Study and Evaluation of Traffic Responsive Control on a Large Arterial Network

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ABSTRACT

Traffic responsive mode of operation with its two mechanisms, threshold-based and pattern matching, is considered one of the effective and efficient signal control modes. This operation mode is underutilized due to its cumbersome configuration procedure. The research presented in this thesis aims to give some guidelines regarding traffic responsive and issues that might improve the system performance.

Four different issues related to traffic responsive are considered: The first issue is the generation of different traffic scenarios that drive the design of the system. This point is not limited to traffic responsive only but it is more general for different traffic engineering applications that need different traffic scenarios. The second issue is presenting an approach to implement traffic responsive control mode of operation in a large arterial network in Northern Virginia. Pattern matching mechanism is used for this application. Compared to time-of-day control mode, traffic responsive control saves up to 26.94% of the average delay and 21.13% of average number of stops for Reston Parkway network.

The third issue is an attempt to improve the current threshold mechanism by relaxing the threshold constraints and using variable thresholds for different levels of plan selection parameters. The last issue is a study for the pedestrian effect on the performance of networks operating by traffic responsive control. The effects of pedestrian calls and pedestrian phases on traffic responsive control are compared and the results shows that pedestrian calls are better for low pedestrian volumes while pedestrian phases are better for high pedestrian volumes.

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Chapter 1 : Introduction

1.1.Problem Statement

Traffic responsive control mode of operation is believed to have significant effect improving overall system performance for coordinated traffic networks. However, such system is not widely used to control traffic networks. Traffic engineers prefer to use time-of-day (TOD) mode of operation because it is much easier to configure and it has less number of parameters to be determined.

Traffic responsive control mode of operation has the advantage of switching timing plans implemented in traffic networks based on traffic variation. Time-of-day mode lacks this ability as it implements the same timing plan everyday at the same time regardless of what is happening in the network. Moreover, using traffic responsive does not require continuous updating for timing plans as it adjusts itself automatically.

Although, many researches show that using traffic responsive control mode of operation improves traffic networks where it is implemented by reducing number of stops as well as delay time, there is a need for more research to emphasize the parameters and different traffic issues that might affect traffic responsive operation. Thus, different traffic responsive controlling concepts are still mysteries for many traffic engineers.

Most of the research performed to date focuses on either small traffic networks--with up to five intersection--or theoretical networks. Also, past research considers only the threshold mechanism to implement traffic responsive in traffic networks because it is widely used by many controller manufacturers. There is very limited research on pattern matching mechanism, which has the potential to perform better than the threshold mechanism.

The work done in this thesis aims to provide guidelines on how to implement traffic responsive control for large arterial networks rather than small ones. In addition, pattern matching mechanism is the one that is used in the entire thesis.

1.2.Thesis Objectives

The objectives of this thesis are as follows:

1. Present a clear approach to generate realistic and accurate traffic scenarios to be used in different traffic engineering applications. One of these applications would be design of signal control systems.
2. Introduce guidelines for implementing traffic responsive control mode, using pattern matching mechanism, in large arterial networks. A real traffic network is used as an example.
3. Improve the performance of current thresholds mechanism by introducing threshold relaxation. This relaxation is to be implemented in traffic controllers.
4. Conduct a preliminary investigation of the effect of pedestrians on traffic responsive control mode and compare the effect of pedestrian calls and pedestrian phases.
5. Introduce a new conceptual approach to accommodate pedestrians with traffic responsive control mode of operation. This is just a conceptual approach that needs further investigations.

1.3.Thesis Layout

This thesis is organized into seven chapters. The second chapter provides a summery for the concepts of traffic responsive control mode and a review of the previous related work concerning such control mode. Chapter three presents the proposed approach to generate different traffic scenarios for any traffic network using what is called significant critical movements. The fourth chapter presents the details of implementing traffic responsive control mode of operation (using pattern matching mechanism) in Reston Parkway larger arterial network. The fifth chapter presents the proposed relaxation for thresholds and summarizes the benefits gained by using the relaxed thresholds. The sixth chapter introduces the conceptual study on pedestrian effects on traffic responsive control and compares the two available methods to consider pedestrians, i.e. pedestrian calls and pedestrian phases, with traffic responsive control. Finally, the seventh chapter concludes with the conclusions of the study and recommendations for further research.

Chapters three and four are papers submitted to 2009 Transportation Research Board (TRB). Chapters five and six are papers already presented in 2008 Application of Advanced Technologies in Transportation (AATT) conference in Athens.

Chapter 2 : Literature Review

2.1.Overview

Nowadays, Adaptive control is considered the most efficient way to control traffic networks. Different modes for adaptive control (such as SCOOT, SCATS, etc.) have been studied and analyzed to determine the most appropriate way to determine the parameters required by each method. The first generation of successful responsive systems includes SCOOT which gives responses to real-time traffic through optimizing cycle length, phase split and offset. Similar to SCOOT is SCATS. These systems began to outperform the best fix-time control strategies with 6%-20% savings in travel time at network level *(1, 2, and 3)*. One of the most effective and efficient adaptive control modes is traffic responsive control.

Although traffic responsive control mode is efficient and effective, not enough research is done to formulize the design procedure for traffic responsive control mode. This chapter presents the basics of traffic responsive control and a comprehensive literature review for the research done in this topic.

Traffic responsive control mode as any adaptive control mode has the ability to switch timing plans being implemented in traffic networks according to traffic variations. This concept assures applying the most appropriate timing plan for existing traffic pattern which increases the overall system performance by minimizing delay and number of stops.

2.2.Traffic Responsive Control Concepts

In order to implement traffic responsive control mode, a set of system detectors should be spread around on the traffic network being studied. Number of system detectors that are supported in traffic controllers differs from controller manufacturer to another. The selection of the system detectors should be accurate as for any adaptive control system because the efficiency of controlling system depends on system detectors used. Guidelines to select system detectors for traffic responsive control are given in a report done by Taxes Transportation Institute (TTI) *(4)* in addition to the limited guidelines provided by the Federal Highway Administration *(5)*. Counts and occupancies of selected system detectors are collected. The treatment method for the collected detector data depends on the traffic responsive methodology provided by traffic controllers operating the entire network.

Two different methodologies are followed to implement traffic responsive control in any traffic network as per The National Transportation Communications for ITS Protocol (NTCIP) 1210 field management stations draft *(6)*: the first is threshold mechanism, and the second is pattern matching mechanism. Each controller manufacturer provides one of those methodologies in their traffic controllers to implement traffic responsive control mode of operation. The concept for these two methodologies is the same but the way to deal with detector data is different. Thus, the required parameters to set up each methodology are different. For the same methodology, different controller manufacturers might call traffic responsive parameters in various names. However, the main concept is the same.

For the threshold mechanism, detector data (counts and occupancies) are aggregated to form what is called computational channel parameters (CC) by multiplying data from each system detector by its corresponding weight. The names and numbers of computational channel parameters differ from one controller manufacturer to another. Computational channel parameters are then aggregated in to plan selection parameters (PS) which are responsible to activate one of the pre-stored timing plans.

Different factors are being used to aggregate counts and occupancies obtained from system detectors to computational channel parameters then plan selection parameters. Three types of factors are generally used scaling, weighting, and smoothing factors *(7, 8, and 9)*. Scaling factors--two for each system detector, one for counts and another one for occupancies--are used to convert counts and occupancies data into a combined value ranging from 0 percent to 100 percent indicating how close the approach is to its capacity so this combined value becomes independent of the approach capacity. Weighting factor is assigned for each system detector so that the detector data are multiplied by the weighting factor corresponding to such detector. Some controller manufacturers allow different weighting factors to counts and occupancies *(4)*.

Smoothing factors are used to eliminate the effect of the 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: filtering approach and averaging approach. The former approach calculates the new value of a variable (count or occupancy) by multiplying the difference between the old smoothed value and the newly collected value of the same variable by a smoothing factor, and adding the result to the last smoothed value of the variable. The later approach averages the values of the variable over the previous time intervals. The greater the number of previous time intervals used, the less sensitive the smoothed value is to changes *(4)*.

Most of controller manufacturers have three PS parameters: offset PS parameter, cycle PS parameter, and split PS parameter. Functions used to aggregate the computational channel parameters into plan selection parameters are, in most cases, predefined by the controller vender. Each one of the PS parameters has different levels separated with PS thresholds between levels. Three thresholds for each PS parameter (forming four different PS levels) are widely used in different traffic controllers. These thresholds are saved in the master traffic controller.

Master traffic controller keeps collecting system detector data and tracking the values of different PS parameters, produced using scaling, weighting, and smoothing factors, then comparing the obtained PS parameters to the predefined set of thresholds. Based on the traffic variation, values of PS parameters differ therefore master traffic controller decides to switch timing plan being implemented when necessary.

Figure 2.1 shows the main idea of threshold mechanism. It presents the threshold mechanism as a cube with three axes; each one simulates a PS parameter. This large cube is then divided by the PS thresholds into forty six small cubes. Each one of these small cubes refers to specific timing plan saved in traffic controllers. Thus, when the obtained PS parameters are calculated, the master controller maps their values in one of the small cubes and switch timing plan to the plan accompanied with such cube, if necessary. Number of timing plans that can be stored in traffic controllers differs from controller manufacturer to another.

Eagle and Naztec Controllers are examples to traffic controllers that support threshold mechanism for implementing traffic responsive control mode in traffic networks. Eagle controllers support up to 64 system detectors, 10 computational channel parameters, and eight original timing plans. Eagle controllers also support an additional eight timing plans using optional computational channel parameters called queue and occupancy CC parameters. Naztec controllers support only three computational channel parameters. However, combinations of these three CC parameters are used to calculate each of the PS parameter levels. Naztec has 24 total numbers of timing plans that can be assigned to each one of the 144 possible combinations of different PS parameter levels *(4)*.

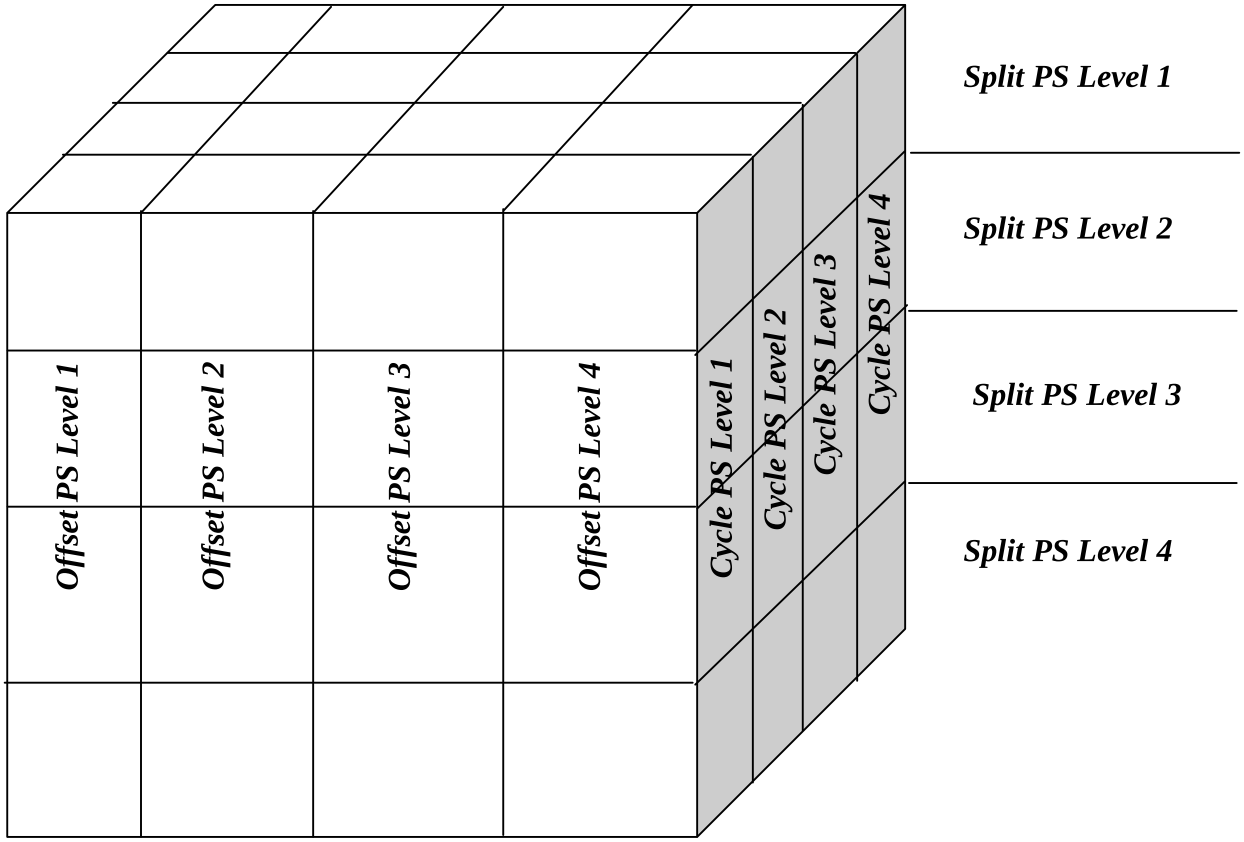

Figure 2.1 Thresholds mechanism to implement traffic responsive control

Pattern matching mechanism deals with detector data (counts and occupancies) as is. In other words, it does not aggregate system detector data to any computational channel parameters or plan selection parameters. In this mechanism, only weighting factors for system detectors are implemented. However, the way these weighting factors are assigned to counts and occupancies of their corresponding detectors is different.

Master traffic controller switches the timing plan being implemented in traffic networks based the sum of the deviations of individual count and occupancy values from those stored in the master for each timing plan. These stored counts and occupancies simulate the thresholds in the threshold mechanism.

In order to clarify this mechanism, 170's controller is presented as it applies pattern matching mechanism to implement traffic responsive control mode. Figure 2.2 summarizes the pattern matching mechanism applied by the 170's controllers. It appears that all system detector counts and occupancies are combined together with the pre-programmed counts and occupancies in only one parameter *(F_j)* for each timing plan. This parameter is calculated for each stored plan in the master controller. The combined F_j parameter depends on different factors such as the VPLUSKO weighting factor *(K)* which is a global factor for the whole system that is used for all detectors and all times of day, and the weight factors for each system detector *(10)*.

170's controllers use the following formula to calculate different F_j plan values *(10)*:

$$F_j = \sum \left| W_i \left[\left(V_i + K * O_i \right) - \left(V_{ij} + K * O_{ij} \right) \right] \right|$$

Where:

F_j = sum overall detectors (i) of the absolute value of the weighted difference between actual detector data and the pre-programmed counts and occupancies accompanied with each plan.

V_i *and* O_i = the measured volumes and occupancies of detector (i), respectively

V_{ij} *and* O_{ij} = the volumes and occupancies stored with plan (j) for detector (i), respectively

K = a user supplied "VPLUSKO" weighting factor whose value is between 0 to 100.

W_i = a detector specific weighting factor used to eliminate detectors from the calculation if they are not to be included for certain times of day, or to emphasize volumes and occupancies measured be selected detectors if their outputs are more important. These values are between 0 and 10. W_i is a detector specific value that can be changed with time of day in the schedule.

It appears that using the pattern matching mechanism can be preferred by many traffic engineers. However, almost no research is done to specify guidelines determining the required parameters because the threshold mechanism is the one that is widely used by most of the controller venders.

2.3.Previous Efforts Concerning Traffic Responsive Control

Different researches are conducted to improve overall performance of different adaptive control modes generally and traffic responsive control mode specifically. An approximate dynamic programming (ADP) is one of the methods proposed *(11)*. It was the first attempt to optimize the traffic control objective dynamically through adaptive approximation of value function. The proposed algorithm depends on the approximation of the value function progressively during operation, while preserving the structural property of the control problem. That research concludes that the new approximate dynamic programming strategy is as good as the best existing control strategies while being efficient and simple in computation.

Another research aims to minimize congestion situations via a traffic-responsive signal control mode founded on a hierarchical Petri net (PN) representation of the system *(12)*. The higher level of the PN representation consists of net modules, each one representing an intersection, a road, a signal staging, etc. the description of each module in terms of deterministic timed Petri nets (DTPN) is given at the lower level. Such a representation leads to a corresponding two-level control procedure. The high-level control system, which acts over the modular representation, switches among internal module structures so as to modify some parts of the model of the traffic system (e.g., signal plans, turning rates, etc.), depending on both state and time. The low-level control system, which acts over the DTPN representation, optimizes the performances of the traffic system, by solving a mathematical programming problem which minimizes the number of vehicles in the system. The research concluded that the high modularity of the proposed PN-based model turns out to be a valuable feature, since it makes possible to use the same modular/switching system to rule the traffic flows through the considered signalized intersections during the whole day.

Fuzzy logic is also considered one of the techniques that can improve the traffic responsive control mode as an adaptive control procedure. A study describing the use of fuzzy logic technique in signal control is conducted for single intersection *(13, and 14)*. This study presents the ability to improve system performance by reducing delay and stops in the network.

Other researchers are focused only on traffic responsive control mode of operation rather than general adaptive control modes. Considering the threshold mechanism, different researches are performed to describe various techniques to determine the thresholds achieving best separation between different traffic scenarios such as principal components and discriminate analysis *(15)*, artificial neural networks and support vector machines *(16)*, and decision-tree classifiers and various forms of nearest neighbor classification methods *(17)*.

A recent study introduces a step-by-step procedure for determining the thresholds for traffic responsive control mode *(18)*. This research proposed a traffic state classification method using modified linear discriminate (LDA) analysis. The proposed approach determined initial thresholds for predefined groups of detector data. The initial thresholds were assumed to be the mid-points between different group centers. Based on these initial thresholds, final thresholds were chosen using the LDA and redefined groups. The research concluded that the proposed LDA achieves thresholds that improves traffic responsive control mode significantly.

Another research was conducted to give general guidelines for threshold mechanism of traffic responsive control mode *(19)*. A multi-objective evolutionary algorithm and a supervised discriminate analysis were used in the research to come up with the guidelines. In that research, three main movements were proposed for many traffic network major external movements, internal local movements, and additional cross-street movements. Using these three movements, different traffic scenarios were generated and the traffic scenario probability was determined for each one of these scenarios. The traffic scenarios probabilities were determined using the probability of occurrence of traffic volume in the major arterial direction, then given this probability, determination of the probability of all other volumes in the other directions.

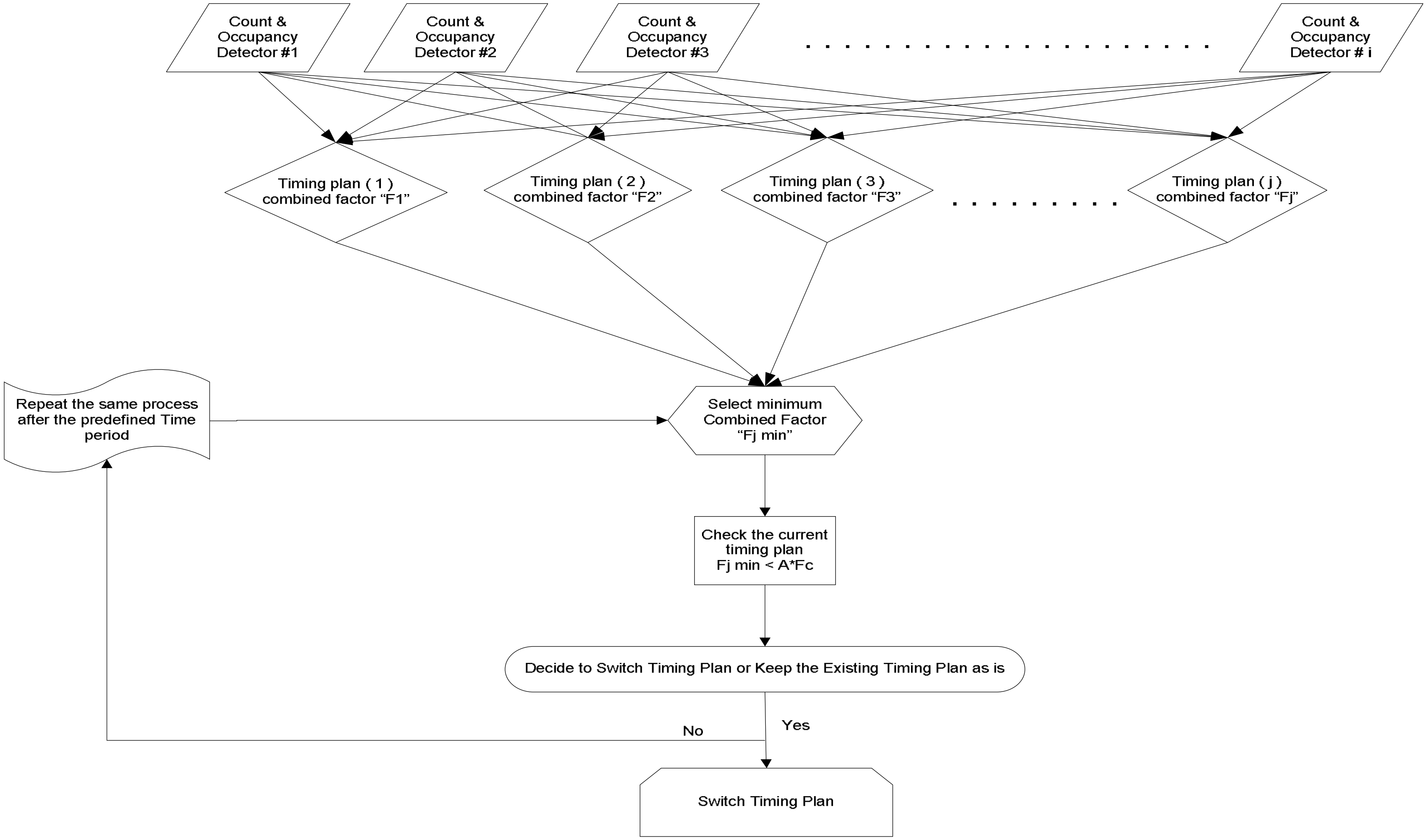

Figure 2.2 Pattern matching control mechanism applied by 170's controllers to implement traffic responsive control

Multi-objective genetic algorithm optimization was used to select the timing plan to be implemented in the network out of many plans obtained from PASSER-V package for each one of the generated traffic scenarios. The concept of degree of detachment (DOD) was introduced in that research. The DOD measures the degree by which a traffic state is detached from adjacent states. This approach was implemented in different traffic networks in Texas showed a significant improvement in network performance.

The drawback of this mechanism is that it assumes each original node produces equal amount of trips and these trips are equally attracted by other nodes in the network. These assumptions are not accurate for most of the traffic networks.

Another 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 *(20)*. Moreover, the city of Milwaukee, Wisconsin, installed a closed-loop traffic responsive system to manage congestion and reduce traffic accidents *(21)*. 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.

Another study was conducted in two networks in Lafayette, Indiana, and compares traffic responsive control 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 traffic responsive mode reduced total system delay by 14 percent compared to TOD mode for the midday traffic pattern. It was also found that the traffic responsive 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 *(22)*.

2.4.Summary

A review of the literature has revealed the following deficiencies in the state-of-knowledge:

1. Limited research has attempted to formalize an approach to implement traffic matching mechanism for traffic responsive control mode of operation in traffic networks or to provide guidelines on how to determine the required parameters for such approach,
2. Limited number of studies has attempted to present the effect of pedestrians and the way of dealing with them (either pedestrian calls or pedestrian phases) on traffic responsive control mode of operation.

The research presented in this thesis attempts to address these deficiencies.

Chapter 3 : Determination of Significant Critical Movements to Generate Traffic Scenarios for Arterial Large Networks

3.1.Abstract

Any traffic signal control mode requires generation of multi-traffic scenarios for design purposes as well as for validation of the control system. The overall system performance depends on the traffic scenarios used to design the entire system. Therefore, all traffic patterns that might exist in a control system should be considered according to their probability of occurrence on daily basis. However, when it comes to large networks, considering all combination of traffic movement levels becomes time consuming and impractical. In this chapter, a new approach to generate traffic scenarios for large networks is proposed. This approach is based on the selection of significant critical movements controlling the network. Selection of these critical movements is performed using statistical correlation analysis of actual detector data, and synthetic origin-destination analysis for the entire network. The proposed approach has been implemented in the design of traffic responsive control mode for Reston Parkway arterial network that has fourteen intersections. Detectors data were then used to validate the results of the proposed approach. The validation shows no significant difference between the actual detector data and the proposed procedure's results, and therefore proves that the traffic system was correctly modeled and sufficiently represented with the proposed approach.

3.2.Introduction

Generation of different traffic scenarios is one of the required steps to conduct different traffic engineering analyses. It is important to generate realistic traffic scenarios representing the actual network characteristics. The generated scenarios should cover wide range of possible traffic variation in the network. The accuracy of the analysis being performed is directly related to the traffic scenarios used in the entire analysis.

There are no clear guidelines or approaches to follow to generate reasonable scenarios. Most of the existing techniques consider all traffic patterns even those that might not exist in reality. Inaccurate traffic patterns leads to inadequacies in the conducted analysis. For example, traffic scenarios for any network should reflect the actual patterns and major movements on such network otherwise the analysis will be far away from the real network.

