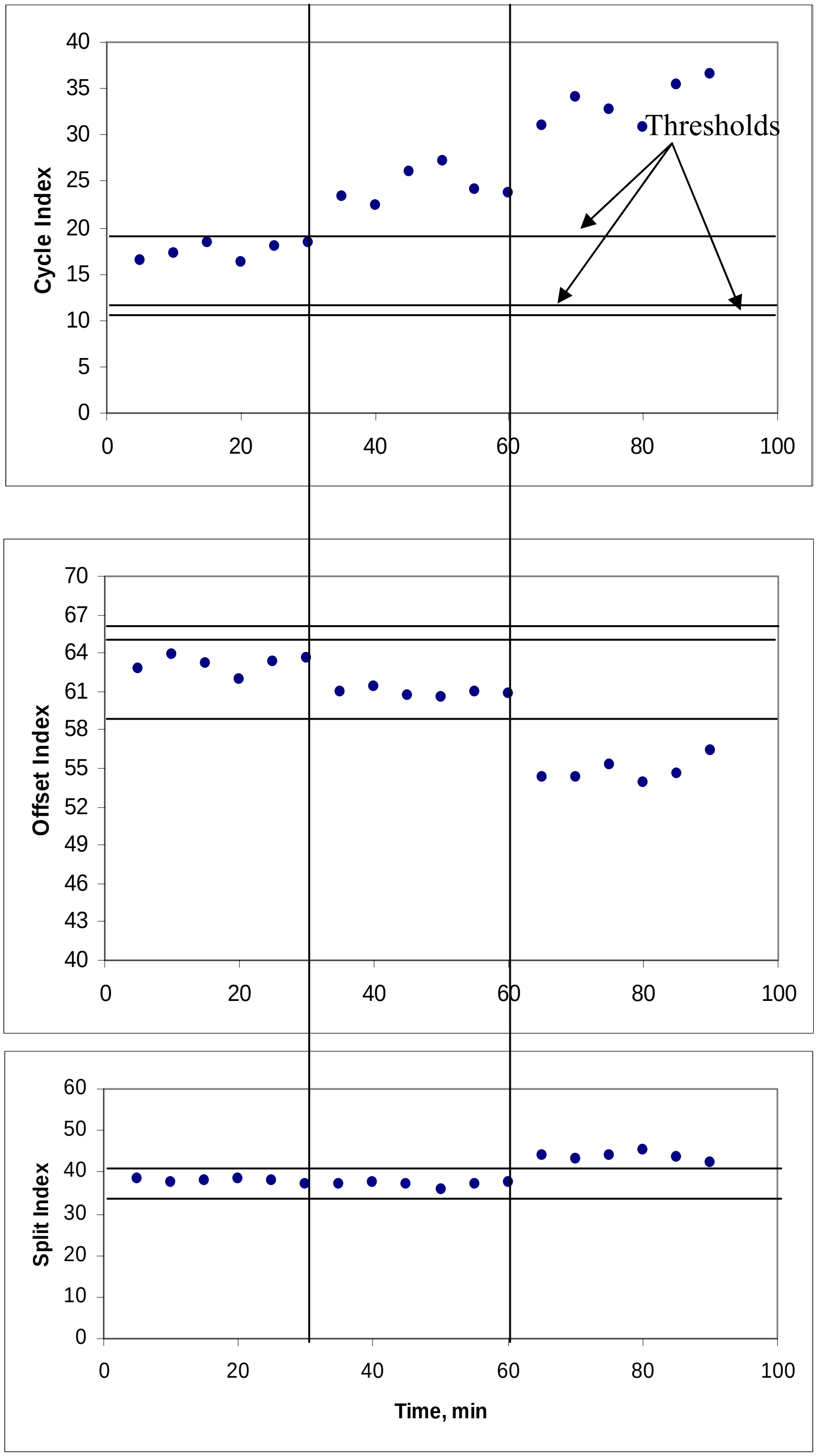
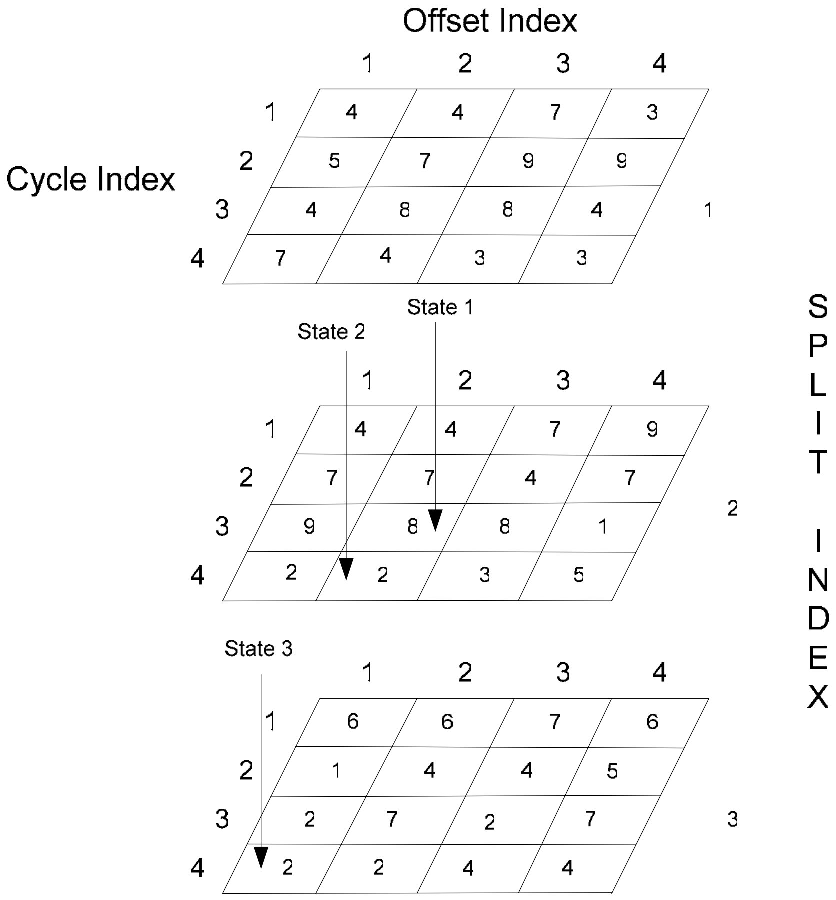