Considering all traffic patterns has the advantage of including the effect of all patterns in the analysis. However, it is not acceptable in some cases to include traffic scenarios that rarely exist in analysis. For example, traffic scenarios being used to design signal control modes should be representative but not comprehensive. Moreover, for large networks, considering all possible traffic patterns becomes time consuming and computationally impossible.

In this chapter, a new approach to generate traffic scenarios is proposed. This approach uses correlation between different movements in the network accompanied with synthetic origin destination analysis to determine the traffic movements controlling the whole network. These movements are called significant critical traffic movements. Using these critical movements, different traffic scenarios are generated. The procedure assures that the generated scenarios cover the actual traffic variation in the network as well as the actual traffic combination.

The proposed approach is implemented in Reston Parkway network in Northern Virginia, USA. The project scope includes designing of traffic responsive control for Reston Parkway network which consequently requires multi-traffic scenarios to be considered during the generation of timing plans for the signal control.

3.3.Background

Very limited literature exists about traffic scenario generation. A report on implementing traffic responsive control in different networks published by Texas Transportation Institute (TTI) indicates that all traffic scenarios for each network are considered while determining optimum timing plans for each network. TTI networks have between three and five intersections. The study used clustering of detector data to determine traffic levels for traffic entering the network from all origins, and then distribute it equally over all destinations *(23)*. The obtained timing plans for each network show good improvement for the network performance.

Although, TTI approach provides good methodology for the networks being considered, equal traffic distribution is not a good assumption for all networks, although it might be applicable for some.

In order to generate more realistic traffic scenarios for large networks, origin-destination matrixes should be estimated, and since these origin-destination matrixes differ with the time of day and it is costly for large networks because of the prohibitive number of required sensors, Synthetic dynamic demand module (SDDM) is proposed to generate dynamic origin destination matrix for traffic networks *(24, 25, and 26)*. In this method, the static detector counts are used to generate the origin destination matrix to be used after that in different analyses. The only drawback of this method is that it requires driver behavior data which is not available for all networks. Another way to estimate origin destination matrix is using Path flow estimator (PFE) to generate and improve origin destination matrix for traffic networks *(27, 28, and 29)*. However, it requires large data to generate accurate results.

In this chapter, a new approach based on significant critical movements is proposed to generate traffic scenarios on the traffic networks. In this approach, the major traffic movements are considered by generating an origin destination matrix then relating it to the correlation between detector counts.

The rest of this chapter describes the research conducted. The first section describes steps for the new proposed approach. The following sections describe the study network and the details of the research methodology and finally, the last section describes the findings and results of the research.

3.4.Study Network

Figure 3.1 shows the Reston Parkway network located in Northern Virginia. The network consists of fourteen intersections with a total length of 16572 ft. the spacing between intersections is ranging from 524 ft to 3309 ft. The speed limit for the main arterial is 45 mph and ranging from 15 mph to 45 mph for the side streets. Eleven intersections are four-leg intersections; intersection number 13 is three-leg intersection, while intersections numbers 6 and

7 are four-leg intersections with one-way side streets. Also, intersection number 10 has only right turn movements for the side streets i.e. no through or left turns from the side streets. This network has a great attractiveness competition between all destination nodes.

Actual detector data from this network are taken for a period of one month starting from April 5th, 2008 to May 6th, 2008. These detectors almost cover the whole network and have a record every 15 minutes. The following sections present the details of the proposed approach to deal with large arterial networks considering Reston Parkway as an example.

3.5.Proposed Approach Analysis Steps

The proposed approach is based on four analysis steps; each one of them affects the others significantly. This section describes the sequence of these four steps as well as the main purpose of each one of them.

Step 1

This step includes clustering of detector counts for both the main arterial and side streets. The purpose of this step is to determine the traffic levels for the movements entering the network.

Step 2

In this step, correlation between different movements on the network is determined. The purpose of this step is to come up with a good understanding of the relationship between different movements in the network.

Step 3

Traffic entering the network from each origin node is distributed over all destinations. The distribution percentages for different traffic levels at each origin node are being determined. This is a very important step to generate realistic traffic patterns.

Step 4

This step combines the results of the previous three steps to determine the significant critical movements that control the entire network. After that, traffic patterns are generated.

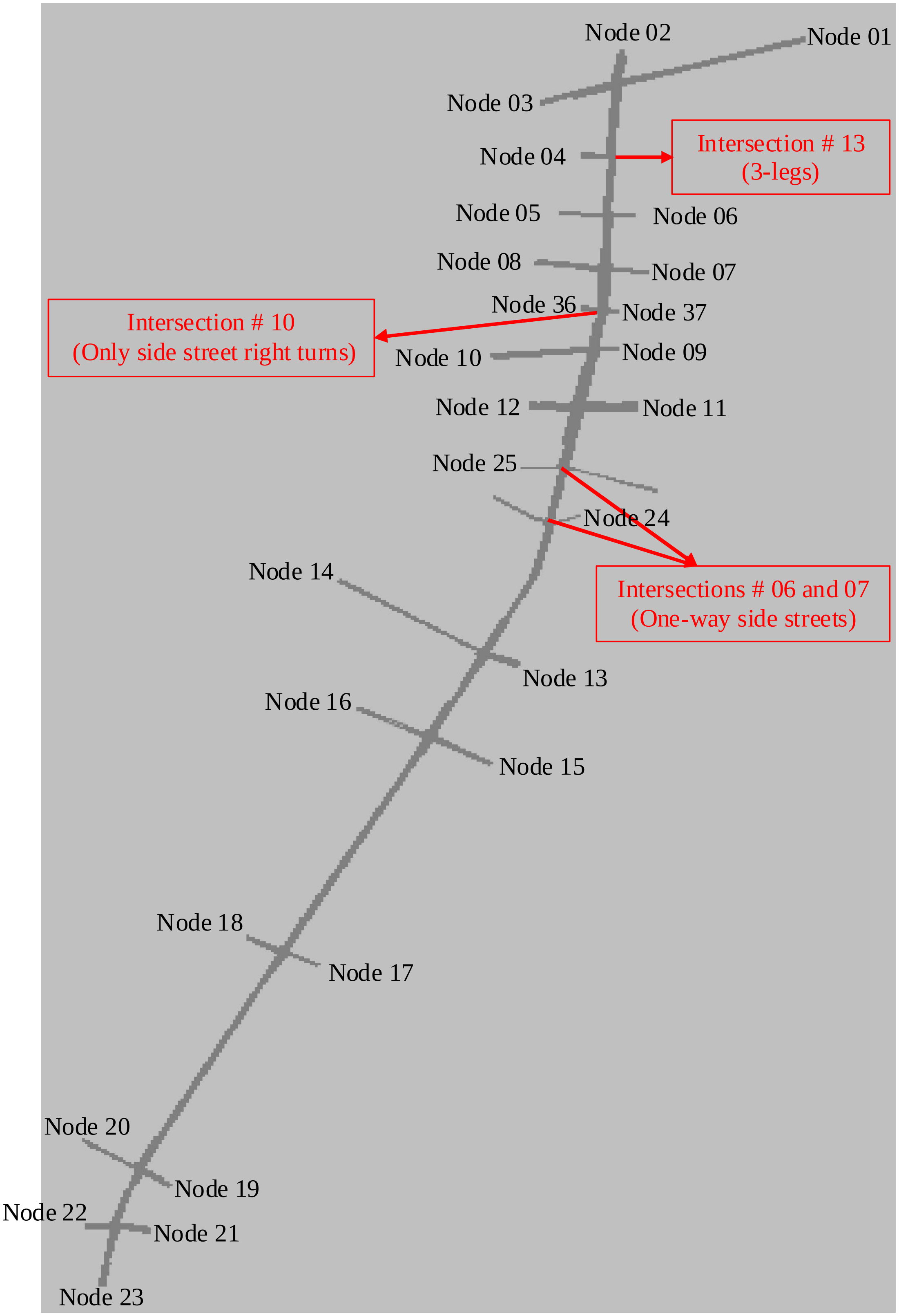

Figure 3.1 Reston Parkway Network in Northern Virginia

3.6.Traffic Patterns Generation for Large Arterial Networks

In this section, the details of the proposed approach to deal with large arterial networks are presented. In order to simplify and clarify the approach steps, Reston Parkway arterial network is considered as an example. The four steps listed above are performed on this network. The details of each step are presented here.

3.6.1. Traffic Level Determination (k-means Clustering)

The first step to generate traffic patterns for any network is to determine the traffic levels for different movements in the entire network. This step is proposed in the TTI approach. Clustering can be based on the volumes of different link movements (i.e. left, through, and right) or link flow volumes. In this chapter the traffic levels are based on the link flow volumes. The clustering should be done for the main arterial as well as side streets separately as it is believed that the side streets are not expected to have high traffic levels as the main arterial.

K-means clustering is proposed to be used for the level determination. MATLAB (30) is used to perform the entire analysis. K-means uses an iterative algorithm that minimizes the sum of distances from each object to its cluster centroid over all clusters. This algorithm moves objects between clusters until the sum cannot be decreased any further. The number of clusters should be provided to the k-mean function as an input so that it attempts to minimize the distances over this given number of clusters. This step is repeated for different number of clusters.

The best number of clusters which represents the number of traffic levels is then determined using the silhouette value. This value determines how good the clustering of data using the given number of clusters is. Finally, to determine the best number of clusters, a graph presenting the number of clusters versus each cluster silhouette value is drawn and selects number of clusters having maximum silhouette value, as presented in Figure 3.2 for the main arterial and Figure 3.3 for side streets. Based on the k-mean analyses performed for the main arterial (i.e. Reston Parkway road) and all side streets, it was found that for the Reston Parkway arterial network five traffic levels for the main arterial and three traffic levels for side streets are the recommended levels to be used to design traffic responsive control.

K-mean results are in the form of a vector including each object and the cluster that this object is assigned to. This vector is used to determine the limit for each level. Figure 3.4 and Figure 3.5 shows the limits for main arterial clusters and side-street clusters respectively. Table 3.1 summarizes the cluster limits for both of main arterial and side streets.

Table 3.1. Cluster Limits for Main Arterial and Side Streets.

Traffic Level	Link Flows Main Arterial (vph)		Link Flows Side Streets (vph)	
	Minimum	Maximum	Minimum	Maximum
1	0	354	0	326
2	355	876	327	933
3	877	1492	934	2735
4	1493	2275	--	--
5	2276	4900	--	--

- *The "--"sign indicates that the traffic level does not exist for the side streets.*

3.6.2. Correlation Analysis for Detectors Data

As discussed previously, the main idea in the proposed approach is to determine the significant critical movements controlling the whole network. The significant critical movements can be defined as the movements that do not have any correlation or have small correlation to other movements. Meanwhile, they have considerable traffic level variation. These movements will be used to generate traffic patterns being considered in the required design.

Based on this definition, traffic movements in any traffic network can be classified into critical movements and non-critical movements. The non-critical movements are the highly correlated movements which mean if the traffic level for one of them increased, all traffic levels for movements that are highly correlated to such movement are going to increase as well and vice versa. The situation is different for the critical movements. If traffic level of one of the critical movements increased, it does not mean that any level in the network is going to increase.

Using these concepts of critical movements and non-critical movements to generate traffic patterns will ensure that the generated patterns are only the patterns that take place in reality. In other words, there will be no pattern with zero probability.

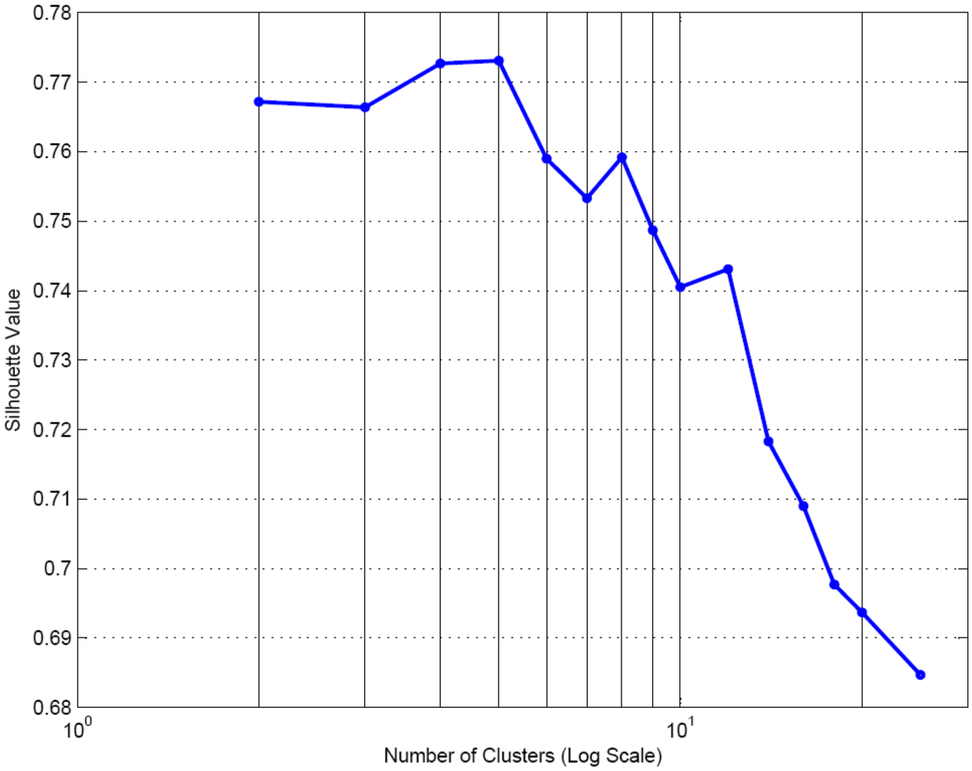

Figure 3.2 Silhouette value corresponding to different number of clusters for main arterial

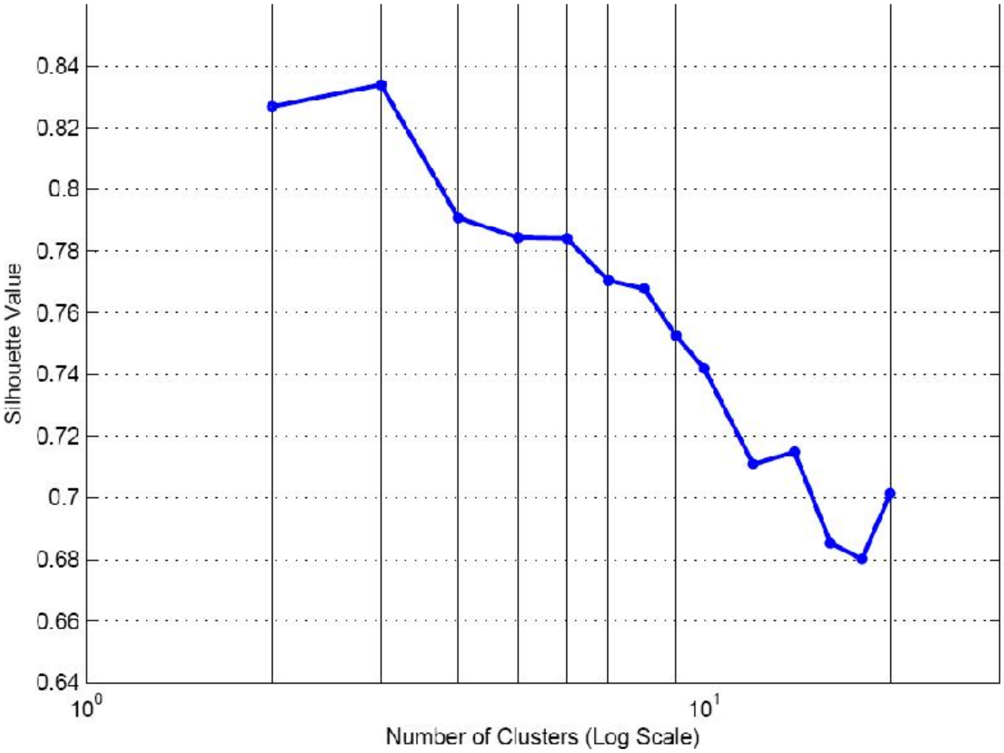

Figure 3.3 Silhouette value corresponding to different number of clusters for side streets

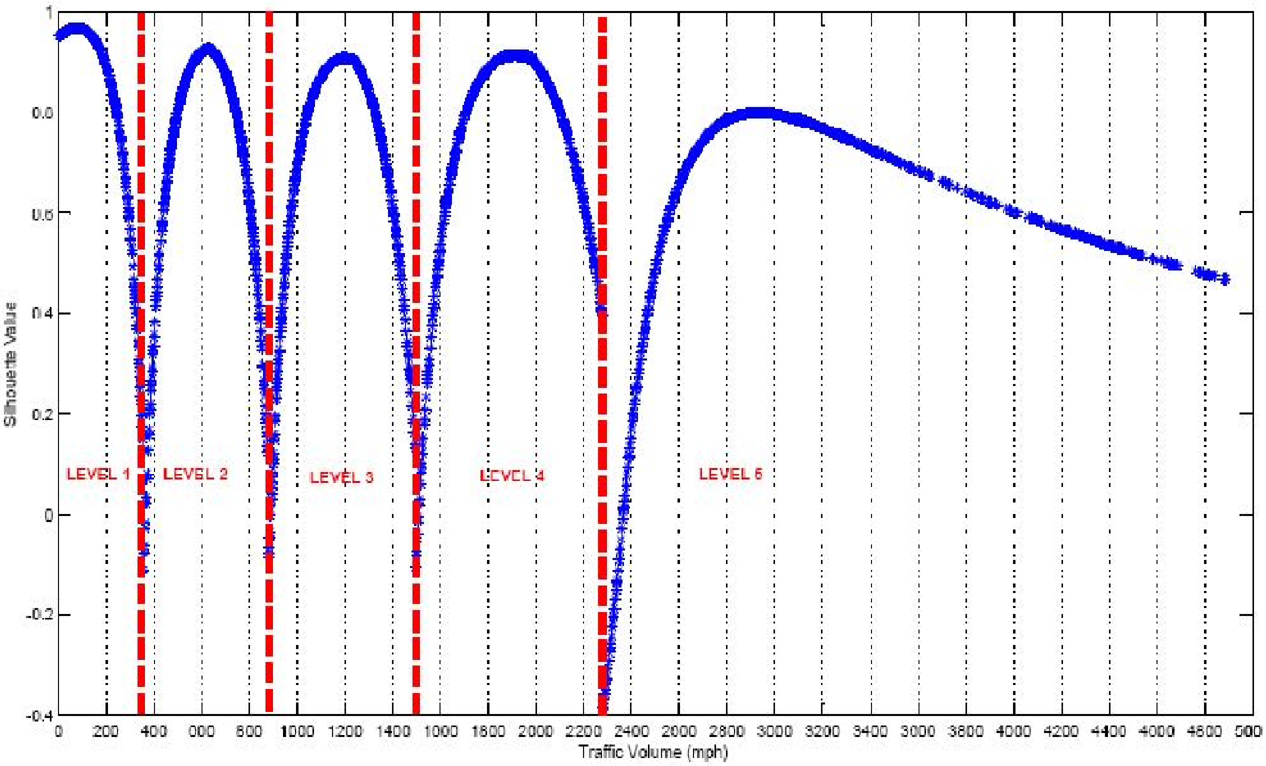

Figure 3.4 Link flow limits for clusters of the main arterial

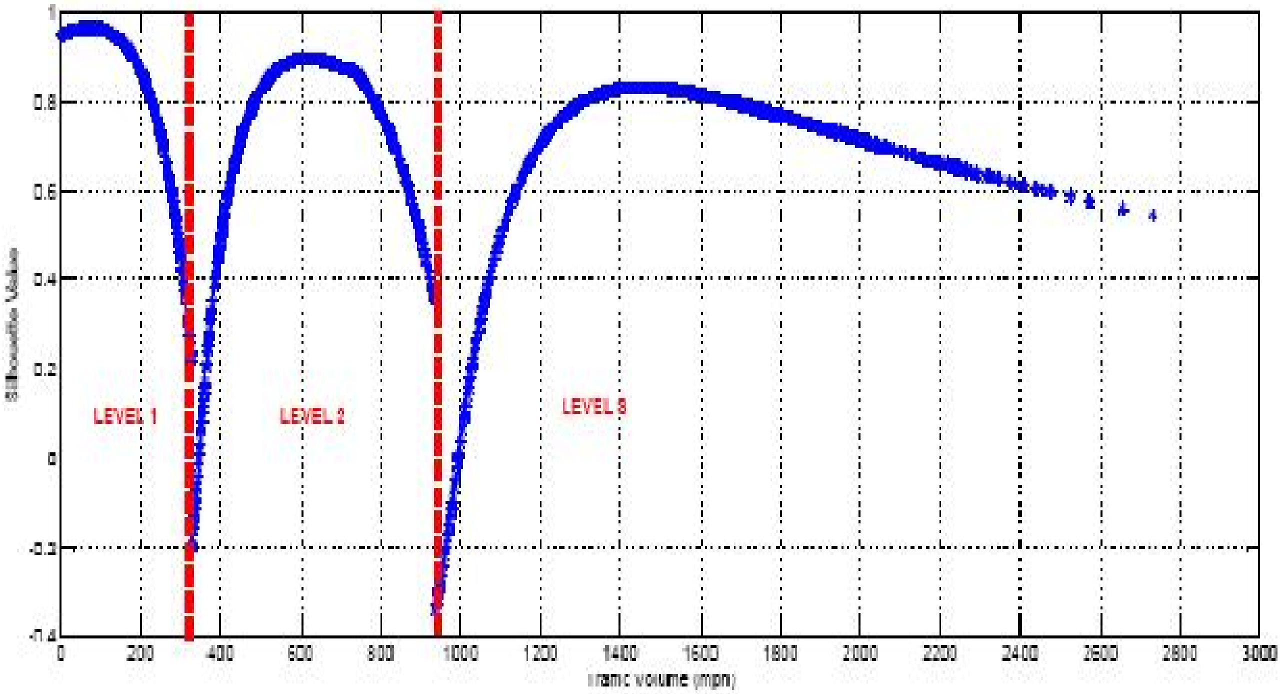

Figure 3.5 Link flow limits for clusters of side streets

It is therefore obvious that correlation analysis should be done for the detector data so that correlation factors between each movement and all other movements can be obtained. SAS statistical package *(31)* was used to perform the entire correlation analysis. This correlation analysis should only concern movements entering the network either from the main arterial or from side streets. However, side-streets through movements are also considered as well because these through movements affect the final timing plans. Thus, two correlation runs should be performed one for all movements entering the network and another one for all side-streets through movements.

For Reston Parkway arterial network, the two correlation runs were performed and the correlation tables are presented in Table 3.2 for movements entering the network and Table 3.3 for side-streets through movements. These correlation factors do not determine which movements can be considered highly correlated to other movements. Therefore, it is important to define a threshold between the highly correlated movements and uncorrelated movements. This threshold is found by running k-means clustering with only two clusters over all correlation factors for both SAS runs. The threshold is found to be 0.50 for movement entering main arterial and 0.60 for side-streets through movements. This means for the movement entering network, if the correlation factor between any two movements is more than 0.50, then these two movements are highly correlated otherwise they are not. In Table 3.2 and Table 3.3 the red cells represent the correlation factors more than 0.50 and 0.60 respectively.

It is obvious from Table 3.2 that there are almost five movements that have small correlations with other movements. Those movements are north bound through and the west bound right at the first intersection, east bound left at the fourth intersection, west bound left at the fifth intersection, and the south bound through at the last intersection. Also it is clear from Table 3.3 that all side streets through movements are highly correlated to each other.

The question now is which one of these five critical movements is significantly critical. In other words, does each one of these movements affect the network significantly? The answer for this question would be based on 1) the maximum actual observed traffic level on links where these movements exist, this maximum observed level should be assigned as a constrain for the level of all movements of such link and 2) if anyone of these movements is found to be on a link having significant variation in its traffic level, then it is important to know at which level such movement is significant. Synthetic O-D analysis gives a clear answer for these two points.

3.6.3. Synthetic Origin-Destination Analysis

Synthetic origin-destination (O-D) analysis aims to determine distribution percentages for traffic entering the network from each origin node to all destination nodes. Since the traffic entering the network from any origin node is constrained by the maximum observed traffic level at this node, synthetic O-D analysis is performed for each one of the possible traffic levels at each node.

It is obvious that for the non-critical movements obtained from correlation analysis, the level of all these movements should increase and/or decrease together. This is because they are highly correlated to each other. If any of these non-critical movements has maximum of one observed level, this level should not be affected by the variation of other movements. Moreover, if one of these movements is found to be on a link having number of observed traffic levels that is less than the maximum number of levels for such link (in Reston Parkway, three levels for side streets and five for main arterial), the maximum level on this link should be applied for higher traffic levels of other links.

For the critical movements, traffic level for links where these movements belong vary regardless of what is happening to other link flow levels. This is also constrained by the maximum observed traffic level for links containing these critical movements. It is a very important point, since small correlation between certain movement and other movements in the network does not mean that such movement affects network performance significantly. Small correlation might happen for any movement while it has only one level, which should not be considered as significant as other movements having wide traffic level variation.

Table 3.2 Correlation Factors between Movements Entering Reston Parkway Arterial Network.

Movement	1 NBT	1 EBL	1 WBR	2 EBR	2 EBL	2 WBR	2 WBL	3 EBR	3 EBL	3 WBR	3 WBL	4 EBL	4 WBR	4 WBL	5 WBR	5 WBL	6 EBL	7 WBL	8 EBR	8 EBL	8 WBL	9 EBR	9 EBL	9 WBR	9 WBL	10 EBR	10 EBL	10 WBR	10 WBL	13 EBR	13 EBL	14 SBT	14 WBL
1 NBT	1.00	0.72	0.37	0.67	0.87	0.53	0.34	0.50	0.58	0.66	0.63	0.25	0.38	0.42	0.60	0.27	0.80	0.67	0.49	0.30	0.37	0.46	0.71	0.53	0.69	0.50	0.24	0.62	0.69	0.22	0.16	0.68	0.71
1 EBL	0.72	1.00	0.38	0.58	0.75	0.51	0.38	0.49	0.59	0.70	0.67	0.27	0.50	0.52	0.62	0.31	0.69	0.60	0.50	0.47	0.41	0.51	0.71	0.70	0.57	0.57	0.79	0.68	0.72	0.45	0.37	0.62	0.73
1 WBR	0.37	0.38	1.00	0.44	0.44	0.37	0.45	0.50	0.36	0.41	0.53	0.35	0.42	0.56	0.52	0.42	0.45	0.55	0.53	0.50	0.41	0.45	0.60	0.75	0.31	0.53	0.57	0.51	0.49	0.63	0.67	0.37	0.51
2 EBR	0.67	0.58	0.44	1.00	0.70	0.53	0.54	0.67	0.54	0.60	0.70	0.44	0.50	0.64	0.67	0.40	0.65	0.71	0.67	0.53	0.54	0.56	0.71	0.62	0.49	0.60	0.51	0.65	0.65	0.71	0.54	0.53	0.66
2 EBL	0.87	0.75	0.44	0.70	1.00	0.60	0.47	0.61	0.62	0.73	0.75	0.35	0.52	0.60	0.73	0.35	0.80	0.74	0.63	0.50	0.50	0.60	0.51	0.69	0.67	0.65	0.64	0.75	0.79	0.52	0.67	0.70	0.80
2 WBR	0.53	0.51	0.37	0.53	0.60	1.00	0.63	0.59	0.51	0.59	0.62	0.37	0.46	0.56	0.58	0.37	0.54	0.59	0.57	0.47	0.47	0.46	0.28	0.81	0.67	0.51	0.37	0.60	0.57	0.66	0.36	0.48	0.58
2 WBL	0.34	0.38	0.45	0.54	0.47	0.63	1.00	0.73	0.42	0.46	0.69	0.53	0.55	0.74	0.64	0.46	0.46	0.69	0.72	0.64	0.60	0.53	0.72	0.30	0.53	0.61	0.52	0.58	0.51	0.48	0.48	0.34	0.52
3 EBR	0.50	0.49	0.50	0.67	0.61	0.59	0.73	1.00	0.54	0.61	0.81	0.68	0.58	0.86	0.80	0.68	0.61	0.83	0.89	0.71	0.71	0.66	0.53	0.53	0.54	0.72	0.57	0.72	0.64	0.56	0.53	0.45	0.65
3 EBL	0.58	0.59	0.36	0.54	0.62	0.51	0.42	0.54	1.00	0.69	0.64	0.29	0.54	0.55	0.55	0.29	0.60	0.57	0.49	0.47	0.40	0.50	0.68	0.55	0.51	0.53	0.46	0.63	0.67	0.44	0.40	0.53	0.66
3 WBR	0.66	0.70	0.41	0.60	0.73	0.59	0.46	0.61	0.69	1.00	0.77	0.35	0.60	0.65	0.71	0.35	0.72	0.66	0.60	0.60	0.50	0.59	0.51	0.74	0.60	0.66	0.54	0.79	0.81	0.59	0.52	0.66	0.82
3 WBL	0.63	0.67	0.53	0.70	0.75	0.62	0.69	0.81	0.64	0.77	1.00	0.56	0.71	0.88	0.86	0.56	0.73	0.85	0.83	0.78	0.69	0.74	0.65	0.50	0.53	0.83	0.70	0.85	0.84	0.70	0.64	0.63	0.84
4 EBL	0.25	0.27	0.35	0.44	0.35	0.37	0.53	0.68	0.29	0.35	0.56	1.00	0.41	0.67	0.61	0.58	0.38	0.60	0.72	0.57	0.60	0.54	0.75	0.69	0.53	0.54	0.47	0.47	0.39	0.44	0.41	0.26	0.41
4 WBR	0.38	0.50	0.42	0.50	0.52	0.46	0.55	0.58	0.54	0.60	0.71	0.41	1.00	0.78	0.63	0.41	0.51	0.66	0.63	0.67	0.54	0.67	0.60	0.60	0.55	0.69	0.69	0.65	0.70	0.67	0.64	0.46	0.67
4 WBL	0.42	0.52	0.56	0.64	0.60	0.56	0.74	0.86	0.55	0.65	0.88	0.67	0.78	1.00	0.87	0.48	0.62	0.88	0.93	0.88	0.78	0.82	0.58	0.50	0.74	0.86	0.79	0.80	0.77	0.78	0.73	0.50	0.76
5 WBR	0.60	0.62	0.52	0.67	0.73	0.58	0.64	0.80	0.55	0.71	0.86	0.61	0.63	0.87	1.00	0.61	0.77	0.85	0.90	0.81	0.75	0.81	0.72	0.50	0.52	0.82	0.68	0.86	0.81	0.76	0.63	0.62	0.83
5 WBL	0.27	0.31	0.42	0.40	0.35	0.37	0.46	0.68	0.29	0.35	0.56	0.58	0.41	0.48	0.61	1.00	0.38	0.60	0.65	0.52	0.42	0.41	0.40	0.23	0.19	0.54	0.47	0.47	0.39	0.48	0.48	0.34	0.41
6 EBL	0.80	0.69	0.45	0.65	0.80	0.54	0.46	0.61	0.60	0.72	0.73	0.38	0.51	0.62	0.77	0.38	1.00	0.76	0.67	0.57	0.54	0.63	0.38	0.53	0.53	0.67	0.47	0.76	0.78	0.51	0.40	0.67	0.80
7 WBL	0.67	0.60	0.55	0.71	0.74	0.59	0.69	0.83	0.57	0.66	0.85	0.60	0.66	0.88	0.85	0.60	0.76	1.00	0.88	0.73	0.71	0.77	0.52	0.48	0.70	0.79	0.64	0.77	0.78	0.61	0.55	0.57	0.78
8 EBR	0.49	0.50	0.53	0.67	0.63	0.57	0.72	0.89	0.49	0.60	0.83	0.72	0.63	0.93	0.90	0.65	0.67	0.88	1.00	0.82	0.79	0.80	0.56	0.67	0.75	0.80	0.67	0.77	0.70	0.69	0.61	0.49	0.71
8 EBL	0.30	0.47	0.50	0.53	0.50	0.47	0.64	0.71	0.47	0.60	0.78	0.57	0.67	0.88	0.81	0.52	0.57	0.73	0.82	1.00	0.69	0.75	0.66	0.53	0.62	0.81	0.77	0.76	0.73	0.83	0.75	0.46	0.71
8 WBL	0.37	0.41	0.41	0.54	0.50	0.47	0.60	0.71	0.40	0.50	0.69	0.60	0.54	0.78	0.75	0.42	0.54	0.71	0.79	0.69	1.00	0.69	0.48	0.54	0.69	0.68	0.60	0.63	0.58	0.61	0.54	0.42	0.60
9 EBR	0.46	0.51	0.45	0.56	0.60	0.46	0.53	0.66	0.50	0.59	0.74	0.54	0.67	0.82	0.81	0.41	0.63	0.77	0.80	0.75	0.69	1.00	0.62	0.38	0.81	0.81	0.74	0.71	0.74	0.75	0.62	0.51	0.71
9 EBL	0.71	0.71	0.60	0.71	0.51	0.28	0.72	0.53	0.68	0.51	0.65	0.75	0.60	0.58	0.72	0.40	0.38	0.52	0.56	0.66	0.48	0.62	1.00	0.38	0.18	0.65	0.71	0.52	0.53	0.66	0.59	0.31	0.51
9 WBR	0.53	0.70	0.75	0.62	0.69	0.81	0.30	0.53	0.55	0.74	0.50	0.69	0.60	0.50	0.50	0.23	0.53	0.48	0.67	0.53	0.54	0.38	0.38	1.00	0.55	0.42	0.32	0.51	0.52	0.32	0.26	0.47	0.54
9 WBL	0.69	0.57	0.31	0.49	0.67	0.44	0.29	0.40	0.51	0.60	0.53	0.19	0.35	0.38	0.52	0.19	0.63	0.50	0.39	0.32	0.31	0.38	0.18	0.55	1.00	0.42	0.26	0.57	0.60	0.30	0.22	0.55	0.60
10 EBR	0.50	0.57	0.53	0.60	0.65	0.51	0.61	0.72	0.53	0.66	0.83	0.54	0.69	0.86	0.82	0.54	0.67	0.79	0.80	0.81	0.68	0.81	0.65	0.42	0.42	1.00	0.78	0.80	0.80	0.75	0.68	0.56	0.78
10 EBL	0.24	0.42	0.45	0.43	0.43	0.37	0.52	0.57	0.46	0.54	0.70	0.47	0.69	0.79	0.68	0.47	0.47	0.64	0.67	0.77	0.60	0.74	0.71	0.32	0.26	0.78	1.00	0.66	0.68	0.76	0.72	0.43	0.66
10 WBR	0.62	0.68	0.51	0.65	0.75	0.60	0.58	0.72	0.63	0.79	0.85	0.47	0.65	0.80	0.86	0.47	0.76	0.77	0.77	0.76	0.63	0.71	0.52	0.51	0.57	0.80	0.66	1.00	0.87	0.74	0.63	0.66	0.87
10 WBL	0.69	0.72	0.49	0.65	0.79	0.57	0.51	0.64	0.67	0.81	0.84	0.39	0.70	0.77	0.81	0.39	0.78	0.78	0.70	0.73	0.58	0.74	0.53	0.52	0.60	0.80	0.68	0.87	1.00	0.73	0.61	0.70	0.89
13 EBR	0.22	0.45	0.43	0.43	0.45	0.40	0.48	0.56	0.44	0.59	0.70	0.44	0.67	0.78	0.76	0.48	0.51	0.61	0.69	0.83	0.61	0.75	0.66	0.32	0.30	0.75	0.76	0.74	0.73	1.00	0.78	0.47	0.70
13 EBL	0.16	0.37	0.40	0.38	0.36	0.36	0.48	0.53	0.40	0.52	0.64	0.41	0.64	0.73	0.63	0.48	0.40	0.55	0.61	0.75	0.54	0.62	0.59	0.26	0.22	0.68	0.72	0.63	0.61	0.78	1.00	0.37	0.61
14 SBT	0.68	0.62	0.37	0.53	0.70	0.48	0.34	0.45	0.53	0.66	0.63	0.26	0.46	0.50	0.62	0.34	0.67	0.57	0.49	0.46	0.42	0.51	0.31	0.47	0.55	0.56	0.43	0.66	0.70	0.47	0.37	1.00	0.72
14WBL	0.71	0.73	0.51	0.66	0.80	0.58	0.52	0.65	0.66	0.82	0.84	0.41	0.67	0.76	0.83	0.41	0.80	0.78	0.71	0.71	0.60	0.71	0.51	0.54	0.60	0.78	0.66	0.87	0.89	0.70	0.61	0.72	1.00

- *Red cells contain correlation factors more than 0.50 which is considered the threshold between highly correlated movements and uncorrelated movements.*
- *Headers in the first columns and first row indicate intersection number then movement, for example “8 EBR” means intersection number 8 and east bound right movement.*
- *NB, SB, WB, and EB refer to north bound, south bound, west bound, and east bound respectively.*
- *L, T, and R refer to left movement, through movement, and right movement respectively.*

Table 3.3 Correlation Factors between Side Streets through Movements in Reston Parkway Arterial Network.

Movement	1 EBT	1 WBT	3 EBT	3 WBT	4 WBT	5 EBT	5 WBT	8 EBT	8 WBT	9 EBT	9 WBT	10 EBT	10 WBT	14 EBT	14 WBT
1 EBT	1.00	0.92	0.73	0.71	0.56	0.70	0.66	0.79	0.64	0.61	0.84	0.69	0.79	0.81	0.76
1 WBT	0.92	1.00	0.84	0.82	0.68	0.76	0.75	0.83	0.76	0.64	0.73	0.81	0.86	0.92	0.88
3 EBT	0.73	0.84	1.00	0.84	0.73	0.68	0.70	0.70	0.75	0.72	0.68	0.81	0.78	0.88	0.85
3 WBT	0.71	0.82	0.84	1.00	0.73	0.65	0.69	0.69	0.72	0.63	0.70	0.79	0.77	0.85	0.84
4 WBT	0.56	0.68	0.73	0.73	1.00	0.51	0.57	0.53	0.61	0.62	0.37	0.71	0.63	0.73	0.74
5 EBT	0.70	0.76	0.68	0.65	0.51	1.00	0.91	0.92	0.92	0.34	0.49	0.83	0.77	0.83	0.77
5 WBT	0.66	0.75	0.70	0.69	0.57	0.91	1.00	0.89	0.91	0.29	0.75	0.86	0.78	0.83	0.80
8 EBT	0.79	0.83	0.70	0.69	0.53	0.92	0.89	1.00	0.86	0.25	0.70	0.81	0.85	0.85	0.80
8 WBT	0.64	0.76	0.75	0.72	0.61	0.92	0.91	0.86	1.00	0.70	0.69	0.89	0.77	0.87	0.84
9 EBT	0.61	0.64	0.72	0.63	0.62	0.34	0.29	0.25	0.70	1.00	0.75	0.80	0.65	0.34	0.30
9 WBT	0.84	0.73	0.68	0.70	0.37	0.49	0.75	0.70	0.69	0.75	1.00	0.46	0.63	0.77	0.55
10 EBT	0.69	0.81	0.81	0.79	0.71	0.83	0.86	0.81	0.89	0.80	0.46	1.00	0.79	0.89	0.87
10 WBT	0.79	0.86	0.78	0.77	0.63	0.77	0.78	0.85	0.77	0.65	0.63	0.79	1.00	0.87	0.87
14 EBT	0.81	0.92	0.88	0.85	0.73	0.83	0.83	0.85	0.87	0.34	0.77	0.89	0.87	1.00	0.94
14 WBT	0.76	0.88	0.85	0.84	0.74	0.77	0.80	0.80	0.84	0.30	0.55	0.87	0.87	0.94	1.00

- *Red cells contain correlation factors more than 0.60 which is considered the threshold between highly correlated movements and uncorrelated movements.*
- *Headers in the first columns and first row indicate intersection number then movement, for example "8 EBT" means intersection number 8 and east bound through movement.*
- *WB and EB refer to west bound, and east bound respectively.*
- *"T" refers to through movement.*

Applying this constrains to the five critical movements obtained from correlation analysis, it is found that the east bound left turn movement at the fourth intersection is belonging to a link having only one traffic level. This means, variation of such movement is not expected to have significant effect on the network. Thus, the east bound left turn movement at the fourth intersection is excluded as it is not a significant critical movement.

The other four movements are found on links having wide range of traffic level variation. Therefore, they are expected to affect the network significantly. However, it needs some more verification. Synthetic O-D provides this verification. It provides distribution percentages for each movement in the network which consequently confirm the significance of such movements. It is important to note that, the correlation analysis does not include all possible movements because it is based on the actual detector data which sometimes cannot inform about traffic volume for right turns and left turns in case of shared lanes. Some of these shared right and/or left movements can be significant critical movements based on their distribution percentages. Synthetic O-D provides a good tool to determine such missing movements.

Synthetic O-D analysis for Reston Parkway arterial network is performed based on the actual detector data. QUEENSO-D software *(32)* is used to perform the required synthetic analysis. One run is done for each traffic level combination of all links subjected to the maximum observed link flow as discussed before.

Synthetic O-D analysis not only provides the distribution percentages for each movement, but also gives the distribution percentages for traffic entering the network from each origin node over all destination nodes. Figure 3.1 includes node numbers used in QUEENSO-D runs. These origin-destination percentages are important since it gives an idea to which major movements in the network are significant. These distribution percentages are expected to change over the day and since time of day is represented here with the traffic level on the network at such time, these distribution percentages are determined for each traffic level. Table 3.4 through Table 3.7 present the distribution percentages for different traffic levels.

Table 3.4 Distribution Percentages for Side Street: Traffic Level 1.

		DESTENATION NODES																											Total % per movement		
		1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25	36	37	L	T	R
ORIGIN NODES	1	-	19.8	34.9	2.8	1.8	1.2	5.4	2.9	0.0	0.0	5.9	2.9	3.6	2.4	1.9	2.7	1.4	0.9	0.0	0.2	0.7	1.1	2.2	0.8	4.5	0.0	0.0	45.2	34.9	19.8
	3	31.1	16.0	-	4.8	2.8	2.1	6.2	3.5	0.0	0.0	6.3	3.2	3.7	2.5	2.1	2.8	1.5	1.0	0.0	0.4	0.8	1.2	2.3	1.0	4.8	0.0	0.0	16.0	31.1	52.9
	4	0.0	12.1	0.0	-	2.7	0.8	12.8	6.1	0.0	0.0	13.4	6.2	7.7	4.9	4.0	5.6	2.7	1.5	0.0	0.2	1.1	2.1	4.6	1.3	10.0	0.0	0.0	12.1	-	87.9
	5	18.0	15.0	12.9	13.4	-	0.4	7.7	3.5	0.0	0.0	6.5	2.9	3.3	2.1	1.7	2.4	1.1	0.6	0.0	0.0	0.4	0.8	1.9	0.5	4.7	0.0	0.0	59.2	0.4	40.4
	6	20.1	20.7	14.3	9.5	0.0	-	5.8	0.0	0.0	0.0	8.3	1.9	4.4	2.0	1.5	2.8	0.5	0.0	0.0	0.0	0.0	0.3	2.3	0.0	5.6	0.0	0.0	35.3	0.0	64.7
	7	0.0	3.0	0.0	0.0	0.0	0.0	-	17.1	0.0	0.0	17.0	9.0	7.9	5.5	4.4	6.0	3.1	2.2	0.2	0.9	1.7	2.4	4.6	2.8	12.1	0.0	0.0	79.9	17.1	3.0
	8	0.8	3.5	0.0	0.0	0.0	0.0	36.3	-	0.0	0.9	11.3	6.8	5.3	4.0	3.2	4.1	2.4	1.9	0.7	1.1	1.5	1.9	3.2	2.8	8.2	0.0	0.0	4.3	36.3	59.4
	9	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	-	0.0	52.3	0.0	16.5	0.0	0.0	4.7	0.0	0.0	0.0	0.0	0.0	0.0	4.7	0.0	21.9	0.0	0.0	100.0	0.0	0.0
	10	0.0	0.7	0.0	0.0	0.0	0.0	0.2	0.0	1.0	-	34.8	8.5	11.3	5.5	3.8	7.0	1.4	0.0	0.0	0.0	0.0	0.8	5.3	0.0	19.7	0.0	0.0	0.9	1.0	98.1
	11	4.2	5.7	3.3	1.7	0.0	0.0	11.7	8.3	6.8	13.4	-	15.4	2.9	0.5	0.1	1.3	0.0	0.0	0.0	0.0	0.0	0.0	1.0	0.0	5.4	0.2	18.1	11.2	15.4	73.4
	12	3.1	4.0	2.6	1.6	0.0	0.0	7.7	5.8	5.2	8.7	25.0	-	3.8	2.4	1.8	2.7	1.1	0.5	0.0	0.0	0.3	0.7	1.9	0.5	8.6	0.9	11.1	50.7	25.0	24.3
	13	3.3	7.1	2.2	0.0	0.0	0.0	10.1	5.7	0.0	4.7	0.0	0.0	-	6.9	0.0	15.2	0.0	0.0	0.0	0.0	11.9	0.0	17.8	10.5	0.0	0.0	4.6	44.9	6.9	48.2
	14	2.1	6.8	0.9	0.0	0.0	0.0	9.5	4.3	0.0	2.4	0.0	0.0	30.8	-	0.0	2.3	0.0	0.0	0.0	0.0	0.0	0.0	2.0	31.9	0.0	0.0	7.0	64.9	30.8	4.3
	15	1.6	2.4	1.3	0.6	0.0	0.0	3.3	2.3	1.1	2.3	0.9	0.0	7.5	3.1	-	15.3	10.5	10.5	3.1	3.8	4.5	5.1	8.5	9.1	0.0	0.0	3.2	45.9	15.3	38.8
	16	3.4	6.9	2.3	0.0	0.0	0.0	9.5	5.6	0.0	4.6	0.0	0.0	10.4	0.0	12.9	-	0.0	0.0	0.0	0.0	0.0	0.0	10.6	25.8	0.0	0.0	8.0	76.4	12.9	10.6
	17	1.4	3.8	0.7	0.0	0.0	0.0	5.0	2.5	0.0	1.6	0.0	0.0	1.1	0.0	4.3	13.9	-	11.3	0.0	2.6	6.3	9.2	21.0	11.5	0.0	0.0	3.7	39.1	11.3	49.6
	18	0.5	4.2	0.0	0.0	0.0	0.0	5.5	1.8	0.0	0.0	0.0	0.0	0.0	0.0	0.0	12.2	29.0	-	0.0	0.0	1.3	6.6	23.3	12.4	0.0	0.0	3.2	39.8	29.0	31.2
	19	0.0	2.1	0.0	0.0	0.0	0.0	2.2	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	-	0.0	9.1	20.3	62.9	3.3	0.0	0.0	0.0	92.3	0.0	7.7
	20	0.1	2.8	0.0	0.0	0.0	0.0	3.4	0.9	0.0	0.0	0.0	0.0	0.0	0.0	0.0	4.5	4.5	0.0	8.6	-	15.8	18.2	33.3	6.2	0.0	0.0	1.7	24.1	8.6	67.2
	21	0.9	2.3	0.5	0.0	0.0	0.0	2.9	1.5	0.0	1.0	0.0	0.0	0.8	0.0	1.9	5.5	7.0	3.6	7.1	6.6	-	20.4	30.0	5.5	0.0	0.0	2.2	30.0	20.4	49.6
	22	1.2	2.8	0.7	0.0	0.0	0.0	3.5	1.9	0.0	1.3	0.0	0.0	1.1	0.0	2.2	5.9	6.9	3.8	6.4	6.7	16.5	-	30.4	6.2	0.0	0.0	2.6	53.1	16.5	30.4
	36	0.0	0.2	0.0	0.0	0.0	0.0	0.1	0.0	0.7	4.3	18.9	12.2	7.7	6.1	4.9	6.1	3.8	3.2	1.5	2.0	2.5	2.9	4.6	5.1	13.3	-	0.0	0.3	-	99.7
	37	0.0	4.6	0.0	0.0	0.0	0.0	8.0	0.0	0.0	0.0	30.0	0.9	15.2	4.7	2.7	8.2	0.0	0.0	0.0	0.0	0.0	0.0	7.1	0.0	18.6	0.0	-	87.4	-	12.6
	38	0.0	7.0	0.0	0.0	0.0	0.0	9.5	0.0	0.0	0.0	0.0	0.0	20.9	0.0	0.3	5.3	0.0	0.0	0.0	0.0	0.0	0.0	4.8	52.1	0.0	0.0	0.0	16.5	52.1	31.4
	39	4.9	5.7	4.2	3.3	1.3	1.1	10.6	8.5	9.0	12.5	12.1	8.2	0.8	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	2.9	14.9	0.8	0.0	99.2

- *the “-“ sign refers to unavailable movement*

Table 3.5 Distribution Percentages for Side Street: Traffic Level 2.