Figure 24. PS Parameter Change during HITL Simulation.



	1	2	3	4
1	4	4	7	3
2	5	7	9	9
3	4	8	8	4
4	7	4	3	3

	1	2	3	4
1	4	4	7	9
2	7	7	4	7
3	9	8	8	1
4	2	2	3	5

	1	2	3	4
1	6	6	7	6
2	1	4	4	5
3	2	7	2	7
4	2	2	4	4

Figure 25. Timing Plans Assignment in Look-Up Table.

SUMMARY

This chapter presented a novel and robust methodology for the selection of TRPS optimal parameters and thresholds. In addition, the chapter presented simplified guidelines in the form of tables for selection of timing plans, detector weights, thresholds, and plan look-up tables for each of the TxDOT-approved controllers.

CHAPTER 5: CONCLUSION

OVERVIEW

Closed-loop traffic control systems can be operated in either TOD mode or TRPS mode. When properly configured, the TRPS mode has the greatest potential to provide 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.

RESEARCH APPROACH

This report documents a novel and comprehensive methodology for robust and optimal selection of TRPS parameters and thresholds. This approach reduces 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 prefer to implement a more customized system for each closed-loop system (to improve optimality 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 operates with a reasonably good performance.

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. The research developed simplified guidelines to use with each of the two TxDOT-approved controllers in the form of charts and tables for ease of implementation. The simplified guidelines are provided in the Appendix in the form of tables and charts.

RECOMMENDATIONS AND FUTURE WORK

This research introduced a novel approach for configuration of TRPS parameters as well as for the selection of optimal timing plans. The product of this research was in the form of simplified guidelines for ease of implementation. These guidelines are designed to address all reasonable traffic states in a typical arterial closed-loop system.

There is a need, however, to be able to customize the TRPS control for any particular system. For example, if the engineer knows that the system will be predominantly operated with a particular range of traffic states, TRPS resources should not be wasted in addressing traffic states that will never occur in that particular system. An analogy to this is the ability of an observer to "zoom in" to a certain part of a map once the area of interest is known. The researchers recommend the following future research:

- development of a procedure to customize the TRPS guidelines for a particular range of traffic conditions,
- development of computer software for TRPS configuration for a particular system, and
- development of improved TRPS control mechanisms.

In addition, researchers recommend further research on TRPS configuration on grid networks, networks that include interchanges, and networks with high pedestrian demands.

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APPENDIX:
0-4421-3 (RESEARCH PRODUCT)
DESIGN CHARTS, TABLES, AND EQUATIONS

PRODUCT DESCRIPTION

This appendix provides the simplified TRPS design guidelines. The guidelines consist of the recommended system detector locations, timing plans, TRPS detector weights, thresholds, and timing plan look-up table indices for each of the two TxDOT-approved controllers. In addition, the guidelines also include tables to determine the phase sequence for any given network.

System Detector Locations

The system detectors are all located 400 feet upstream of the traffic signal in the inside lane; except for detectors 3, 6, 10, and 12 that are located 300 feet upstream of the left turn approach as shown in Figure 26.

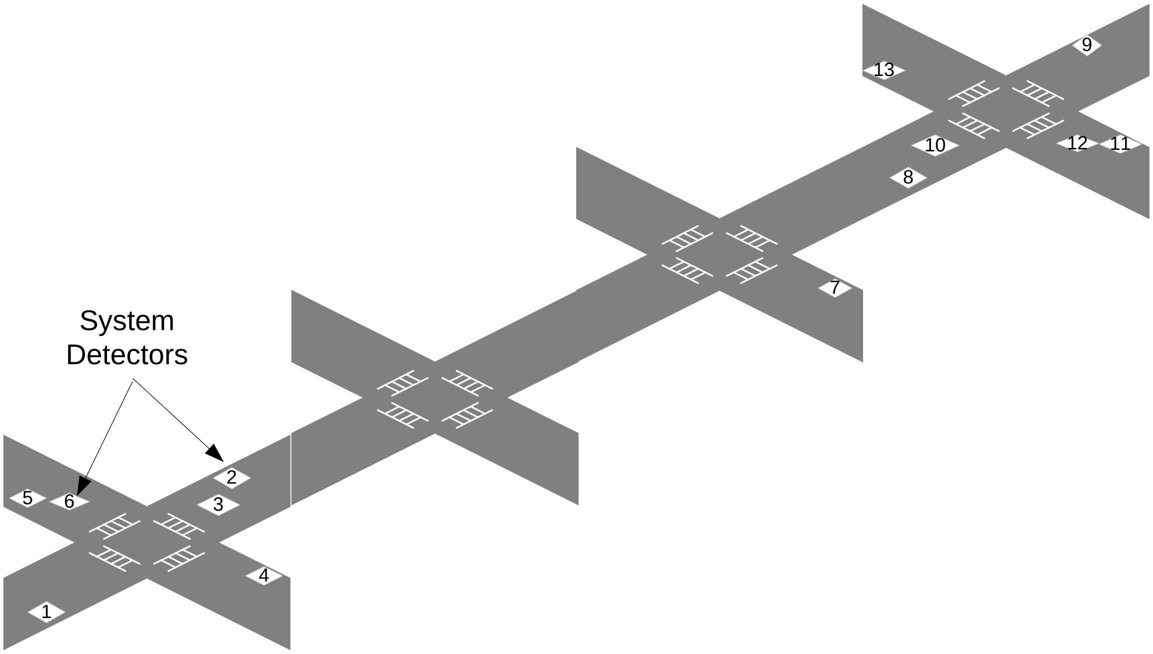


Figure 26. System Detector Locations.