ORIGIN NODES	DESTENATION NODES																											Total % per movement		
	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25	36	37	L	T	R
1	-	22.1	36.5	3.5	2.5	1.9	3.9	2.4	0.0	0.0	3.9	3.9	3.5	1.6	1.4	1.4	0.1	0.0	0.0	0.0	1.0	0.9	5.3	0.0	3.9	0.0	0.0	41.4	36.5	22.1
3	34.3	19.1	-	4.8	3.0	2.4	4.4	2.7	0.0	0.0	4.3	4.3	3.8	1.8	1.5	1.5	0.1	0.0	0.0	0.0	1.1	1.0	5.6	0.0	4.2	0.0	0.0	19.1	34.3	46.6
7	0.0	4.2	0.0	0.0	0.0	0.0	-	20.5	0.0	0.0	12.9	13.0	8.8	4.3	3.6	3.7	0.4	0.1	0.0	0.3	2.5	2.2	12.0	0.0	11.6	0.0	0.0	75.3	20.5	4.2
8	0.0	3.0	0.0	0.0	0.0	0.0	36.0	-	0.0	0.0	10.3	10.3	6.9	3.5	2.9	3.0	0.6	0.3	0.0	0.4	2.1	1.8	9.2	0.5	9.2	0.0	0.0	3.0	36.0	61.1
10	5.3	12.9	3.7	0.0	0.0	0.0	15.6	8.6	0.0	-	10.2	10.2	8.4	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	15.5	0.0	9.6	0.0	0.0	46.1	0.0	53.9
11	2.3	3.6	1.9	0.3	0.0	0.0	5.1	3.8	1.8	5.0	-	32.4	5.4	3.5	2.8	2.9	1.3	1.2	0.8	1.0	1.9	1.7	5.7	2.7	11.6	0.0	1.0	42.5	32.4	25.0
12	2.1	3.1	1.7	0.5	0.0	0.0	4.2	3.3	1.9	4.0	28.1	-	5.6	4.1	3.3	3.5	1.9	1.8	1.4	1.6	2.2	2.1	5.4	4.2	12.5	0.3	1.2	22.3	28.1	49.6
13	2.6	3.6	3.4	1.4	0.0	0.0	4.1	4.9	2.8	3.7	5.7	3.8	-	5.6	0.7	0.6	8.0	0.0	0.0	0.0	12.3	0.0	25.0	5.5	3.0	1.2	2.3	46.5	5.6	47.9
14	2.9	4.8	2.5	0.4	0.0	0.0	4.9	3.6	1.1	3.1	4.8	4.9	25.1	-	3.1	3.6	0.0	0.0	0.0	0.0	0.9	0.6	16.2	16.0	0.7	0.0	0.9	50.6	25.1	24.3
15	1.3	2.2	1.1	0.2	0.0	0.0	2.2	1.6	0.5	1.3	2.0	2.1	5.8	1.1	-	9.3	9.5	11.2	5.9	5.8	7.3	6.4	16.5	5.6	0.3	0.0	0.4	62.7	9.3	28.0
16	2.9	7.2	2.2	0.0	0.0	0.0	5.7	3.3	0.0	1.0	3.5	3.6	6.1	0.0	1.1	-	0.0	0.0	0.0	0.0	3.2	2.2	44.2	13.9	0.0	0.0	0.0	49.3	1.1	49.5
17	1.7	3.9	1.3	0.0	0.0	0.0	3.1	1.9	0.0	0.7	2.0	2.1	3.0	0.0	2.6	7.2	-	7.5	0.0	2.1	8.7	7.1	38.5	6.6	0.0	0.0	0.0	56.5	7.5	36.0
18	1.6	4.7	1.2	0.0	0.0	0.0	3.4	1.8	0.0	0.1	1.7	1.8	1.4	0.0	0.0	6.4	7.7	-	0.0	0.0	7.9	6.3	47.0	7.0	0.0	0.0	0.0	31.1	7.7	61.2
20	1.2	3.2	0.9	0.0	0.0	0.0	2.3	1.3	0.0	0.2	1.2	1.2	0.9	0.0	0.2	3.0	3.1	2.2	10.3	-	12.4	10.3	42.3	3.9	0.0	0.0	0.0	24.8	10.3	65.0
21	1.5	3.3	1.2	0.0	0.0	0.0	2.6	1.6	0.0	0.8	1.7	1.7	2.1	0.0	1.8	4.1	5.0	3.9	7.4	7.5	-	8.6	40.9	4.5	0.0	0.0	0.0	40.9	8.6	50.5
22	1.8	5.5	1.2	0.0	0.0	0.0	3.7	1.9	0.0	0.0	1.5	1.6	0.7	0.0	0.0	3.8	3.3	2.3	4.3	8.1	8.8	-	46.0	5.7	0.0	0.0	0.0	45.2	8.8	46.0
36	2.9	6.0	2.2	0.0	0.0	0.0	7.3	4.6	0.0	2.2	13.2	13.2	7.4	4.2	3.4	3.6	1.1	0.9	0.5	0.9	2.4	2.2	9.1	1.6	11.1	-	0.0	23.1	-	76.9
39	4.0	4.8	3.6	2.6	1.5	1.4	7.2	6.3	7.0	8.9	14.9	15.0	3.3	1.1	0.8	0.8	0.0	0.0	0.0	0.0	0.4	0.3	4.2	0.0	3.9	2.9	5.1	11.1	3.9	85.1

- *the “-“ sign refers to unavailable movement*

Table 3.6 Distribution Percentages for Side Street: Traffic Level 3.

		DESTENATION NODES																											Total % per movement		
		1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25	36	37	L	T	R
ORIGIN NODES	1	-	17.2	33.0	2.2	3.6	3.1	3.8	2.9	0.0	0.0	3.0	5.2	4.6	3.0	1.7	2.2	0.4	2.0	0.1	0.4	1.1	0.9	2.8	2.2	4.9	0.0	0.0	49.9	33.0	17.2
	3	26.9	14.8	-	3.6	4.8	4.2	4.5	3.4	0.0	0.0	3.3	5.8	4.9	3.3	1.8	2.4	0.5	2.1	0.2	0.4	1.2	1.0	2.9	2.4	5.4	0.0	0.0	14.8	26.9	58.3
	8	2.1	4.0	1.6	0.0	0.0	0.0	31.9	-	0.0	1.2	6.3	10.2	6.6	4.7	2.7	3.4	1.0	3.0	0.6	0.9	1.7	1.5	3.8	4.1	8.7	0.0	0.0	7.7	31.9	60.4
	11	4.1	4.7	3.7	3.0	2.2	2.0	8.1	7.1	5.4	8.8	-	28.3	4.2	1.7	0.0	0.5	0.0	0.4	0.0	0.0	0.0	0.0	1.6	0.0	6.9	1.2	6.2	15.3	28.3	56.5
	12	5.0	6.0	4.5	3.2	1.8	1.5	9.6	8.1	3.7	7.9	2.9	-	7.9	4.6	1.5	2.6	0.0	2.1	0.0	0.0	0.5	0.3	3.5	2.8	13.6	0.3	6.1	57.7	2.9	39.4
	13	3.1	3.6	2.9	2.4	1.9	1.8	4.5	4.1	2.7	3.7	0.3	4.5	-	0.0	3.6	6.6	16.4	4.2	0.0	0.0	0.9	0.6	19.7	4.7	3.0	1.3	3.3	52.2	0.0	47.8
	14	3.4	4.6	3.1	1.9	0.7	0.5	5.3	4.4	0.7	2.6	0.0	3.6	29.7	-	0.0	3.8	0.0	2.1	0.0	0.0	0.0	0.0	5.8	25.4	0.0	0.0	2.6	58.7	29.7	11.7
	15	2.1	2.8	1.9	1.2	0.5	0.4	3.2	2.7	0.6	1.7	0.0	2.2	7.5	1.6	-	9.9	5.2	16.3	2.8	3.3	5.2	4.4	10.8	12.0	0.1	0.0	1.6	48.0	9.9	42.1
	21	1.8	3.2	1.6	0.3	0.0	0.0	2.9	2.1	0.0	0.1	0.0	0.5	0.9	0.0	0.8	6.1	6.7	34.7	0.0	0.0	-	7.0	21.8	9.0	0.0	0.0	0.3	21.8	7.0	71.2
	39	5.7	6.2	5.3	4.5	3.9	3.7	10.0	9.0	8.0	10.7	2.7	17.1	1.9	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	3.0	8.4	1.9	0.0	98.1

- *the "-" sign refers to unavailable movement*

Table 3.7 Distribution Percentages for Main Arterial: Different Traffic Levels.

		DESTENATION NODES																											Total % per movement		
Main Arterial Level 1																															
		1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25	36	37	L	T	R
ORIGIN	2	14.4	-	17.1	5.5	4.0	3.5	6.9	4.4	0.0	0.0	7.2	4.1	4.6	3.3	2.8	3.6	2.1	1.6	0.4	0.8	1.3	1.7	3.0	1.8	5.7	0.0	0.0	14.4	68.6	17.1
NODES	23	1.5	2.4	1.2	0.3	0.0	0.0	3.1	2.1	0.7	1.9	0.4	0.0	3.1	1.1	4.6	6.8	9.4	6.9	11.6	8.5	15.0	10.9	-	6.0	0.0	0.0	2.7	10.9	74.1	15.0
Main Arterial Level 2																															
ORIGIN	2	12.8	-	16.3	8.3	5.4	5.3	5.1	4.9	1.8	2.3	4.2	3.9	3.1	2.5	2.0	2.5	1.7	1.6	1.2	1.3	1.5	1.6	2.7	2.1	4.0	1.7	0.1	12.8	70.9	16.3
NODES	23	1.9	3.0	1.5	0.6	0.0	0.0	2.8	2.2	0.7	1.4	2.7	2.7	3.1	0.5	5.6	5.9	9.5	8.1	13.7	10.7	13.2	4.0	-	5.0	0.8	0.4	0.2	4.0	82.8	13.2
Main Arterial Level 3																															
ORIGIN	2	13.5	-	17.5	13.1	6.9	6.9	4.1	3.4	1.7	2.1	3.0	2.9	2.1	1.9	1.7	1.9	1.4	1.8	1.1	1.2	1.3	1.2	1.7	1.8	2.8	2.2	1.0	13.5	69.1	17.5
NODES	23	1.5	1.4	1.4	1.3	1.4	1.4	1.9	1.8	2.1	2.1	3.2	2.3	3.7	2.7	5.3	6.0	7.8	6.4	11.0	6.9	11.6	5.0	-	6.7	2.3	0.9	1.8	5.0	83.4	11.6
Main Arterial Level 4																															
ORIGIN	2	13.5	-	17.5	13.1	6.9	6.9	4.1	3.4	1.7	2.1	3.0	2.9	2.1	1.9	1.7	1.9	1.4	1.8	1.1	1.2	1.3	1.2	1.7	1.8	2.8	2.2	1.0	13.5	69.1	17.5
NODES	23	1.6	1.4	1.4	1.2	1.4	1.4	2.1	2.1	1.9	2.2	3.5	2.3	4.3	3.0	5.6	6.1	8.8	7.5	11.3	7.3	9.9	4.7	-	5.6	0.6	1.1	1.8	4.7	85.5	9.9
Main Arterial Level 5																															
ORIGIN	2	13.5	-	17.5	13.1	6.9	6.9	4.1	3.4	1.7	2.1	3.0	2.9	2.1	1.9	1.7	1.9	1.4	1.8	1.1	1.2	1.3	1.2	1.7	1.8	2.8	2.2	1.0	13.5	69.1	17.5
NODES	23	1.6	1.5	1.5	1.4	1.5	1.5	2.0	2.1	2.3	2.4	3.4	2.4	5.0	3.8	6.0	6.2	8.2	7.3	10.9	7.1	8.4	3.7	-	5.6	1.1	1.1	2.0	3.7	87.9	8.4

- *the "-" sign refers to unavailable movement*

3.6.4. Determination of Significant Critical Movements

To finally determine the significant critical movements for Reston Parkway network, both the correlation analysis and the synthetic O-D analysis were considered and analyzed at the same time. Each one of these two analyses has an advantage that the other one lacks.

For Reston Parkway, it was found that five movements were not correlated to any other movements. One of those five movements, the east bound left turn movement at the fourth intersection, was found to be on a link having only one traffic level. Thus, it has been excluded. The other four movements were considered critical.

Synthetic O-D analysis confirms that the remaining four movements have a great effect on the network since each one of them has high distribution percentage for the traffic coming from the link it belongs to. Moreover, from Table 3.4 through Table 3.6, another movement which is west bound right at intersection number seven (not shown in the correlation analysis due to being a shared right turn) is found to be significant to the network. The distribution percentage for this movement is found to be very high (85% and more). In addition, it belongs to a link having three traffic levels. This movement is then confirmed with Virginia department of transportation (VDOT) to be a significant critical movement.

Synthetic O-D analysis also shows other movements that belong to links with three or two traffic levels and have high distribution percentages such as east bound right turn movement at the third intersection, west bound left turn movement at the fourth intersection, west bound right turn movement at the fifth intersection. Although these movements have satisfied the required two conditions for being significant critical movements, they were not considered as significant as they appear. This can be explained from the correlation analysis since all these movements are highly correlated to each other. In other words, their levels increase and/or decrease together therefore they are considered non-critical movements from the beginning.

Thus, the final significant critical movements for Reston Parkway network are as follows: north bound through and the west bound right at the first intersection, west bound left at the fifth intersection, west bound right at the seventh intersection and the south bound through at the last intersection. Figure 3.6 shows major movements for each one of the selected critical movements. These major movements are determined based on the distribution percentages obtained from the synthetic O-D.

3.7.Validation of the Proposed Approach

Using those five significant critical movements obtained by combining the correlation analysis results with synthetic O-D results and the distribution percentage for traffic entering the network from each origin node over all destinations for all possible traffic levels combinations, different traffic patterns were generated. These patterns were to be used to obtain timing plans to be implemented in the entire network. The selection of timing plans is beyond the scope of this chapter.

The obtained traffic patterns should be verified before using them to obtain timing plans. This verification aims to make sure that these patterns are not significantly different from the actual patterns on the network. The validation process was performed by comparing the obtained traffic patterns to the actual detector data.

Table 3.8 and Table 3.9 show some of the obtained traffic patterns and how they match with the actual detector data. These two tables show very small difference between the obtained traffic patterns using the proposed approach and the actual traffic pattern obtained from detector data.

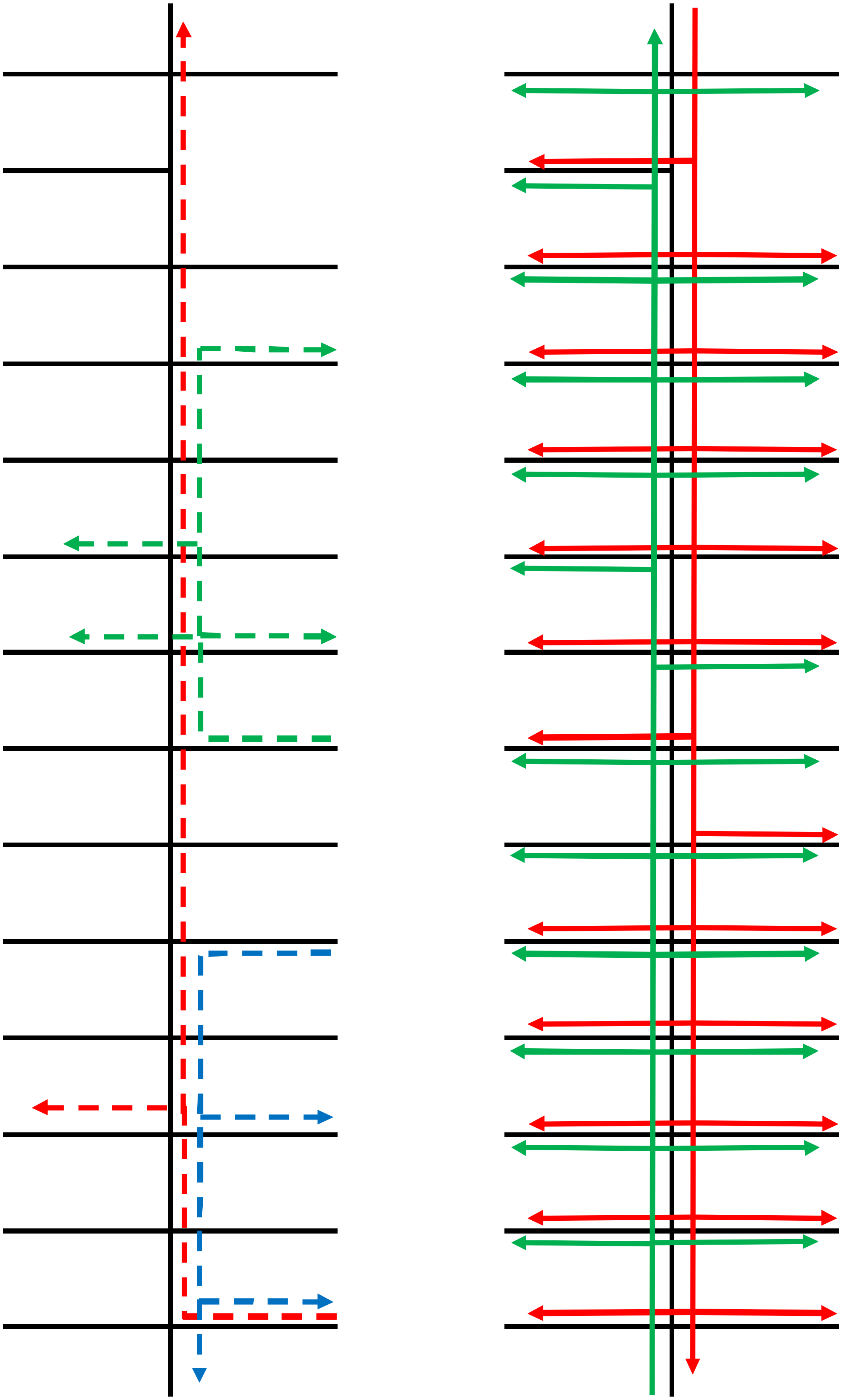

Figure 3.6 Major Distributions of the Critical Traffic Movements in Reston Parkway Network

Table 3.8 Example for One Traffic Pattern Generated Using Proposed Approach.

Intersection	East bound			West bound			North bound			South bound		
	L	T	R	L	T	R	L	T	R	L	T	R
1	172	54	100	98	67	161	39	261	54	164	724	251
2	76	29	221	303	0	23	74	434	86	23	615	43
3	128	95	103	129	37	160	50	388	95	107	449	86
4	248	43	35	154	50	122	164	465	47	124	453	240
5	210	101	15	24	56	246	19	734	82	395	778	160
6	51	0	105	-	-	-	-	686	504	0	1228	-
7	-	-	-	3	0	323	0	822	-	-	1277	454
8	171	82	84	40	51	244	27	1079	46	688	1607	210
9	4	4	324	329	0	0	179	1237	78	3	1852	18
10	-	-	333	-	-	43	-	935	291	-	1251	0
11	15	119	200	269	56	10	175	447	355	142	782	79
12	195	2	140	120	0	213	5	466	4	29	754	37
13	40	-	293	-	-	-	103	771	-	-	534	26
14	53	102	171	147	65	114	161	423	227	51	242	61

- *The "-" sign refers to movement that does not exist,*
- *L, T and R refer to left, through and right turns respectively*

Table 3.9 Actual Traffic Pattern Obtained from Detector Data.

Intersection	East bound			West bound			North bound			South bound		
	L	T	R	L	T	R	L	T	R	L	T	R
1	150	38	106	105	50	130	67	228	25	153	637	190
2	80	15	184	287	0	34	61	394	73	18	545	63
3	94	115	89	121	35	143	64	374	126	84	429	92
4	250	63	40	163	53	116	153	450	62	110	402	212
5	195	104	2	34	60	263	15	752	74	375	743	164
6	56	0	105	-	-	-	-	720	482	0	1194	-
7	-	-	-	15	0	303	0	796	-	-	1279	465
8	163	94	55	34	41	216	9	1104	52	649	1573	197
9	0	10	293	352	0	0	183	1173	64	0	1903	7
10	-	-	314	-	-	54	-	896	224	-	1200	0
11	20	104	195	253	47	0	162	427	374	152	752	63
12	178	14	136	120	0	273	10	354	0	24	743	26
13	36	-	257	-	-	-	85	738	-	-	491	17
14	37	94	174	129	55	97	153	387	296	47	219	51

- *The "-" sign refers to movement that does not exist,*
- *L, T and R refer to left, through and right turns respectively*

3.8.Summary

Generation of traffic patterns is a very important step for different traffic engineering applications. For small arterial networks having up to five or six intersections, all possible traffic patterns can be considered since the computations are do-able and the assumption of equally traffic distribution for traffic generated from each origin over all destinations is acceptable to certain degree.

For large arterial networks, it is impossible to consider all traffic combinations. The computations will be time consuming. Moreover, the equally traffic distribution assumption is not acceptable. The proposed approach is to simplify the process of generating traffic patterns for large networks.

Correlation analysis and synthetic O-D analysis were used together to obtain what is called significant critical movements defined as the movements that are not correlated to any other movements and spanning a wide range of traffic variation. Significant critical movement concept has been implemented in the generation of traffic scenarios for Reston Parkway network and the obtained traffic scenarios were validated with the actual detector data. This approach shows great results compared to the actual traffic data.

This chapter presented a methodology for the generation of "design" traffic scenarios on large arterial network. The generated scenarios can be used to determine the timing plans on the network for either time-of-day or traffic responsive control modes.

Acknowledgements

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Chapter 4 : Evaluation of Pattern Matching Traffic Responsive Control Mode in a Large Arterial Network

4.1.Abstract

Traffic responsive control is considered as one of the effective operational modes in traffic signal systems. Capturing variations in traffic patterns and switching timing plans based on exiting traffic conditions gives the traffic responsive mode an advantage over other coordination modes such as time of day (TOD). This chapter summarizes the steps that were conducted to determine a pattern-matching based 170 controller traffic responsive parameters and timing plans for Reston Parkway arterial network in Northern Virginia. Simulation analysis revealed that implementation of traffic responsive control mode in Reston Parkway network can achieve an average saving of 26.94% for delay and 14.45% for stops in weekends and 17.72% for delay and 21.13% for stops in regular week days, respectively.

4.2.Introduction

This chapter evaluates the impact of implementing traffic responsive control mode in a larger arterial network in Northern Virginia (Reston Parkway). The chapter describes the analysis steps to determine timing plans for traffic responsive control and the parameters required to operate the entire system.

Reston Parkway network consists of fourteen intersections and it is 16572 ft in length. Speed limit for the main arterial is 45 mph. 170's controllers are being used to control the network. These controllers use the pattern matching mechanism to implement traffic responsive control mode. Time-of-day (TOD) mode of operation is the control method currently implemented in Reston Parkway network. Different traffic scenarios are generated based on the actual detector data obtained form system detectors in the network. Timing plans with different cycle lengths, offsets and splits are obtained for each traffic scenario using PASSER optimization package.

Mutli-objective genetic algorithms optimization and supervised discriminate analysis are used to select the best timing plans for traffic responsive control mode. Considering these timing plans, traffic responsive control parameters are determined to minimize several performance objectives (delay, stops, and transitioning effects).

The obtained timing plans and parameters were verified using actual traffic scenario for one weekend (April 5th 2008), and one regular week day (April 9th 2008). Simulation results showed that using traffic responsive control in Reston Parkway achieved an average savings of 26.94% for delay and 14.45% for stops over the week end, while for the week day, an average saving of 17.72% for delay and 21.13% for stops were achieved.

4.3.Overview for Traffic Responsive Control

The traffic responsive control mode has the ability to switch timing plans according to traffic variations. This concept strives to apply the most appropriate timing plan for existing traffic pattern to increase the overall system performance. In order to implement traffic responsive control mode, a set of system detectors should be spread around the network. Counts and occupancies of these system detectors are collected and aggregated to form cycle, offset, and split PS parameters for threshold mechanism or being used directly in the case of pattern matching mechanism *(6)*.

Considering actual traffic patterns when activating a timing plan provides the TRPS mode with a good advantage over the other control modes. Traffic responsive control mode switches the system's current plan to a better plan when unexpected events, incidents, or temporal changes in traffic volumes occur. In addition, traffic responsive control mode reduces the need for frequent redesign/update of the signal timing plans for new traffic patterns as required under the TOD control mode *(4)*.

Past research aimed to improve the performance of traffic responsive control mode as one of the most efficient signal system control modes. Fuzzy logic, approximate dynamic programming, and deterministic timed Petri nets are some examples for the techniques proposed to improve overall system performance *(11, 12, 13, and 14)*. Other research focused on selecting the most appropriate parameters for traffic responsive threshold mechanism such as using the principal components and discriminate analysis *(15)*, artificial neural networks and support vector machines *(16)*, decision-tree classifiers and various forms of nearest neighbor classification methods *(17)*, and modified linear discriminate analysis *(18)*.

Although several studies *(20, 21, and 22)* concluded that using traffic responsive control mode improves system efficiency by decreasing total system delay, traffic responsive control mode has not been commonly used because there were limited guidelines that describe design detail for traffic responsive control mode. Texas Transportation Institute (TTI) published a report published in 2005 to provide some guidelines for choosing all the important variables required for traffic responsive system *(4)*. This report provided a methodology for robust and optimal selection of traffic responsive parameters for the threshold mechanism. The report presents an innovative framework of traffic responsive system setup following a comprehensive approach that incorporates a multi-objective evolutionary algorithm and a supervised discriminate analysis. The developed guidelines were presented in simplified tables to facilitate their implementation. These guidelines were verified by using hardware-in-the loop simulations and field implementation.

4.4.Reston Parkway Arterial Network

Reston Parkway arterial network locates in Northern Virginia, USA. It is considered one of the most congested networks in Virginia. The network consists of fourteen intersections with a total length of 16572 ft. the spacing between intersections is ranging from 524 ft to 3309 ft. The speed limit for the main arterial is 45 mph and ranging from 15 mph to 45 mph for the side streets.

As shown in Figure 4.1, eleven intersections are four-leg intersections; intersection number 13 is three-leg intersection, while intersections numbers 6 and 7 are four-leg intersections with one-way side streets. Also, intersection number 10 has only right turn movements for the side streets i.e. no through or left turns from the side streets. This network has a great attractiveness competition between all destination nodes.

Actual detector data for this network are taken for a period of one month from April 5th, 2008 to May 6th, 2008. These detectors almost cover the whole network and have a record every 15 minutes.

Reston Parkway network is currently operated using TOD mode. In addition to the free control, five different timing plans control the entire network during regular week days and only one plan during weekends. The following sections present the details of the analysis done to implement traffic responsive control mode in Reston Parkway network.

170’s traffic controllers are used to operate the entire network and are planned to be used for setting up traffic responsive control in this network. The 170’s controllers use pattern matching algorithms for traffic responsive control mode. Thus, the final output for this chapter is the parameters required to set up such mechanism in Reston Parkway network in addition to optimum timing plans.

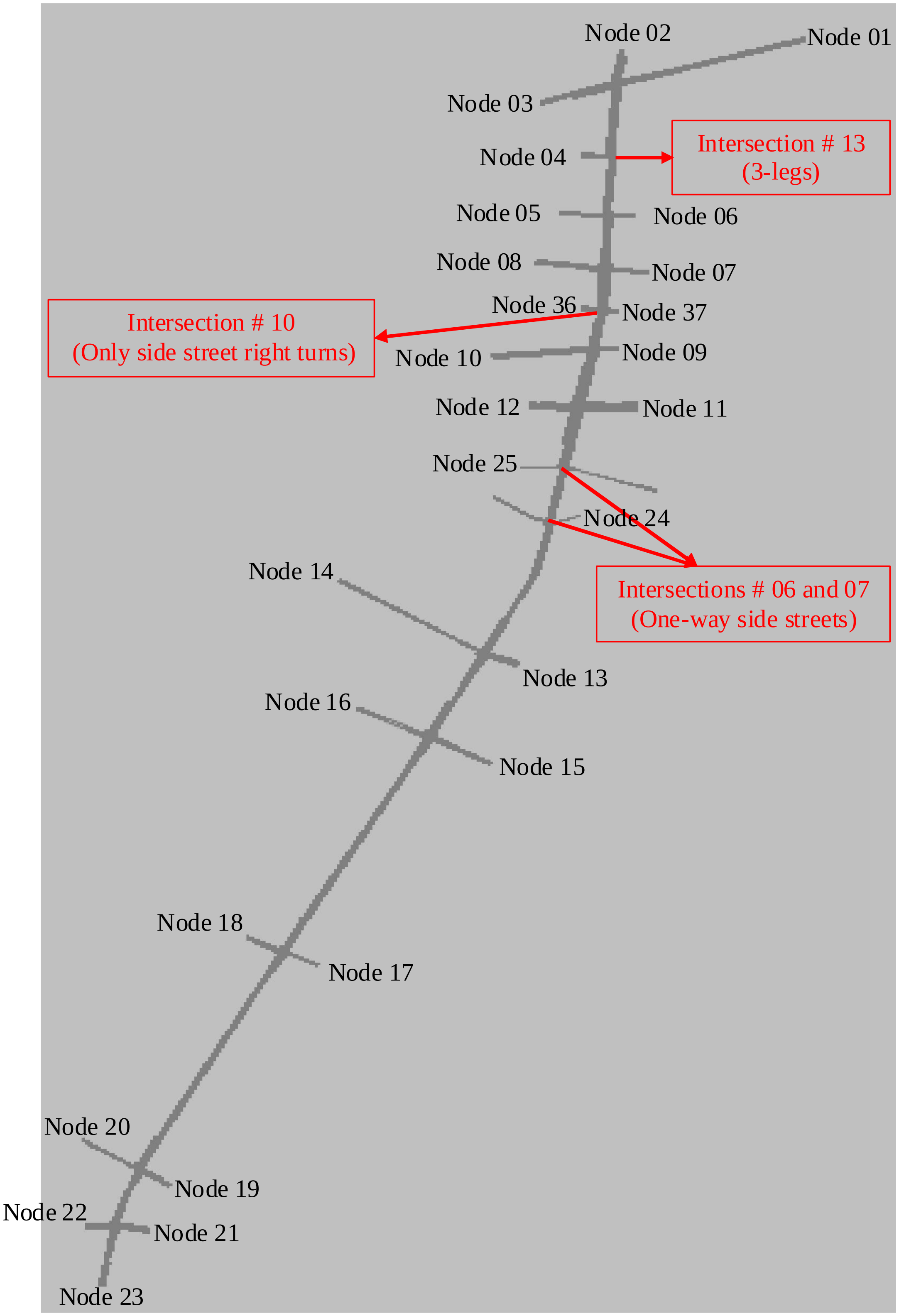


Figure 4.1 Reston Parkway Network in Northern Virginia

4.5.Analysis Steps for Reston Parkway Network

The major analysis steps followed to implement traffic responsive control in Reston Parkway network are presented in this section. The details of each step are presented in the following sections of this chapter. These steps are summarized as follows:

1. Generation of optimum timing plans for each traffic scenario,

2. Selection of the best traffic plans to be considered in the traffic responsive control,

3. Determination of the parameters required to set up the system in the real network,

4. Final validation of the selected timing plans with actual traffic patterns obtained from the available system detector data.

4.6.Generation of Optimum Timing Plans

A total of 675 different traffic scenarios were generated based on the traffic levels for movements entering the network. These levels were confirmed to match with actual detector data.

For each traffic scenario, different timing plans were generated using PASSER V optimization package *(33)*. VDOT requested that the existing phase sequences (i.e. lead-lead, lag-lag, lead-lag, or lag-lead) being kept the same as the sequence being implemented in the current TOD control operation, because this sequence is governed by the geometry at each intersection. Thus, the optimization of PASSER phase sequence was blocked.

It was important to develop the timing plans such they have cycle lengths that are factors of the periods that the master controller use to collect sample. In Reston Parkway network, this period was 15 minutes (900 seconds). Thus, only timing plans with cycle lengths of 90, 100, 150, and 180 were considered. Therefore, for each traffic scenario, there were four timing plans that can be implemented in the traffic responsive control mode. Therefore, 2700 timing plans were generated (675 traffic scenario x 4 cycle lengths).

4.7.Selection of Best Timing Plans

Due to the limited number of timing plans that can be stored in traffic controllers as well as the number of plans assuring that the system will not keep switching plans and reducing the overall efficiency, it was required to determine a maximum of 5 plans to be stored in traffic controllers in addition to the exiting plans being used in time of day operation. It is the requirement of VDOT to add to the plans being used in the time of day operation and not to abandon them.

Evaluation for each timing plan with all traffic scenarios was performed using the batch mode run option in the research version of PASSER V. this evaluation was important since it provided estimated values for the total delay and total number of stops for each combination of timing plan and traffic scenario.

The delay and stops estimations do not consider oversaturation of different links in the network. However, they are acceptable as this is the initial step to reduce the number of timing plans. In the next step, CORSIM runs for all selected timing plans with all traffic scenarios were performed to account for the oversaturation effect *(34)*. The PASSER V Initial selection analysis was necessary since CORSIM runs can take a very long time if it were to be performed for all plan-scenario combinations (2700 plans x 675 scenarios).

The Degree of detachment (DOD) introduced in TTI *(4)* was used to select the best five plans out of the 2700 obtained plans. Multi-objective genetic algorithm optimization was used to select the best five plans based on an optimization of delay, stops and DOD. The delay and stops were the estimated values obtained from PASSER V.

Figure 4.2 shows the results of the multi-objective genetic algorithm optimization. The selected solution was found to include only four plans: two of 90 seconds cycle length, one of 100 seconds cycle length, and one of 150 seconds cycle length. All these plans have the same phase sequence at each intersection.

As described above, VDOT requires adding new plans to the current time of day plans. However, current time of day plans were modified to make their cycle lengths a factor of the 900 seconds proposed to be used in traffic responsive control. This modification increases the cycle length to the four cycle lengths indicated before. One of the modified TOD plans (with cycle length of 150 seconds) was found to be identical with one of the four plans obtained from multi-objective optimization. Table 4.1 shows the four plans obtained from the multi-objective genetic algorithm optimization and the five modified time of day plans. It is clear from Table 4.1 that the fourth new plan is the same as the second modified time of day plan.

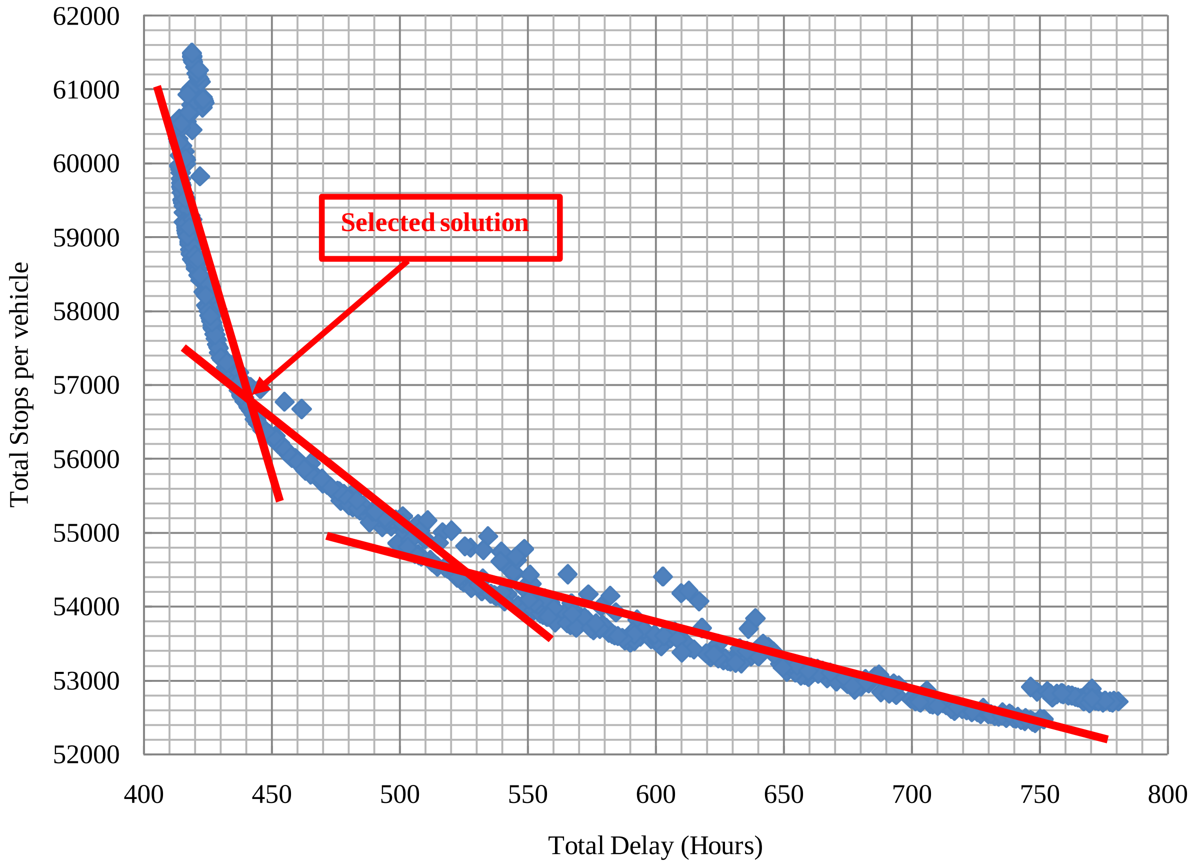


Figure 4.2 Results of the multi-objective genetic algorithm optimization and the selected solution

4.8.Pattern Matching Parameters

The pattern matching parameters required to set up traffic responsive control mode should be identified and stored in the master traffic controller. For pattern matching mechanism in 170’s controllers, there is one global system variable, one local variable for each system detector, and two variables for each detector corresponding to different timing plans that should be determined.

The global variable is called the K factor (used to calculate VPLUSKO values to account for the effect of occupancy). The K value is applied to all detectors at all times. This value ranges from 0 to 100. On the other hand, each system detector has a local variable, which is the weighting factor for each detector. These weighting factors are used to eliminate detectors from the calculation if they are not to be included for certain time of day, or to emphasize volumes and occupancies measured by selected detectors if their outputs are more effective in distinguishing different patterns. These weighting factors range from 0 to 10, and can be changed with time of day in the schedule. Only one value is used for the proposed traffic responsive control mode. The last two variables are the counts and occupancies for each system detector accompanied with different timing plans. The rational of providing count and occupancy values for each plan is that the pattern matching algorithm would calculate the distances between the existing traffic pattern and each one of timing plans. The least distance would indicate the timing plan that “matches” the existing pattern—and hence the pattern matching nomenclature.

Eleven system detectors were used in Reston Parkway network. The location of these system detectors are shown in Figure 4.3. Six system detectors were associated with the significant critical movements entering the network. The other five system detectors were located at the exit links to “sense” the amount of traffic that goes through the network versus the traffic that disappears locally.

In order to determine the required pattern matching parameters, it was necessary to determine values for the delay and number of stops considering oversaturation conditions. Thus, CORSIM runs were performed for all traffic scenarios with the final eight timing plans and the free control mode.

Table 4.1 Proposed Four Timing Plans and Modified Time of Day Plans.

	New				Modified TOD				
Scheme #	1	2	3	4	5	6	7	8	9
Intersection No. 1									
Cycle (sec.)	100	90	90	150	180	150	180	150	150
Offsect (sec.)	36	19	19	101	163	101	73	92	100
Phase 1	17	17	17	22	51	22	27	20	22
Phase 2	49	39	39	44	45	44	69	46	44
Phase 3	17	17	17	43	43	43	43	43	43
Phase 4	17	17	17	41	41	41	41	41	41
Phase 5	17	17	17	17	17	17	17	17	17
Phase 6	49	39	39	49	79	49	79	49	49
Intersection No. 2									
Cycle (sec.)	100	90	90	150	180	150	180	150	150
Offsect (sec.)	61	20	31	85	150	85	85	72	75
Phase 1	33	23	17	28	25	28	20	27	24
Phase 2	33	33	39	56	93	56	98	49	62
Phase 3	17	17	17	19	17	19	17	23	18
Phase 4	17	17	17	47	45	47	45	51	46
Phase 5	17	17	17	19	17	19	17	23	18
Phase 6	49	39	39	65	101	65	101	53	68
Intersection No. 3									
Cycle (sec.)	100	90	90	150	180	150	180	150	150
Offsect (sec.)	11	69	71	21	124	21	135	13	11
Phase 1	17	17	17	17	27	17	25	18	25
Phase 2	49	49	39	108	27	108	58	105	54
Phase 3	17	17	17	17	27	17	22	17	24
Phase 4	17	17	17	38	27	38	45	40	47
Phase 5	39	39	29	17	27	17	23	18	25
Phase 6	27	27	27	108	27	108	60	105	54
Phase 7	17	17	17	17	27	17	22	17	24
Phase 8	17	17	17	38	27	38	45	40	47
Intersection No. 4									
Cycle (sec.)	100	90	90	150	180	150	180	150	150
Offsect (sec.)	61	29	32	97	50	97	5	92	11
Phase 1	17	17	17	25	33	25	27	25	30
Phase 2	49	39	35	61	80	61	91	51	50
Phase 3	17	17	20	18	19	18	17	23	21
Phase 4	17	17	18	46	48	46	45	51	49
Phase 5	38	28	22	18	17	18	26	23	21
Phase 6	28	28	30	68	96	68	92	53	59
Phase 7	17	17	17	18	24	18	18	23	21
Phase 8	17	17	21	46	43	46	44	51	49
Intersection No. 5									
Cycle (sec.)	100	90	90	150	180	150	180	150	150
Offsect (sec.)	80	60	48	101	31	101	174	73	42
Phase 1	17	17	17	20	26	20	32	23	23
Phase 2	49	39	38	71	69	71	75	49	58
Phase 3	17	17	17	38	38	38	38	38	38
Phase 4	17	17	18	21	47	21	32	40	31
Phase 5	25	20	17	17	17	17	21	17	17
Phase 6	41	36	38	74	78	74	89	55	64
Intersection No. 6									
Cycle (sec.)	100	90	90	150	180	150	180	150	150
Offsect (sec.)	9	89	39	4	28	4	53	31	49
Phase 2	83	73	73	103	136	103	117	111	98
Phase 4	17	17	17	47	44	47	63	39	52
Phase 6	83	73	73	103	136	103	117	111	98
Intersection No. 7									
Cycle (sec.)	100	90	90	150	180	150	180	150	150
Offsect (sec.)	9	89	39	25	146	25	17	1	135
Phase 2	71	64	71	97	112	97	93	96	96
Phase 3	29	26	19	53	68	53	87	54	54
Phase 5	17	17	17	31	32	31	31	28	32
Phase 6	54	47	54	66	80	66	62	68	64

	New				Modified TOD				
Scheme #	1	2	3	4	5	6	7	8	9
Intersection No. 8									
Cycle (sec.)	100	90	90	150	180	150	180	150	150
Offsect (sec.)	34	24	24	149	143	149	29	3	125
Phase 1	24	21	20	19	17	19	17	24	20
Phase 2	42	35	36	57	68	57	93	55	54
Phase 3	17	17	17	21	37	21	18	22	19
Phase 4	17	17	17	53	58	53	52	49	57
Phase 5	24	21	20	19	18	19	42	24	20
Phase 6	42	35	36	57	67	57	68	55	54
Phase 7	17	17	17	18	20	18	17	17	19
Phase 8	17	17	17	56	75	56	53	54	57
Intersection No. 9									
Cycle (sec.)	100	90	90	150	180	150	180	150	150
Offsect (sec.)	46	30	25	20	150	20	17	135	147
Phase 1	19	17	17	17	18	17	17	17	18
Phase 2	37	33	37	69	96	69	99	69	66
Phase 3	21	19	17	17	18	17	17	17	18
Phase 4	23	21	19	47	48	47	47	47	48
Phase 5	19	17	17	34	45	34	49	35	33
Phase 6	37	33	37	52	69	52	67	51	51
Phase 7	17	17	19	17	18	17	17	17	18
Phase 8	27	23	17	47	48	47	47	47	48
Intersection No. 10									
Cycle (sec.)	100	90	90	150	180	150	180	150	150
Offsect (sec.)	25	71	70	93	97	93	146	103	71
Phase 2	71	63	60	93	123	93	120	98	94
Phase 4	29	27	30	57	57	57	60	52	56
Phase 6	71	63	60	93	123	93	120	98	94
Intersection No. 11									
Cycle (sec.)	100	90	90	150	180	150	180	150	150
Offsect (sec.)	62	41	48	141	166	141	12	1	143
Phase 1	17	17	17	33	36	33	34	32	30
Phase 2	44	38	30	46	70	46	73	51	49
Phase 3	22	18	26	23	28	23	31	21	23
Phase 4	17	17	17	48	46	48	42	46	48
Phase 5	23	18	19	28	36	28	41	31	28
Phase 6	38	37	28	51	70	51	66	52	51
Phase 7	17	17	17	23	25	23	24	21	23
Phase 8	22	18	26	48	49	48	49	46	48
Intersection No. 12									
Cycle (sec.)	100	90	90	150	180	150	180	150	150
Offsect (sec.)	73	63	63	137	7	137	174	144	143
Phase 1	17	17	17	24	24	24	24	24	26
Phase 2	38	38	46	78	108	78	108	78	74
Phase 4	45	35	27	48	48	48	48	48	50
Phase 5	17	17	17	31	28	31	36	36	26
Phase 6	38	38	46	71	104	71	96	66	74
Phase 8	45	35	27	48	48	48	48	48	50
Intersection No. 13									
Cycle (sec.)	100	90	90	150	180	150	90	75	75
Offsect (sec.)	64	46	38	47	59	47	72	61	60
Phase 2	58	59	67	109	135	109	72	55	55
Phase 4	42	31	23	41	45	41	18	20	20
Phase 5	24	18	17	37	43	37	19	21	21
Phase 6	34	41	50	72	92	72	53	34	34
Intersection No. 14									
Cycle (sec.)	100	90	90	150	180	150	180	150	150
Offsect (sec.)	0	0	0	0	0	0	0	0	0
Phase 1	20	17	19	35	40	35	24	34	32
Phase 2	24	22	22	40	52	40	71	45	43
Phase 3	39	27	26	36	36	36	55	37	34
Phase 4	17	24	23	39	52	39	30	34	41
Phase 5	20	17	19	36	37	36	45	38	33
Phase 6	24	22	22	39	55	39	50	41	42

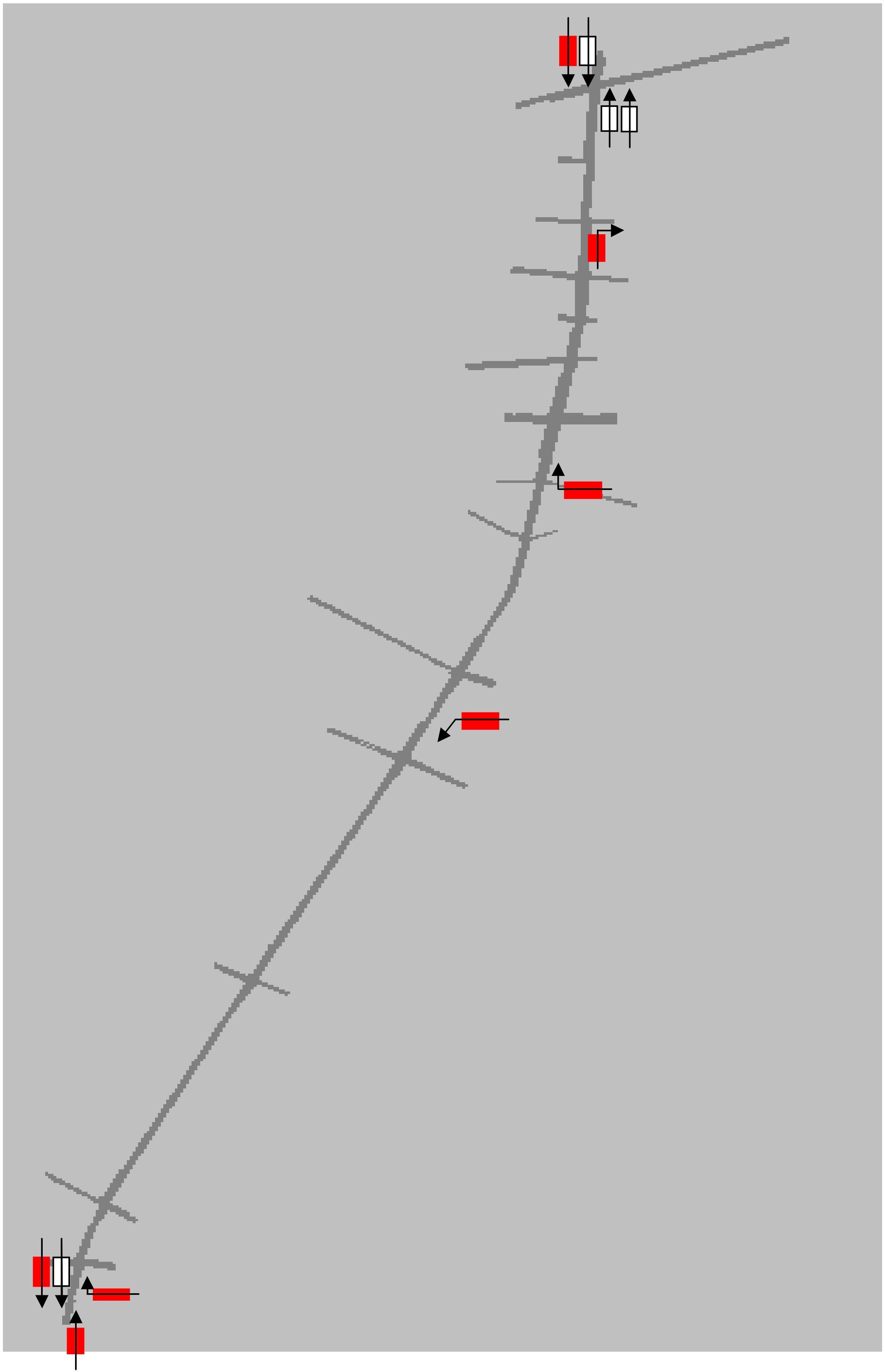


Figure 4.3 System detectors in Reston Parkway arterial network

A special evolutionary code using genetic algorithm and supervised discriminate analysis was used to determine the required pattern matching parameters. This code has the formula by which 170’s controllers implement traffic responsive in any network. Not only does the evolutionary code provide the required parameters for setting up traffic responsive control mode using multi-objective optimization for the delay, stops, and classification error, but it also reassigns timing plans to different traffic pattern based on CORSIM results, which consider oversaturation for different links.