Recommended timing plans for normal intersection operation are shown in Table 20. Recommended timing plans for intersections with side street split phasing are shown in Table 21.

Table 20. Recommended Timing Plans.

Timing Plan	Inter-section	Cycle	Phase							
			1	2	3	4	5	6	7	8
1	1	60	10	28	10	12	10	28	12	10
	2	60	10	30	10	10	10	30	10	10
	3	60	10	30	10	10	10	30	10	10
	4	60	10	26	11	13	13	23	11	13
2	1	100	17	29	24	30	10	36	21	33
	2	100	13	59	13	15	11	61	12	16
	3	100	10	61	13	16	14	57	13	16
	4	100	10	50	30	10	22	38	18	22
3	1	60	11	26	11	12	10	27	13	10
	2	60	10	30	10	10	10	30	10	10
	3	60	10	30	10	10	10	30	10	10
	4	60	10	26	14	10	13	23	11	13
4	1	60	10	24	12	14	10	24	12	14
	2	60	10	30	10	10	10	30	10	10
	3	60	10	30	10	10	10	30	10	10
	4	60	10	26	10	14	10	26	11	13
5	1	75	11	39	12	13	10	40	15	10
	2	75	10	45	10	10	10	45	10	10
	3	75	10	45	10	10	10	45	10	10
	4	75	10	36	14	15	11	35	13	16
6	1	60	10	30	10	10	10	30	10	10
	2	60	10	30	10	10	10	30	10	10
	3	60	10	30	10	10	10	30	10	10
	4	60	10	29	11	10	10	29	10	11
7	1	90	22	38	14	16	10	50	10	20
	2	90	14	55	10	11	10	59	10	11
	3	90	10	59	10	11	10	59	10	11
	4	90	10	55	10	15	12	53	12	13
8	1	90	22	39	13	16	10	51	19	10
	2	90	14	55	10	11	10	59	10	11
	3	90	10	59	10	11	10	59	10	11
	4	90	10	55	10	15	12	53	12	13
9	1	75	11	37	12	15	10	38	13	14
	2	75	10	45	10	10	10	45	10	10
	3	75	10	45	10	10	10	45	10	10
	4	75	10	40	10	15	10	40	12	13
10	1	90	12	54	11	13	10	56	14	10
	2	90	10	60	10	10	10	60	10	10
	3	90	10	60	10	10	10	60	10	10
	4	90	10	53	17	10	12	51	12	15

Table 20. Recommended Timing Plans (Cont.).

Timing Plan	Inter-section	Cycle	Phase							
			1	2	3	4	5	6	7	8
11	1	90	18	32	18	22	10	40	10	30
	2	90	14	46	14	16	12	48	13	17
	3	90	10	50	13	17	16	44	14	16
	4	90	10	41	10	29	23	28	18	21
12	1	75	15	27	15	18	10	32	15	18
	2	75	11	39	11	14	10	40	11	14
	3	75	10	40	11	14	13	37	11	14
	4	75	10	33	10	22	20	23	15	17
13	1	75	15	26	16	18	10	31	18	16
	2	75	11	40	11	13	10	41	11	13
	3	75	10	40	11	14	13	37	11	14
	4	75	10	33	17	15	20	23	15	17
14	1	90	19	23	19	29	10	32	19	29
	2	90	14	41	14	21	12	43	12	23
	3	90	10	44	13	23	17	37	14	22
	4	90	10	35	11	34	20	25	18	27

Table 21. Recommended Timing Plans with Side-Street Split Phasing.