Different K factors, ranging from 0 to 100, are provided to the evolutionary code one at a time so that the pareto front for each K is obtained. The optimum solution for each K factor is selected based on the obtained parteo front for such factor. Figure 4.4 through Figure 4.7 shows the pareto front for K factor of 90 and the selected optimum solution for this K factor.

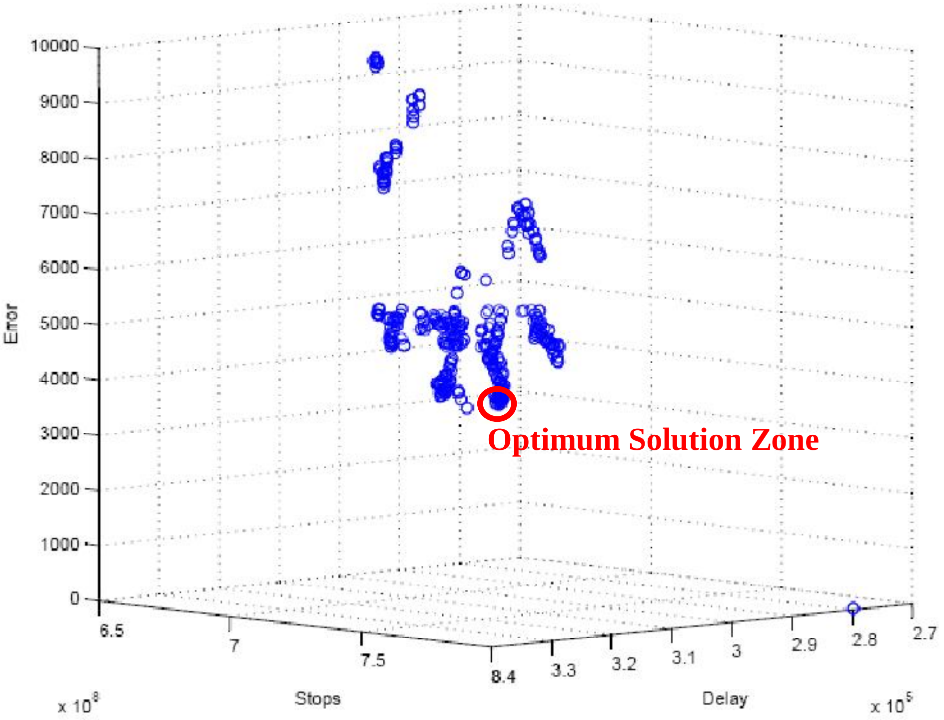


Figure 4.4 Pareto front for 170's evolutionary code (K = 90%)

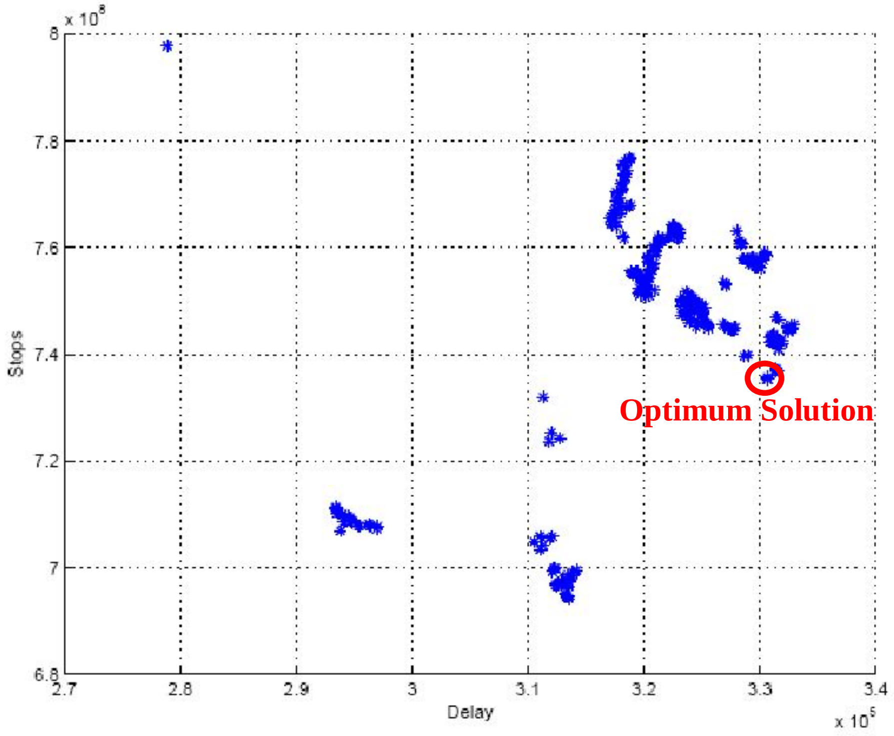


Figure 4.5 Delay-stops plan (K = 90%)

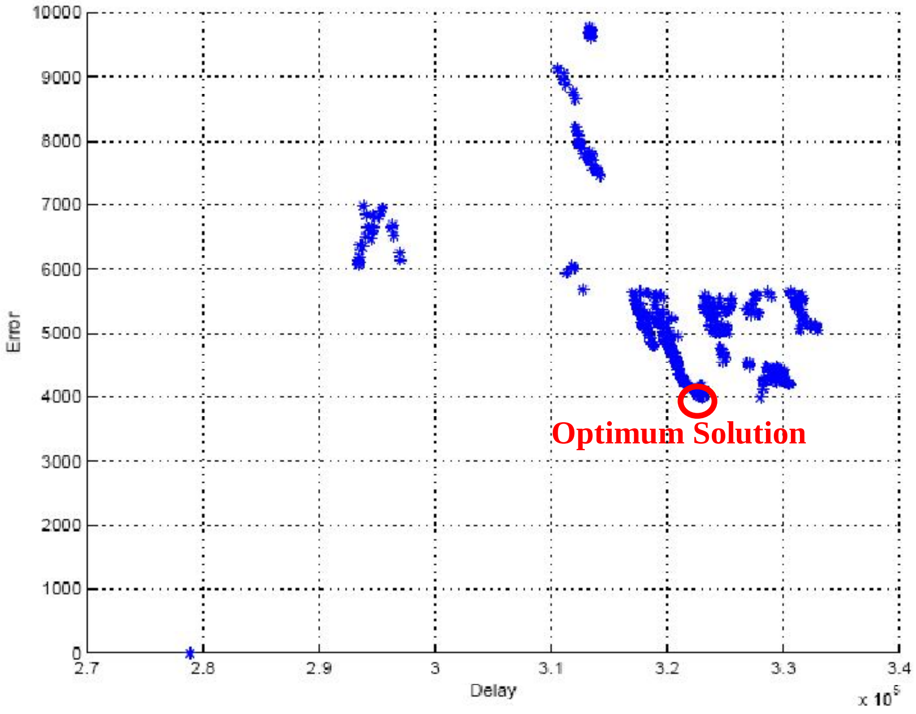


Figure 4.6 Delay-error plan (K = 90%)

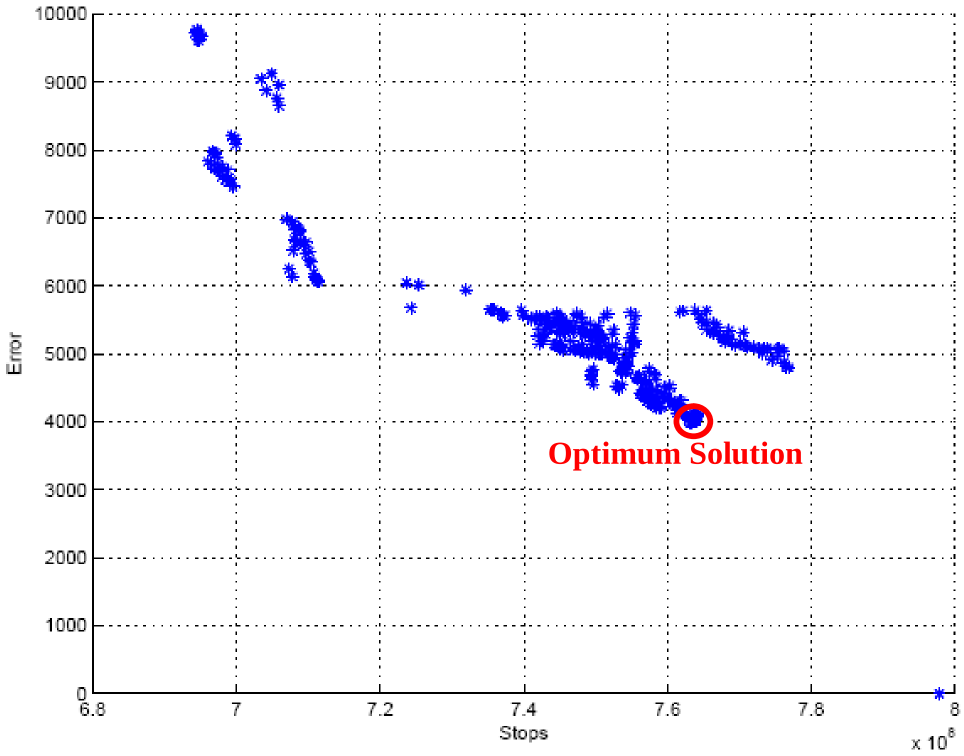


Figure 4.7 Stops-error plan (K = 90%)

It is noticed that there is one point with zero classification error. However, this point is not considered the optimum solution because only one timing plan is assigned for all traffic scenarios. This is one feasible solution but it is not acceptable as it corresponds to very high stops.

Variation ranges (i.e. minimum, average, and maximum) for belay, stops, and classification error are plotted to show the improvement in results. Figure 4.8 though Figure 4.10 shows that the number of generation used in the run is enough to achieve the required stabilization in the results. This means that the obtained optimum solution cannot be improved any more.

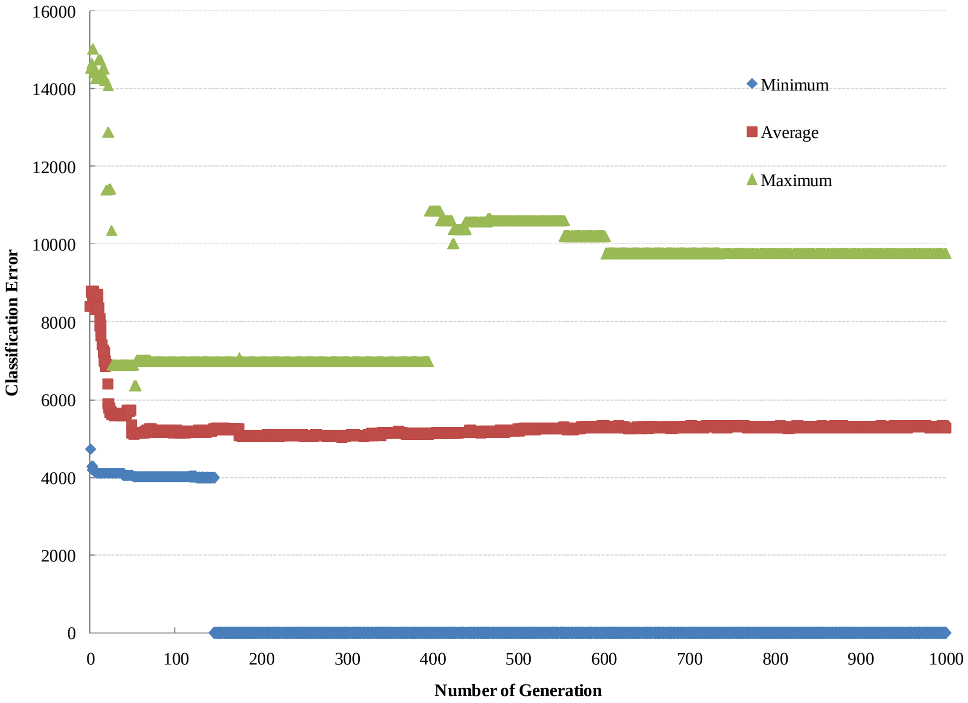


Figure 4.8 Range for the classification error (K = 90%)

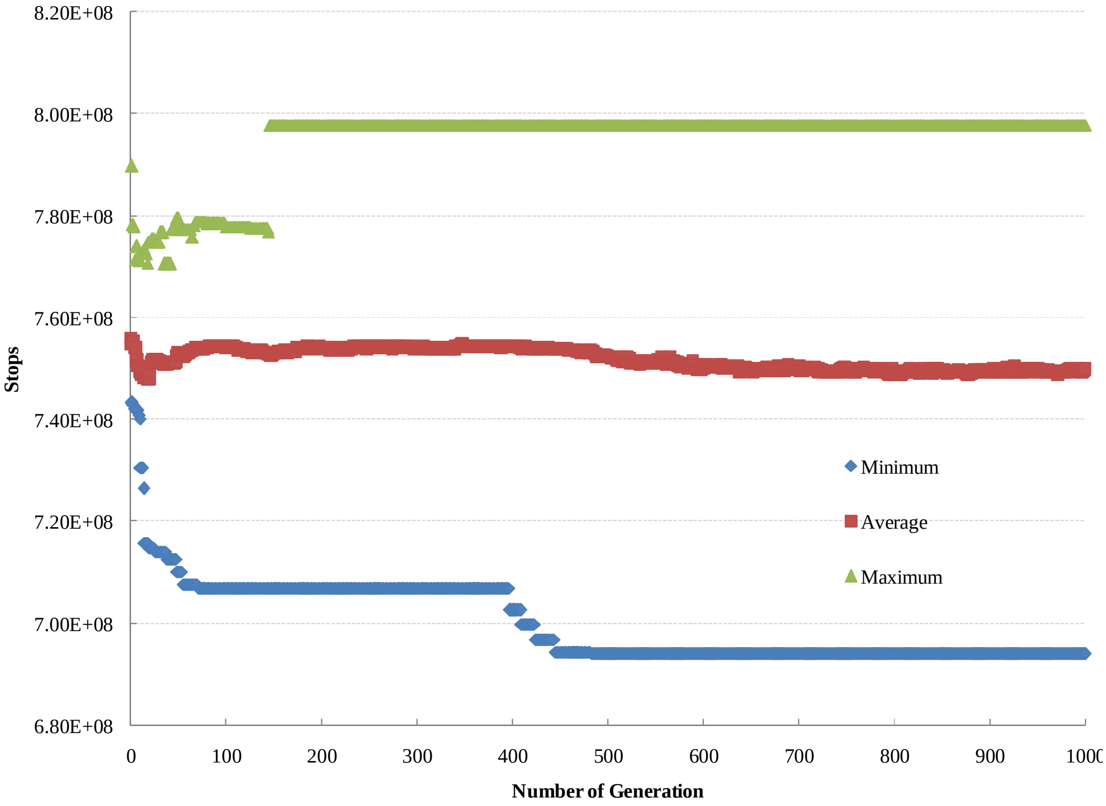


Figure 4.9 Range for stops (K = 90%)

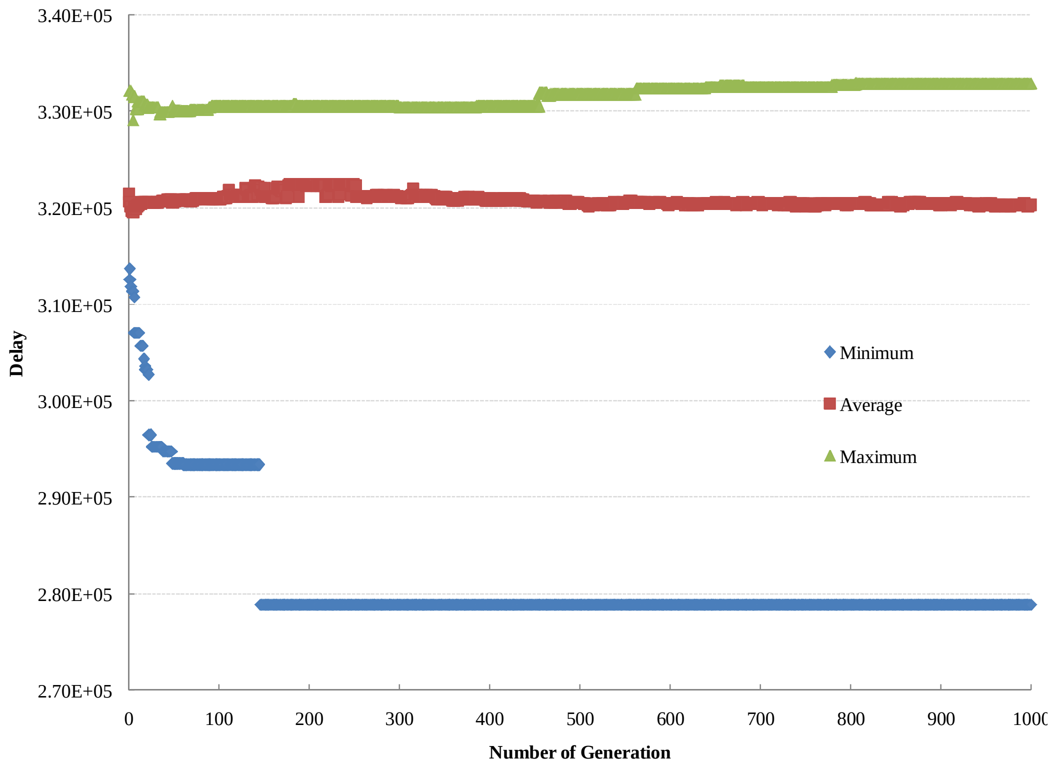


Figure 4.10 Range for delay (K = 90%)

Delay, stops and classification error corresponding to the optimum solutions of different K factors are determine and plotted versus the K factor in order to determine the optimum K factor to be used. Figure 4.11 through Figure 4.13 present the optimum values for delay, stops, and classification error, respectively, for different K factors.

It is noticed that classification error is improved with increasing K factor. For K factor equal to zero, i.e. neglecting system detector occupancies; classification error is the highest which means that occupancies improve pattern recognition. Moreover, for K factors more than 50%, stops do not affect the selection as it becomes almost constant with negligible variation.

It is also clear that for small K factors (up to 50%), stops and classification error are very high. Therefore, K factors less than 50% are not considered optimum. From these figures and the previous discussion, a K factor of 90% is selected to be the optimum K as it is corresponding to the minimum delay and minimum classification error (stops is constant).

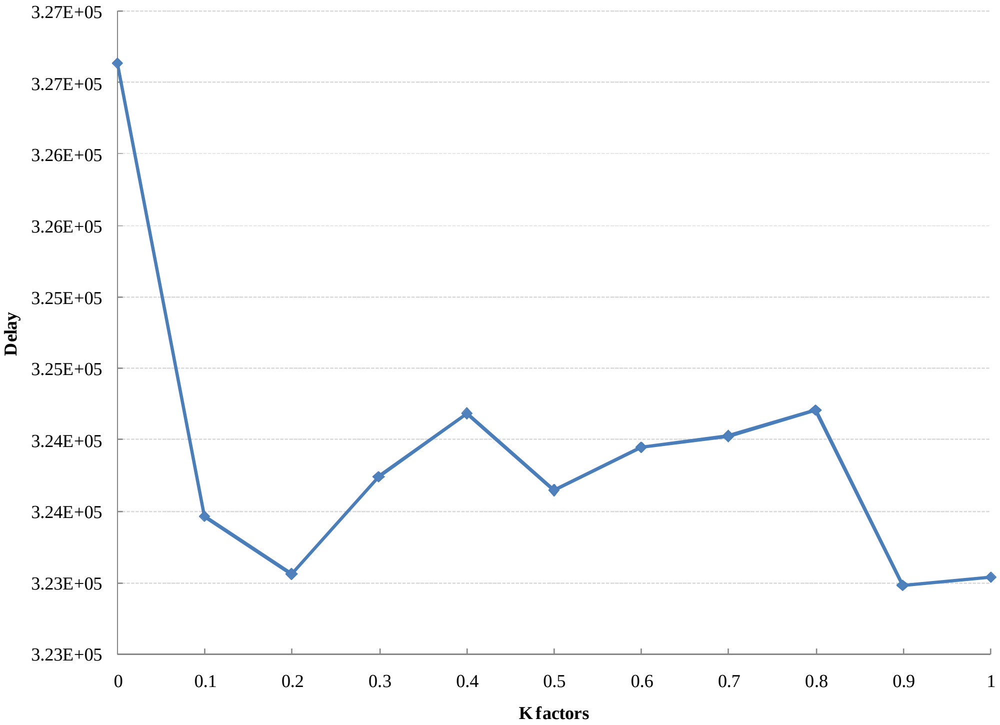


Figure 4.11 Optimum delay values for different K factors

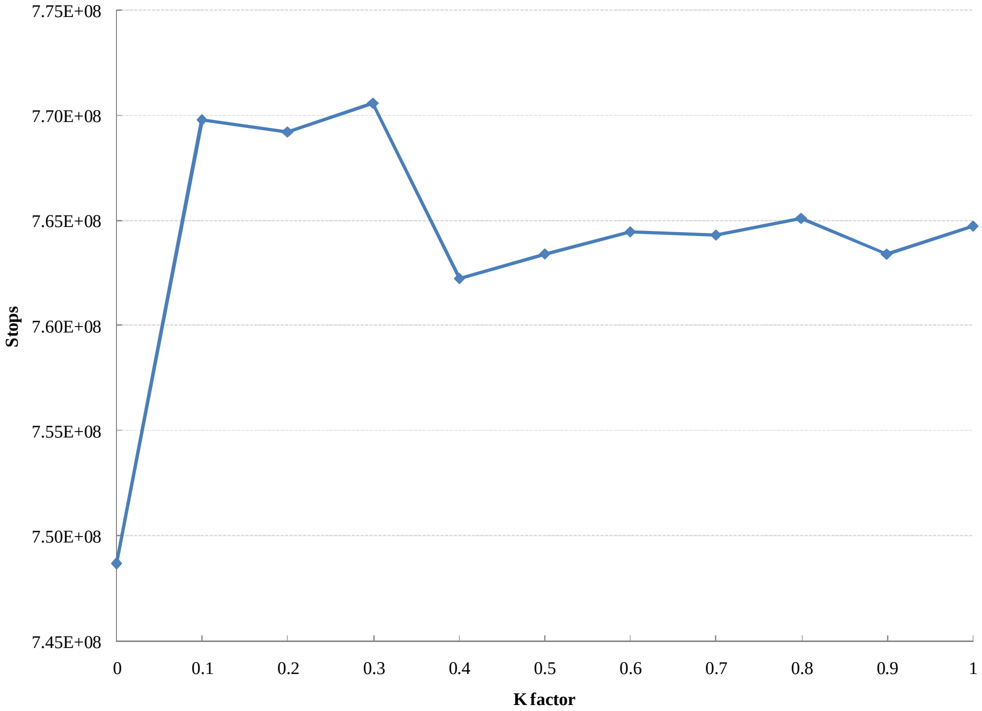


Figure 4.12 Optimum stop values for different K factors

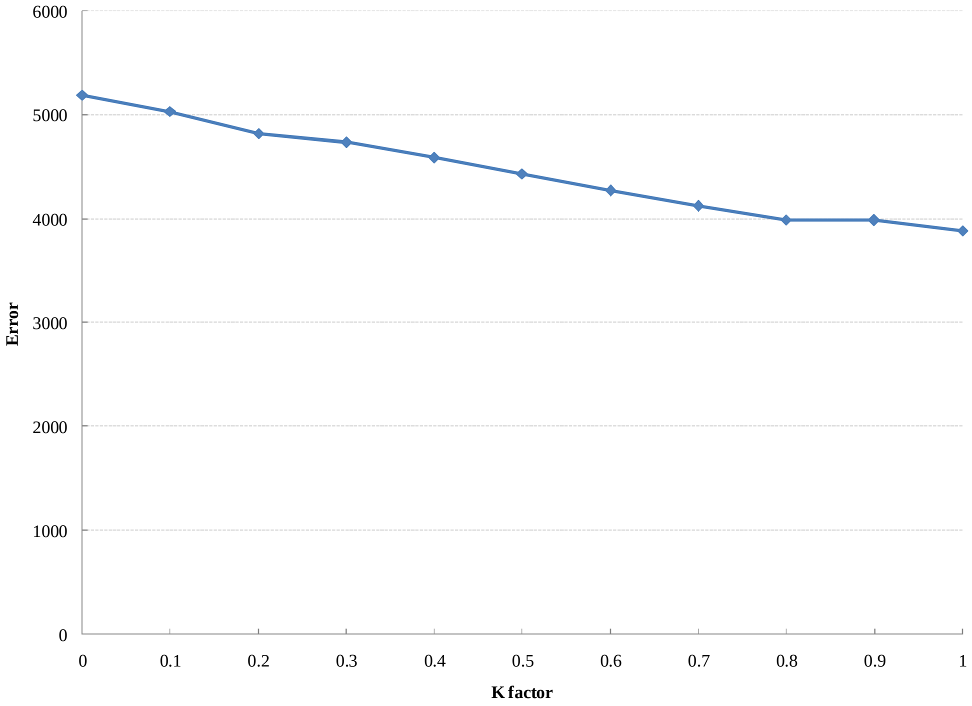


Figure 4.13 Optimum classification error values for different K factors

Table 4.2 shows the system detector weighting factors for K = 90%. It is clear that detectors number 2, 4, 5, and 7 have weighting factors of zero which means they should not be considered in pattern recognition because there data do not improve the recognition process. The red detectors in Figure 4.3 are those being used in the proposed pattern matching mechanism for Reston parkway, i.e. there weighting factors are not zeros.