Timing Plan	Inter-section	Cycle	Phase							
			1	2	3	4	5	6	7	8
1	1	60	10	26	10	14	10	26	14	10
	2	60	10	30	10	10	10	30	10	10
	3	60	10	30	10	10	10	30	10	10
	4	60	10	26	11	13	13	23	13	11
2	1	100	17	29	33	21	10	36	21	33
	2	100	13	59	13	15	11	61	15	13
	3	100	10	61	16	13	14	57	13	16
	4	100	10	45	30	15	20	35	15	30
3	1	60	10	26	10	14	10	26	14	10
	2	60	10	30	10	10	10	30	10	10
	3	60	10	30	10	10	10	30	10	10
	4	60	10	24	16	10	13	21	10	16
4	1	60	10	24	14	12	10	24	12	14
	2	60	10	30	10	10	10	30	10	10
	3	60	10	30	10	10	10	30	10	10
	4	60	10	23	10	17	10	23	17	10
5	1	75	11	36	10	18	10	37	18	10
	2	75	10	45	10	10	10	45	10	10
	3	75	10	45	10	10	10	45	10	10
	4	75	10	36	14	15	11	35	15	14
6	1	60	10	27	13	10	10	27	10	13
	2	60	10	30	10	10	10	30	10	10
	3	60	10	30	10	10	10	30	10	10
	4	60	10	26	14	10	10	26	10	14

Table 21. Recommended Timing Plans with Side-Street Split Phasing (Cont.).

Timing Plan	Inter-section	Cycle	Phase							
			1	2	3	4	5	6	7	8
7	1	90	20	34	23	13	10	44	13	23
	2	90	14	55	10	11	10	59	11	10
	3	90	10	59	11	10	10	59	10	11
	4	90	10	55	13	12	12	53	12	13
8	1	90	21	37	11	21	10	48	21	11
	2	90	14	55	10	11	10	59	11	10
	3	90	10	59	11	10	10	59	10	11
	4	90	10	55	13	12	12	53	12	13
9	1	75	11	37	14	13	10	38	13	14
	2	75	10	45	10	10	10	45	10	10
	3	75	10	45	10	10	10	45	10	10
	4	75	10	36	10	19	10	36	19	10
10	1	90	12	52	11	15	10	54	15	11
	2	90	10	60	10	10	10	60	10	10
	3	90	10	60	10	10	10	60	10	10
	4	90	10	49	20	11	11	48	11	20
11	1	90	17	29	24	20	10	36	20	24
	2	90	14	46	14	16	12	48	16	14
	3	90	10	50	16	14	16	44	14	16
	4	90	10	40	21	19	23	27	19	21
12	1	75	15	26	16	18	10	31	18	16
	2	75	11	39	11	14	10	40	14	11
	3	75	10	40	14	11	13	37	11	14
	4	75	10	30	16	19	18	22	19	16
13	1	75	15	26	16	18	10	31	18	16
	2	75	11	40	11	13	10	41	13	11
	3	75	10	40	14	11	13	37	11	14
	4	75	10	33	17	15	20	23	15	17
14	1	90	18	21	25	26	10	29	26	25
	2	90	13	39	17	21	12	40	21	17
	3	90	10	42	21	17	16	36	17	21
	4	90	10	35	27	18	20	25	18	27

Naztec Controller Guidelines

Out of the 14 possible timing plans shown in Table 20, only 9 plans are used for the Naztec configuration. Table 23 shows the 9 selected plan indexes.

Table 23. Final Selection of Timing Plans for Naztec Controller.

Timing Plan Index	1	2	3	4	5	6	7	8	9
Timing Plan Number	1	4	5	6	9	10	11	12	13

The detector weights for Naztec controller are listed in Table 24. The entering thresholds are listed in Table 25. The initial value for an exiting threshold should be set equal to that of the corresponding entering thresholds, until fine-tuned in the field. The plan table look-up entries are listed in Table 26.

Table 24. Naztec Controller Detector Weights.

Direction	Actuation	Detector												
		1	2	3	4	5	6	7	8	9	10	11	12	13
Inbound	Count	13	83	27	14	92	76	1	12	59	77	92	65	85
	Occupancy	12	21	75	9	10	52	16	52	21	25	5	26	13
Outbound	Count	98	52	22	63	91	5	1	99	44	4	6	61	1
	Occupancy	86	68	45	10	63	38	34	38	60	13	5	43	27
Cross	Count	3	53	15	79	33	1	74	10	90	10	95	79	91
	Occupancy	52	12	34	72	29	22	14	22	11	56	12	15	25

Table 25. Naztec Controller TRPS Thresholds.

Level	Cycle	Offset	Split
1	11	59	34
2	12	65	41
3	19	66	

Table 26. Naztec Controller TRPS Plan Look-Up Table Entries.

Cycle	Offset	Split		
		1	2	3
1	1	4	4	6
1	2	4	4	6
1	3	7	7	7
1	4	3	9	6
2	1	5	7	1
2	2	7	7	4
2	3	9	4	4
2	4	9	7	5
3	1	4	9	2
3	2	8	8	7
3	3	8	8	2
3	4	4	1	7
4	1	7	2	2
4	2	4	2	2
4	3	3	3	4
4	4	3	5	4

Eagle Controller Guidelines

Only five plans are used for the Eagle configuration. Table 27 shows the five selected plan indexes.

Table 27. Final Selection of Timing Plans for Eagle Controller.

Timing Plan Index	1	2	3	4	5
Timing Plan Number	2	3	5	9	11

Table 28 lists the detector weights for the Eagle controller. The entering thresholds are listed in Table 29. The initial value for an exiting threshold should be set equal to that of the corresponding entering thresholds, until fine-tuned in the field.

Table 30 lists the plan table look-up entries. Duplicate plans will need to be entered in each controller. The user can do this using the “Coordination Copy” feature in the Eagle controller.

Table 28. Eagle Controller Detector Weights.

Direction	Factors	Detector												
		1	2	3	4	5	6	7	8	9	10	11	12	13
ART (CS1 &CS2)	Weight	94	44	6	62	80	59	43	63	83	62	9	22	95
NART	Weight	40	56	0	10	81	80	59	38	59	53	29	83	88

Table 29. Eagle Controller TRPS Thresholds.

Level	Cycle	Split	Offset
1	18	56	--
2	21	59	--
3	32	60	

Table 30. Eagle Controller TRPS Plan Look-Up Table Entries.

Cycle	Split	Plan Index
1	1	5
1	2	5
1	3	5
1	4	5
2	1	1
2	2	2
2	3	2
2	4	2
3	1	2
3	2	2
3	3	5
3	4	5
4	1	2
4	2	2
4	3	5
4	4	3

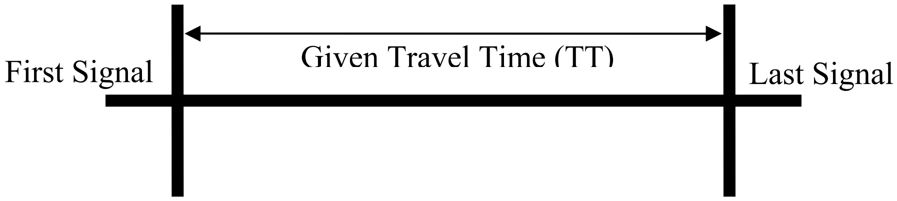
Offset Calculations

Offset = Travel time mod cycle.

Phase Sequence Calculations

Determination of phase sequences for the signal system is performed in two steps, as shown in Figure 27:

Step 1: Determine Offset and Sequences for First and Last Signals in the System.



Step 2: One by One, Determine Offset and Sequences for Each Signal in the Middle.