Table 4.2 Weighting Factor for Each System Detector.

VPLUSKO factor = 90 %

Weight Factors for system detectors

Det:1	Det:2	Det:3	Det:4	Det:5	Det:6	Det:7	Det:8	Det:9	Det:10	Det:11
2	0	1	0	0	1	0	4	9	2	5

As described before, evolutionary code reassigns timing plans to different traffic scenarios based on oversaturation results from CORSIM. For the selected optimum solution at K = 90%, it is found that timing plan number 8, one of VDOT modified plans, is not included in the new assignment. This means that this plan is not optimum any more for the proposed traffic responsive system. Table 4.3 and Table 4.4 present counts and occupancies, respectively, for each active system detector with each selected timing plan.

Table 4.3 Counts for Active System Detector Accompanied with Different Selected Timing Plans.

Counts for each system detector

Plan	Det:1	Det:3	Det:6	Det:8	Det:9	Det:10	Det:11
1	150.00	10.00	50.00	10.00	60.00	450.00	10.00
2	150.00	10.00	150.00	10.00	60.00	390.00	10.00
3	400.00	10.00	100.00	10.00	60.00	400.00	80.00
4	150.00	10.00	50.00	0.00	60.00	75.00	10.00
5	420.00	10.00	50.00	0.00	75.00	50.00	75.00
6	150.00	10.00	150.00	0.00	60.00	130.00	10.00
8	350.00	10.00	65.00	10.00	60.00	300.00	235.00
9	150.00	10.00	175.00	5.00	60.00	275.00	10.00

Table 4.4 Occupancies for Active System Detector Accompanied with Different Selected Timing Plans.

Plan	Det:1	Det:3	Det:6	Det:8	Det:9	Det:10	Det:11
1	76.03	55.38	88.03	16.41	89.12	71.74	90.28
2	70.56	67.34	97.32	14.64	89.64	92.50	89.48
3	57.23	84.94	71.33	5.88	92.82	44.95	72.36
4	62.48	2.93	92.38	0.00	66.76	37.25	61.04
5	85.11	97.17	96.14	0.00	84.72	77.35	89.92
6	27.00	9.38	97.81	0.00	77.11	92.78	68.53
8	78.27	98.62	79.54	8.81	96.04	60.04	73.96
9	33.52	17.87	72.89	1.16	81.55	88.03	82.76

4.9.Validation for the Obtained Parameters and Timing Plans

The final step in this analysis was to verify the obtained timing plans and traffic responsive parameters. In this step, simulation runs were performed for a regular week day and one weekend day, to confirm that the system is working as it should be and to determine the effect on implemented traffic responsive control in Reston Parkway before the actual implementation of the proposed system.

Wednesday April 9th, 2008 and Saturday April 5th, 2008 were selected as an example for weekday and weekend, respectively. Actual traffic scenarios for both days were generated and used in the simulation. VISSIM simulation package was used to perform the required verification *(35)*. Vehicle actuated program (VAP) script was used to simulate 170's controllers in VISSIM runs *(36)*. One VAP file was generated for each controller.

Using the obtained values for traffic responsive variables and actual traffic scenarios for the selected days, timing plan being implemented during the whole day was determined. Figure 4.14 and Figure 4.15 shows the traffic responsive timing plan versus TOD plan for the selected weekend and week day respectively. In this figures timing plan number 10 refers to the free control mode.

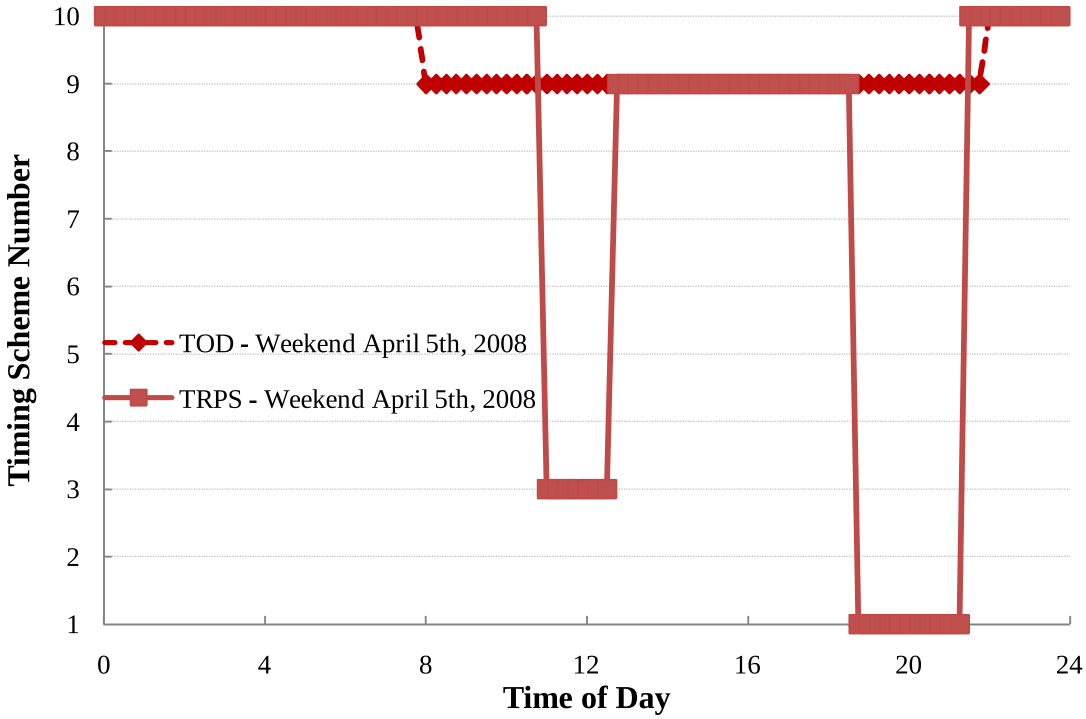


Figure 4.14 Timing Plans for Traffic Responsive control versus TOD for weekend

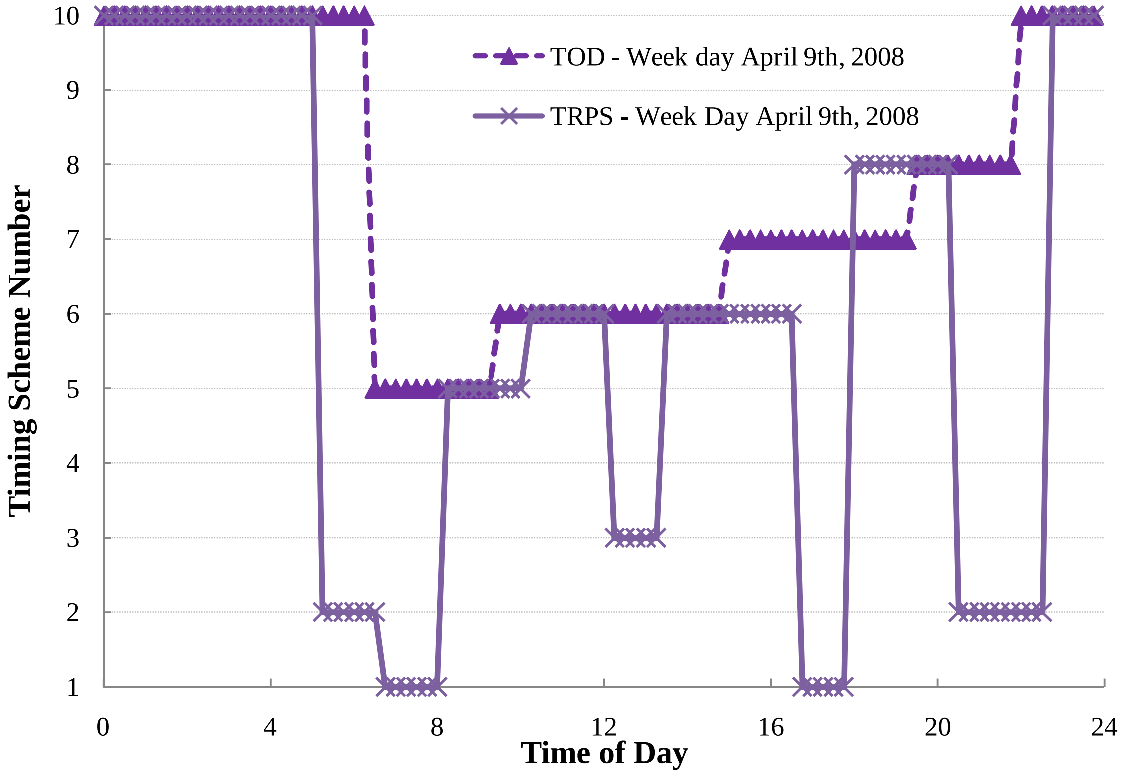


Figure 4.15 Timing Plans for Traffic Responsive control versus TOD for week day

These simulations showed improvement in the overall network performance as well as the performance for each link in the network. Table 4.5 and Table 4.6 show the measures of Effectiveness (MOEs) for different movements at each intersection considering time of day and traffic responsive control mode for the selected weekend and selected week day, respectively. It can be deduced from these two tables that using traffic responsive control mode of operation generally improves the performance for all movements in the networks by reducing the delay and number of stops.

Table 4.5 MOEs for Selected Weekend.

Intersection #	Movement		MOEs for TOD		MOEs for Traffic Responsive	
	From	To	Average Delay (sec.)	Average Stops	Average Delay (sec.)	Average Stops
1	North	South	10.60	1.05	6.95	0.26
	North	West	7.10	0.72	0.76	0.00
	North	East	7.80	0.31	3.92	0.30
	South	North	6.90	0.68	1.60	0.22
	South	West	11.00	1.22	2.07	0.47
	South	East	7.00	0.65	0.00	0.00
	West	South	4.20	0.40	0.95	0.21
	West	North	11.40	1.48	7.85	0.88
	West	East	13.60	1.46	5.75	0.58
	East	South	9.80	0.59	2.93	0.50
	East	North	5.60	0.55	2.52	0.15
	East	West	8.00	0.61	3.30	0.60
2	North	South	19.10	1.15	14.90	0.54
	North	West	6.40	0.04	0.32	0.00
	North	East	11.30	0.58	4.43	0.41
	South	North	11.90	0.86	6.83	0.32
	South	West	8.50	1.09	2.69	0.37
	South	East	5.40	0.11	0.35	0.00
	West	South	11.00	0.93	1.66	0.34
	West	North	63.40	1.03	57.04	0.84
	West	East	72.80	1.84	64.71	0.91
	East	South	58.10	1.39	51.28	0.92
	East	North	5.60	1.08	0.97	0.18
	East	West	47.60	1.04	45.15	0.93
3	North	South	20.50	1.55	15.80	0.57
	North	West	14.30	1.18	6.41	0.46
	North	East	11.90	0.14	3.25	0.00
	South	North	18.00	1.12	13.20	0.51
	South	West	18.60	1.82	12.59	0.84
	South	East	4.40	0.26	0.42	0.00
	West	South	6.40	0.70	1.72	0.26
	West	North	28.00	1.33	25.84	0.84
	West	East	34.50	2.14	27.74	1.26
	East	South	29.50	1.52	22.46	0.75
	East	North	8.20	0.59	1.86	0.18
	East	West	37.90	1.92	34.70	0.95
4	North	South	25.60	1.13	20.11	0.77
	North	West	16.40	0.81	12.75	0.64
	North	East	2.50	0.36	0.43	0.00
	South	North	23.80	0.80	16.81	0.55
	South	West	28.20	1.43	19.55	0.93
	South	East	6.40	0.56	0.35	0.00
	West	South	6.70	0.89	3.44	0.19
	West	North	31.40	1.51	28.18	0.86
	West	East	34.45	1.32	30.22	1.07
	East	South	54.40	2.06	48.50	1.14
	East	North	13.60	0.43	5.57	0.22
	East	West	54.60	1.61	47.92	1.13
5	North	South	52.00	1.68	43.35	1.67
	North	West	13.40	1.03	8.92	0.51
	North	East	3.70	0.52	0.65	0.00
	South	North	23.00	1.16	18.18	0.91
	South	West	7.90	0.43	4.51	0.42
	South	East	2.00	0.24	0.00	0.00
	West	South	26.00	1.03	17.58	0.45
	West	North	42.80	1.84	37.79	0.84
	West	East	42.10	1.77	36.02	0.83
	East	South	20.80	16.95	15.40	16.80
	East	North	8.30	1.14	1.89	0.21
	East	West	29.80	27.40	25.34	26.80
6	North	South	34.44	10.97	26.99	10.91
	North	West	34.51	0.92	27.64	0.82
	South	North	16.77	4.29	14.60	4.05
	South	West	19.17	12.74	13.93	11.79
	East	South	16.46	11.01	10.63	10.51
	East	North	34.27	14.42	29.66	14.17
7	North	South	17.12	7.91	13.14	7.53
	North	East	18.51	10.42	9.68	10.32
	South	North	37.52	0.45	31.63	0.09
	South	East	17.62	10.79	14.13	10.28
	West	South	39.03	8.10	31.71	7.92
8	North	South	13.00	4.27	7.78	2.66
	North	West	8.28	2.66	3.40	1.12
	North	East	30.19	8.66	24.29	7.21
	South	North	41.27	11.68	34.88	10.55
	South	West	8.13	9.91	5.66	8.55
	South	East	7.82	9.15	5.82	8.36
	West	South	12.32	5.07	5.28	3.82
	West	North	22.93	0.83	18.03	0.52
	West	East	9.49	8.99	6.22	8.32
	East	South	23.20	14.91	19.02	14.06
	East	North	32.52	11.33	30.38	10.65
	East	West	9.64	7.04	3.23	5.86
9	North	South	18.80	16.11	13.11	14.67
	North	West	34.28	15.95	30.64	14.60
	North	East	25.95	8.45	19.60	7.15
	South	North	5.20	7.77	0.12	6.86
	South	West	40.46	10.23	34.10	9.46
	South	East	18.39	10.05	12.12	9.22
	West	South	8.19	4.71	0.90	2.94
	West	North	21.59	7.85	19.20	6.78
	West	East	12.44	4.39	7.63	3.50
	East	South	26.61	3.05	24.11	1.82
	East	North	31.02	13.08	24.52	12.15
	East	West	39.36	6.83	33.56	5.67
10	North	South	9.47	14.46	1.64	13.94
	North	West	38.94	13.12	32.91	12.24
	South	North	6.25	9.90	1.55	9.22
	South	East	24.74	12.19	19.52	11.41
	West	North	25.42	12.53	20.97	11.63
	East	South	13.68	3.15	6.89	2.87
11	North	South	19.96	13.50	16.86	12.86
	North	West	5.33	1.12	2.40	0.01
	North	East	18.43	2.00	12.50	1.50
	South	North	10.27	0.38	2.71	0.06
	South	West	40.94	0.87	34.87	0.13
	South	East	19.61	15.14	12.40	13.51
	West	South	21.12	2.76	17.69	1.59
	West	North	10.65	4.48	3.85	3.15
	West	East	15.21	11.21	12.35	10.49
	East	South	23.21	9.16	20.54	7.30
	East	North	23.14	11.70	18.82	11.27
	East	West	30.29	3.58	28.03	1.99
12	North	South	37.06	9.10	29.30	8.17
	North	West	19.74	5.23	17.09	3.78
	North	East	36.38	1.51	30.65	0.67
	South	North	38.38	8.97	32.80	8.60
	South	West	15.52	15.22	13.45	13.92
	South	East	21.15	3.66	16.14	2.47
	West	South	24.27	10.88	20.12	9.70
	West	North	38.02	16.10	34.63	14.17
	West	East	22.56	5.93	17.98	4.66
	East	South	10.98	2.00	7.72	0.89
	East	North	27.85	13.69	20.89	12.67
	East	West	3.07	3.38	0.02	2.79
13	North	South	15.32	13.68	13.08	12.61
	North	East	26.54	13.14	19.13	11.93
	South	North	7.57	5.36	4.63	4.26
	South	East	18.05	12.68	10.20	10.95
	East	South	31.28	14.14	23.45	13.23
	East	North	34.53	4.85	28.00	4.58
14	North	South	36.20	15.51	32.14	14.66
	North	West	4.63	6.80	1.05	5.64
	North	East	17.04	3.49	10.71	2.65
	South	North	28.52	10.48	24.46	9.84
	South	West	30.51	5.66	23.93	3.83
	South	East	13.60	4.58	6.76	3.70
	West	South	35.11	9.38	28.28	8.33
	West	North	28.82	4.19	24.18	2.76
	West	East	35.81	10.67	33.10	9.28
	East	South	42.49	10.62	35.49	9.24
	East	North	21.08	0.41	14.46	0.32

Table 4.6 MOEs for Selected Week Day.

Intersection #	Movement		MOEs for TOD		MOEs for Traffic Responsive	
	From	To	Average Delay (sec.)	Average Stops	Average Delay (sec.)	Average Stops
1	North	South	47.91	4.17	40.76	0.41
	North	West	19.14	4.80	12.31	0.23
	North	East	34.30	3.45	26.38	1.20
	South	North	51.92	5.13	42.62	0.29
	South	West	40.07	4.45	36.04	1.08
	South	East	17.30	3.50	8.49	0.08
	West	South	50.49	6.11	43.28	0.33
	West	North	29.42	5.16	22.68	1.21
	West	East	51.28	6.55	47.23	1.54
	East	South	15.38	3.57	8.79	0.78
	East	North	51.60	5.30	46.11	0.45
	East	West	20.41	5.20	10.18	1.55
2	North	South	26.64	3.78	21.32	1.51
	North	West	46.16	2.20	40.76	0.91
	North	East	25.12	6.02	23.36	0.45
	South	North	28.67	7.95	23.20	1.08
	South	West	53.97	4.83	44.46	1.31
	South	East	39.14	4.55	35.41	0.00
	West	South	22.44	6.19	16.25	0.39
	West	North	34.06	6.83	23.72	0.92
	West	East	28.65	7.88	21.98	1.47
	East	South	19.34	4.41	15.17	1.60
	East	North	50.57	4.79	41.98	0.42
	East	West	32.81	7.83	27.15	1.46
3	North	South	19.88	2.82	17.24	1.35
	North	West	45.48	3.64	40.79	1.35
	North	East	16.12	6.90	10.51	0.39
	South	North	25.23	6.96	21.81	1.39
	South	West	21.20	2.83	16.93	1.29
	South	East	36.43	2.16	31.83	0.50
	West	South	16.82	2.54	11.06	0.86
	West	North	26.42	2.31	23.92	1.13
	West	East	48.75	7.63	38.32	1.70
	East	South	49.75	6.15	40.82	1.00
	East	North	19.43	5.11	14.48	0.90
	East	West	15.96	5.48	11.94	1.02
4	North	South	31.65	6.34	25.04	1.70
	North	West	42.90	4.76	39.61	0.93
	North	East	27.65	2.44	19.86	0.22
	South	North	13.28	6.60	9.03	0.70
	South	West	43.27	8.33	35.78	1.46
	South	East	28.00	2.66	26.78	0.22
	West	South	46.53	7.50	39.49	0.82
	West	North	20.53	7.28	11.52	1.21
	West	East	24.22	4.50	17.33	1.39
	East	South	43.59	3.70	35.88	1.45
	East	North	11.14	3.37	7.46	0.56
	East	West	43.06	7.55	34.94	1.94
5	North	South	54.33	9.13	47.42	2.36
	North	West	28.32	3.80	21.63	0.74
	North	East	30.72	1.91	25.90	0.58
	South	North	53.83	6.43	46.50	1.76
	South	West	48.30	2.37	40.57	1.36
	South	East	42.28	1.62	35.92	0.39
	West	South	35.89	3.97	30.00	0.57
	West	North	22.41	2.93	19.05	1.70
	West	East	53.61	7.30	47.95	0.90
	East	South	12.46	21.38	10.14	16.93
	East	North	54.73	5.09	49.34	0.55
	East	West	19.95	32.22	14.71	27.19
6	North	South	47.40	13.73	38.88	11.78
	North	West	25.87	4.68	18.02	1.82
	South	North	27.88	7.00	21.37	4.83
	South	West	33.27	15.56	23.72	12.35
	East	South	37.60	17.37	27.27	11.27
	East	North	41.96	17.11	38.00	15.08
7	North	South	46.31	12.69	41.65	7.71
	North	East	27.73	15.65	22.93	10.84
	South	North	24.81	2.99	22.74	0.76
	South	East	29.94	17.83	25.16	11.10
	West	South	26.75	15.37	22.10	8.62
8	North	South	13.36	7.90	8.09	3.58
	North	West	51.59	7.28	46.71	1.63
	North	East	20.56	12.85	16.30	8.88
	South	North	31.84	14.79	24.95	11.24
	South	West	21.02	15.28	16.35	9.23
	South	East	29.02	11.58	23.47	8.11
	West	South	46.28	6.63	37.29	4.61
	West	North	28.07	4.10	23.14	0.76
	West	East	53.78	14.50	45.32	8.61
	East	South	45.22	16.21	38.06	15.03
	East	North	10.94	14.12	7.24	11.29
	East	West	41.36	10.21	37.45	6.55
9	North	South	27.36	16.93	19.84	15.36
	North	West	19.50	20.32	14.38	14.36
	North	East	19.16	14.14	14.90	7.82
	South	North	19.65	13.71	13.83	6.44
	South	West	16.28	15.24	13.96	8.92
	South	East	40.63	16.48	31.57	9.95
	West	South	53.50	7.95	45.23	3.21
	West	North	44.67	12.41	37.43	7.85
	West	East	14.39	10.06	6.94	3.99
	East	South	39.91	4.66	32.60	2.47
	East	North	34.55	17.11	28.36	11.65
	East	West	32.36	9.88	24.04	5.74
10	North	South	19.08	17.58	11.21	13.57
	North	West	51.55	19.56	45.30	13.35
	South	North	37.73	13.08	31.59	9.02
	South	East	33.55	17.56	29.99	12.28
	West	North	47.85	16.43	41.17	11.33
	East	South	53.09	8.24	46.48	2.96
11	North	South	9.77	17.57	4.55	13.48
	North	West	37.51	6.24	34.12	0.34
	North	East	17.57	8.22	11.67	0.95
	South	North	21.94	7.57	18.71	1.02
	South	West	43.66	5.97	38.74	0.06
	South	East	48.40	17.00	42.77	14.41
	West	South	18.70	3.70	15.04	1.66
	West	North	23.23	5.30	19.35	3.46
	West	East	13.51	15.55	6.59	11.49
	East	South	15.98	14.45	13.53	8.59
	East	North	44.39	14.50	41.82	11.61
	East	West	31.66	5.36	22.99	1.96
12	North	South	35.11	12.72	28.50	9.13
	North	West	33.47	9.93	28.90	4.54
	North	East	37.79	4.69	32.79	0.68
	South	North	47.17	12.20	37.55	8.51
	South	West	33.31	19.22	28.59	14.96
	South	East	48.16	9.96	44.79	2.27
	West	South	30.58	16.94	22.77	10.05
	West	North	21.90	22.10	13.07	14.87
	West	East	22.99	12.06	18.84	5.27
	East	South	32.26	8.38	26.59	1.19
	East	North	16.62	19.11	10.82	12.68
	East	West	28.08	4.72	20.65	3.18
13	North	South	14.56	15.49	9.73	12.99
	North	East	21.17	16.21	17.30	12.65
	South	North	39.36	11.32	31.88	3.60
	South	East	43.40	18.24	39.42	11.46
	East	South	47.37	18.46	45.32	12.74
	East	North	39.05	12.54	34.46	4.95
14	North	South	51.65	19.18	43.03	15.56
	North	West	17.29	7.69	14.96	6.03
	North	East	31.43	7.10	24.64	3.53
	South	North	35.88	16.30	30.77	9.83
	South	West	22.94	7.63	15.86	4.86
	South	East	30.47	10.71	21.38	3.84
	West	South	54.06	13.56	48.86	8.71
	West	North	29.84	4.89	26.09	2.88
	West	East	29.67	14.80	19.74	9.59
	East	South	30.06	15.49	23.84	9.32
	East	North	42.20	7.50	33.41	0.88

The results of the simulation also show 62.45 second/vehicle average delay and 1.73 stops/vehicle average number of stops for the time of day control in weekend (i.e. April 5th 2008). While, for the same day the average delay is 45.63 seconds/vehicle and the average number of stops is 1.48 stops/vehicle using traffic responsive control mode of operation. This means about 26.94% saving in delay and 14.45% savings in number of stops.