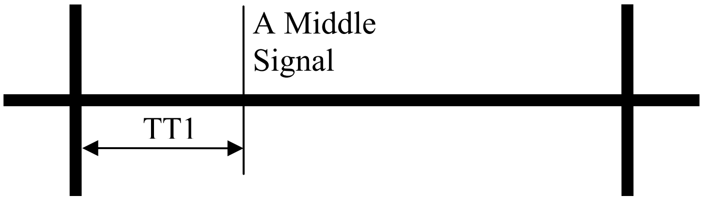


Figure 27. Optimal Selection of Offsets and Phase Sequences.

The phase sequence of the first and last intersections can be obtained from Table 31. The phase sequence for the intermediate intersection can be obtained from Table 32. In both tables, the sequence obtained can be explained as follows:

- 1: Lead-Lag (phases 2+5 start at the arterial barrier),
- 2: Lag-Lead (phases 1+6 start at the arterial barrier),
- 3: Lead-Lead (phases 1+5 start at the arterial barrier), and
- 4: Lag-Lag (phases 2+6 start at the arterial barrier).

Table 31. Recommended Phase Sequence at the First and Last Signals.

(Offset × 12) / Cycle	Sequence
1	13, 14, 32, 42
2	12
3	12
4	21
5	23, 24, 31, 41
6	11, 22, 33, 34, 43, 44
7	13, 14, 32, 42
8	12
9	12
10	21
11	23, 24, 31, 41
12	11, 22, 33, 34, 43, 44

Table 32. Recommended Phase Sequence at Intermediate Signals.

(External Offset × 12) / Cycle	(Internal Offset × 12) / Cycle											
	1	2	3	4	5	6	7	8	9	10	11	12
1	2	2	1	1	1	2	2	2	1	1	3	2
2	2	1	1	1	3	2	2	1	1	1	3	2
3	2	1	1	1	3	2	2	1	1	1	3	2
4	3	2	2	2	1	1	3	2	2	2	1	1
5	3	2	2	1	1	1	3	2	2	1	1	1
6	3	2	1	1	1	2	3	2	1	1	3	2
7	2	2	1	1	1	2	2	2	1	1	3	2
8	2	1	1	1	3	2	2	1	1	1	3	2
9	2	1	1	1	3	2	2	1	1	1	3	2
10	3	2	2	2	1	1	3	2	2	2	1	1
11	3	2	2	1	1	1	3	2	2	1	1	1
12	3	2	1	1	1	2	3	2	1	1	3	2

Example Offset and Phase Sequence Calculations

For two external intersections that are 14,300 feet apart and with a design speed of 45 mph, the link travel time would be calculated as 14,300/(45 × 1.467) ≈ 217 seconds. The offset to the last intersection for a plan that has a 60-second cycle length is equal to TT mod cycle = 217 mod 60 = 37 seconds (the mod function throws away all multiples of cycle lengths and leaves only the remainder). Using Table 31 to find the appropriate sequence at the last intersection requires the calculation of the look-up term "(offset × 12)/cycle." The look-up term = 37 × 12/60 = 7.4. A value of 7 in Table 31 suggests that any of the following two sequences will work at the first and last intersections, respectively: lead-lag and lead-lead, lead-lag and lag-lag, lead-lead and lag-lead, and lag-lag and lag-lead.

For an intermediate intersection 5240 feet from the first intersection, TT1 = 5240/(45 × 1.467) ≈ 79 seconds. The offset calculation for the same plan of 60-second cycle length is TT1 mod 60 = 79 mod 60 =19 seconds. From the external intersection's calculations, the first look-up factor in Table 32 = (External Offset × 12)/Cycle = 37 × 12/60 = 7.4. The second look-up factor = (Internal Offset × 12)/Cycle = 19 × 12/60 = 3.8. Using Table 32, the recommended sequence for the intermediate intersection is 1 (lead-lag).