For the week day April 9th 2008, it was found that using time of day control mode the average delay was 150.42 seconds/vehicle and the average number of stops was 2.84 stops/vehicle and using traffic responsive control mode of operation the average delay was 123.76 seconds/vehicle and the average number of stops was 2.24 stops/vehicle. Thus, a 17.72% savings on delay and 21.13% savings in stops are expected.

4.10.Summary

It is concluded that using traffic responsive control mode of operation in Reston Parkway can improve the overall network performance in the weekends as well as in regular week day. For the weekends 26.94% savings in delay and 14.45% savings in number of stops were found while for the regular week days, it was found that the traffic responsive mode resulted in 17.72% savings in delay and 21.13% in number of stops.

Acknowledgements

This work was sponsored by the Virginia Transportation Research Council (VTRC). The materials and methods presented were developed as part of VTRC Project “Evaluation of Traffic Responsive Control Mode in Northern Virginia”

Chapter 5 : Improvement of Traffic Responsive Plan Selection Efficiency Using Neural Networks and Constraint Relaxation

5.1.Abstract

The main purpose of Traffic Responsive Plan Selection (TRPS) operation mode is to change timing plans in response to changes in traffic demands. Several timing plans are typically needed to respond to all traffic patterns in any particular network efficiently. However, each traffic controller has a limited number of timing plans that can be used, forcing the TRPS designer to cluster different traffic states into a limited number of traffic groups to be addressed by certain timing plans. This fact usually leads to a percentage of traffic state misclassification, resulting in frequent transitioning and reduction in system efficiency. This chapter proposes a relaxation to the thresholds mechanism in TRPS operation to improve TRPS classification accuracy. K-Means clustering analysis is used to for homogeneous traffic states clusters. Artificial Neural Networks (ANN) is used to determine the optimal thresholds for best classification. Comparison of the proposed TRPS classification mechanism to the traditional mechanism on a study network in Northern Virginia showed that the new mechanism can reduce delay by up to 15 percent, and stops by up to 19%.

5.2.Introduction

TRPS mode of operation can be used to operate a system of coordinated intersections in a closed-loop system. TRPS has an advantage of selecting the most appropriate timing plan based on the exiting traffic pattern by capturing the variation in traffic. Counts and occupancies of system detectors spread around the network are collected and aggregated together forming the pattern selection (PS_ parameters. The system master controller keeps track of these PS parameters and compares them to corresponding predefined set of thresholds. The accuracy of the TRPS depends on how accurate these thresholds are.

The TRPS mode has seen limited implementation because of its numerous parameters and the need for calibration to have a stable system. TRPS thresholds are particularly important to be determined in a robust way--assuring that switching from certain plan to another is done when a considerable traffic variation happens. Otherwise, frequent switching between different plans might negatively affect the overall system performance. In this chapter, we propose a Neuro-based methodology to determine the optimal and robust threshold values. In order to facilitate the implementation of the proposed method, a constraint relaxation of the existing TRPS mechanism is described.

The rest of this chapter describes the research conducted, with the first two sections dedicated to the TRPS background and existing threshold mechanism. The following sections describe the research methodology and the study network. Finally, the last two sections describe the findings and conclusions of the chapter.

5.3.Background

Coordinating traffic networks is one of the most challenging fields in traffic engineering generally and traffic signal control specially. There are four modes to operate traffic networks free control mode, Time of Day (TOD) control mode, manual control mode, and TRPS control mode *(23).*Free control mode operates each intersection independently and without considering any other intersections in the network so it does not deal with coordinated systems. In TOD control mode--with is the most commonly used mode-- repetitive traffic patterns are assumed to occur. Considering these repetitive patterns, different timing plans are selected and implemented at the same time every day, so actual traffic pattern does not affect the selection of the timing plan at any time. TOD requires continues timing plans updating such that the plans match the temporal distribution of traffic patterns. Timing plan updating is an effort and time consuming. Manual control mode is achieved by operating all intersections under a constant plan, unless changed by the system operator *(23).*

The TRPS control mode has the same concept of TOD mode, but it has the ability of switching timing plans according to traffic variations. This concept assures the application of the most appropriate timing plan for existing traffic pattern to increase system performance. In order to implement TRPS mode, a set of system detectors should be spread around the network. Counts and occupancies of these system detectors are collected and aggregated to form cycle, offset, and split PS parameters. Certain number of thresholds, as well as different timing plans should be stored in the master controller. The master controller keeps track of the calculated PS parameters and continuously compares them to the predefined thresholds. If any of the new PS parameter values exceed their corresponding thresholds, the master controller selects a different timing plan from the stored library of timing plans.

Considering actual traffic pattern when activating a timing plan gives TRPS mode a good advantage over other control modes. TRPS mode switches the system’s current plan to a better plan when unexpected events, incidents, or temporal changes in traffic volumes occur. In addition, TRPS control mode reduces the need for frequent redesign/update of the signal timing plans for new traffic patterns as required under the TOD control mode.

Although several studies *(4, 20, 21, 22, 37, 38, and 39)* concluded that using TRPS control mode improves system efficiency by decreasing total system delay, TRPS control mode has not been commonly used because there were limited guidelines that describe methods for plan selection, PS parameters calculations, and thresholds determination. Texas Transportation Institute *(23)* had a report published in 2005 to give some guidelines for choosing all the important variables required for TRPS system. This report provided a 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 discriminate analysis. The developed guidelines were presented in simplified tables to facilitate their implementation. These guidelines were verified by using hardware-in-the loop simulations and field implementation.

TTI guidelines consist of four steps designing timing plans for all significant levels of traffic state conditions, running each timing plan with all traffic states in a batch mode to obtain system performance measures if the traffic state was to be associated with that timing plan, degree of detachment (DOD) concept is newly developed and used in the optimization to reduce switching of timing plan that reduces the efficiency of the TRPS system, and the last step is conducting multi-objective optimization for delay, stops, and DOD using a non dominated sorting genetic algorithm to select the optimum timing plans. These steps were followed in the analysis done in this chapter.

Sharma and Abbas *(40)* examined the use of ANN to determine thresholds. Their approach showed an improvement in pattern classification accuracy for the study network This chapter build on the previous work and propose a constraint relaxation to the existing controller mechanism to improve the classification accuracy.

5.4.Existing TRPS Threshold Mechanism

Existing TRPS mechanism collects detector counts and occupancies from system detectors and aggregates them at the master controller level. Master controller then utilizes some computational channels (CC) that are used to calculate the pattern selection (PS) parameters. Each controller manufacture has CC parameters that usually differ from other manufactures. However, most traffic controller manufactures agree on the name and number of the PS parameters namely cycle, split, and offset PS parameters. Thus, EAGLE controller also has these three PS parameters. In EAGLE controllers, up to 64 system detectors could be defined for TRPS system. Maximum of eight system detectors are used to utilize each CC parameter.

The master controller keeps track and compares the calculated PS parameters with a predefined set of thresholds. These thresholds are divided to cycle, split, and offset thresholds. The cycle PS parameters are compared to cycle thresholds and the same for split and offset PS parameters. Comparing the PS parameter values to their corresponding thresholds identifies the appropriate PS parameter level (cycle, offset, and split) in the TRPS selection cuboid. The cube determined from the combination of cycle-offset-split PS parameter levels is typically assigned a timing plan number, which would be the most appropriate timing plan for the existing traffic condition.

In this approach, each threshold for certain PS parameter is a constant number for all levels of other PS parameters. For example, if the traffic controller supports four level of cycle PS parameter, then it will accept only three values for cycle threshold for different levels of split and offset PS parameters. Figure 5.1 shows different levels of PS parameters with the constant thresholds considered in this approach.

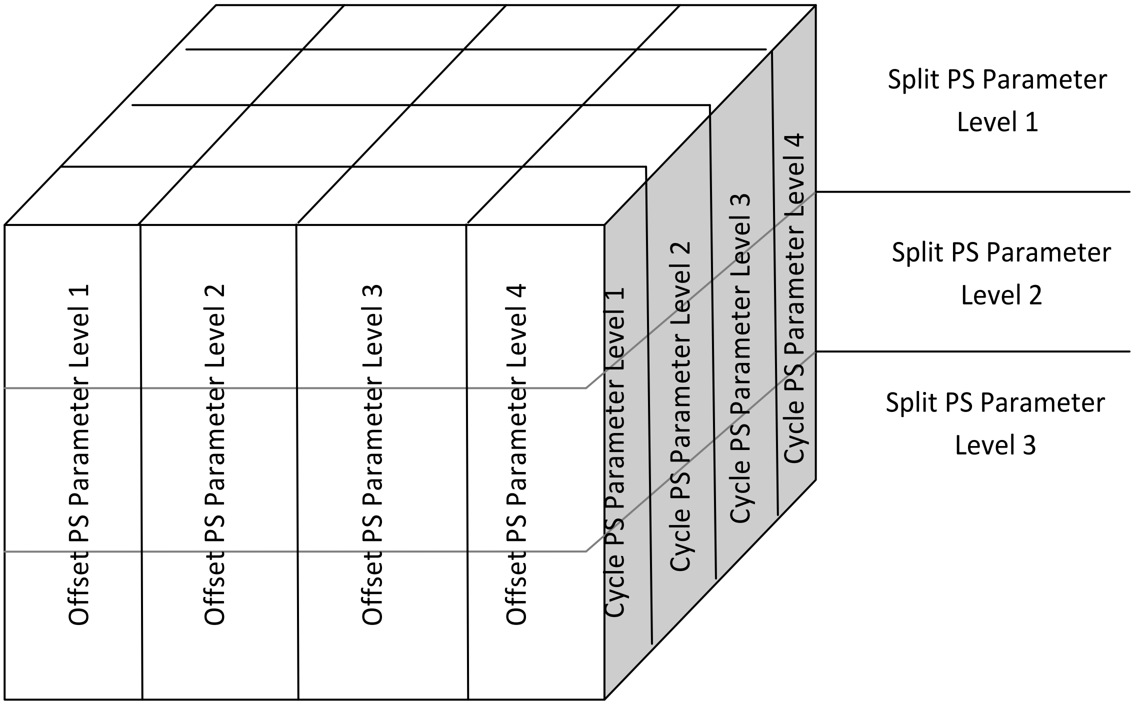


Figure 5.1 Different levels of PS parameters with constant thresholds

A simplification for the three dimensional thresholds system is used to illustrate the proposed methodology. This simplification is carried out by considering only two dimensional PS parameter system cycle and offset PS parameters. Despite this simplification, the main idea proposed could be applied for TRPS systems having any number of PS parameters. Figure 5.2 shows the simplified two dimensional TRPS system.

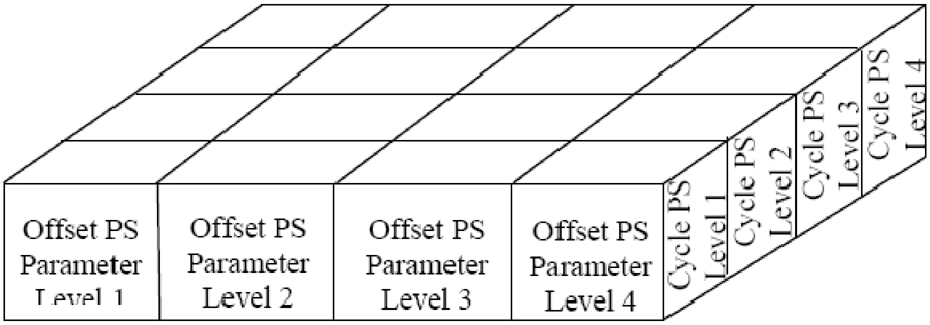


Figure 5.2 Simplified two dimensional TRPS system

5.5.ANN Approach

In the ANN approach, the counts and occupancies from system detectors are collected and scaled to be in the range of 0 to 100. The Scaling factor for counts is the maximum count among all detectors, and the scaling factor for occupancies is the maximum occupancy among all detectors. The K-means clustering algorithm is run over all these scaled counts and occupancies for all traffic states to determine the optimum number of clusters. This is done using Silhouette width. There is considerable number of research chapters describing pattern recognition and clustering techniques using neural network and K-means clustering *(40, 41, 42, 43, 44, and 45)*.

ANN is then used with the scaled counts and occupancies to classify each data to one of the corresponding clusters. This is being done in two steps: (a) using some data to train the network, and (b) using different set of data to validate the trained network. Training data as well as validation data are selected randomly. The network being used consists of an input layer including scaled detector counts and occupancies, two hidden layers, and an output layer. Numbers of neurons in the output layer are equal to the number of clusters obtained for the K-means analysis. MATLAB toolboxes for K-means and ANN are used to perform the required analysis *(40)*.

Different traffic status are developed and run with the trained and validated network to determine the cluster of each one. Knowing weights of each system detector, different PS parameters for each state are determined. Areas presenting each category are displayed in a plot for the PS parameters so that any traffic pattern can be easily classified.

5.6.Study Network

A real traffic network (shown in Figure 5.3) is used in this analysis. The study network is on Reston Parkway Street in Northern Virginia, USA. The network consists of five intersections with spacing between each other ranging from 700 ft to 5940 ft. The speed limit for the main arterial is 45 mph and for the side streets ranging from 25 mph to 35 mph . First intersection is a three legs intersection while all other intersections are four legs intersections.

VISSIM simulation package is used to simulate the network accompanied with Vehicle Actuated Programming (VAP) for simulating EAGLE controllers that control these intersections. On other words, instead of using hardware in the loop simulation, software in the loop simulation is used to simulate traffic controllers. One VAP file is developed to simulate traffic controller at each intersection based on real phases being operated at that intersection.

Phases 4 and 8 at second intersection represent through, right and left movements for east and west bounds respectively. Phases 4 and 8 for third and fourth intersections are split phases and also represent through, right and left movements for east and west bounds respectively. On the other hand, the fifth intersection has a full NEMA 8-phasing. In the design of timing plans, an all-red time of 1second and 3 seconds yellow time are used for all phases.

System detectors are distributed in the network entrances so that traffic entered the network is detected. 16 system detectors are used in the entire network.

5.7.Analysis and Methodology

A large number of traffic patterns (states) that have different optimum timing plan were used in this analysis. These traffic patterns are classified through their perceived system detectors counts and occupancies. The K-means algorithm was used with the scaled counts and occupancies to determine the optimum number of clusters. Using this cluster number as the number of neurons in the output layer of ANN, each traffic pattern is then applied to a certain category. Drawing each category area on the same plot, constant thresholds could be drawn such that it achieves maximum separation between these areas.

Simulation runs were conducted with traffic patterns from different categories to study the classification efficiency of the selected thresholds. Also, the same run is performed but after using variable thresholds and the network performances in the two cases are finally compared. This procedure is further illustrated in the next paragraphs.

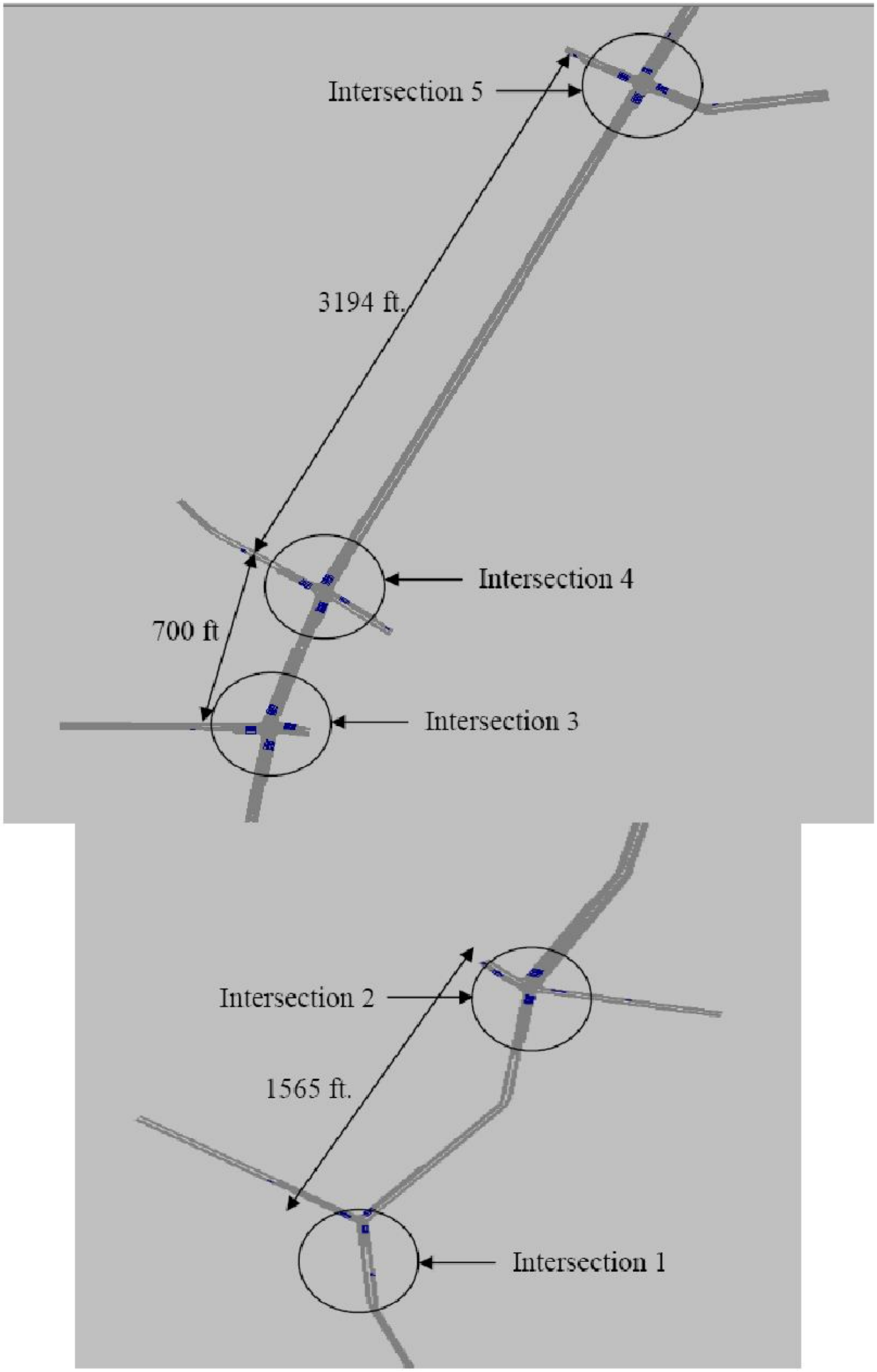


Figure 5.3 Reston parkway network

5.7.1. K-means Analysis

Detector counts and occupancies for each traffic pattern are collected and scaled before being fed to the K-means algorithm in MATLAB with assumed number of clusters. For each number of clusters, Silhouette width is determined and the same step is repeated for different number of clusters. The optimum number of clusters is the one that corresponds to the maximum Silhouette width value. Figure 5.4 shows Silhouette width corresponding to each number of clusters.

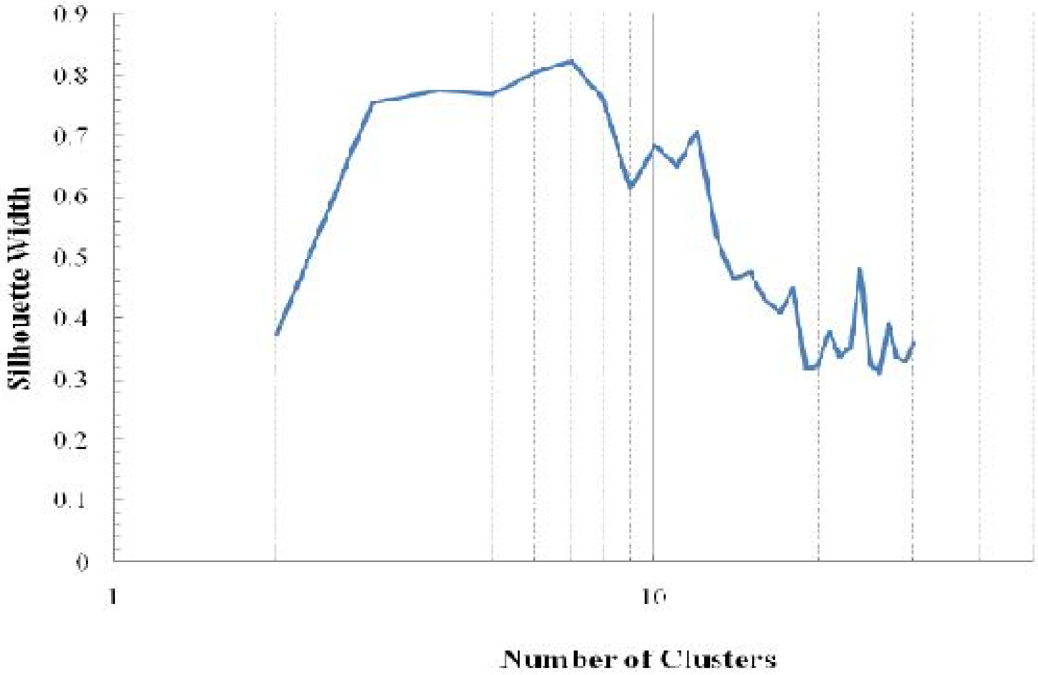


Figure 5.4 Silhouette widths versus number of clusters

It is clear for the above figure that the optimum number of clusters that can efficiently represent all traffic patterns is seven clusters, which corresponds to the highest Silhouette width value of 0.82.

5.7.2. ANN Analysis

Knowing that number of neurons in the output layer is seven as obtain from the K-means analysis, ANN was used to classify each traffic pattern to only one cluster. The network used in the analysis has one input layer, two hidden layers and the output layer. Number of nodes in the input layer is equal to twice the number of system detectors used in the entire network, i.e. 32 nodes. This is because the input layer represents two data obtained from each system detector counts and occupancy. Weights from the input layer to the first hidden layer represent the weights assigned to each detector. ANN is left to determine these weights so that the best patterns classification is achieved. A linear function is used in the first hidden layer while a sigmoid activation function is used in the second hidden layer. The network was trained using training data and then validated using validation data. Training and validation data are selected randomly from system detector data. Figure 5.5 presents the training curve of that network. This training network achieves classification efficiency of 91%.

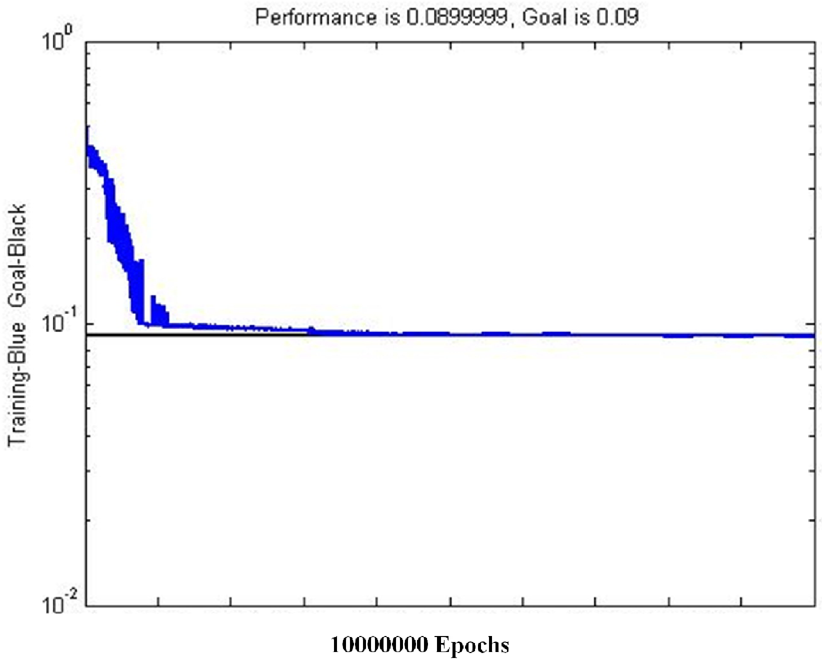


Figure 5.5 Training for the ANN

The trained network was then used to select one cluster for each traffic pattern. Getting the weighting factors for each system detector from the ANN and knowing counts and occupancies for each detector, these values were aggregated to cycle and offset PS parameters. This way each cluster is defined by an area obtained from all traffic patterns that belong to this cluster. The separation in PS parameter for each clusters was then plotted in different colors (as shown in Figure 5.6) to show this separation. Each cluster represents a zone that has to have an optimum timing plan to be implemented if the cycle and offset PS parameters for actual traffic were located in this zone. This approach would be superior if the traffic controller supported thresholds as areas or zones. In reality, however, constant thresholds must be drawn to achieve maximum separation between different timing plans areas as shown in Figure 5.7. An approximation of these optimal threshold could be obtained by relaxing the constraint of constant (solid line) cycle threshold for all offset levels, and vice versa.

Figure 5.8 shows this constraint relaxation by using variable thresholds that can break through different levels to achieve maximum separation between different clusters or timing plans.

While the relaxed thresholds would not completely achieve maximum separation similar to the ANN approach, they can increase the classification accuracy significantly. Variable thresholds appear to have more classification efficiency than constant thresholds and less than ANN approach.

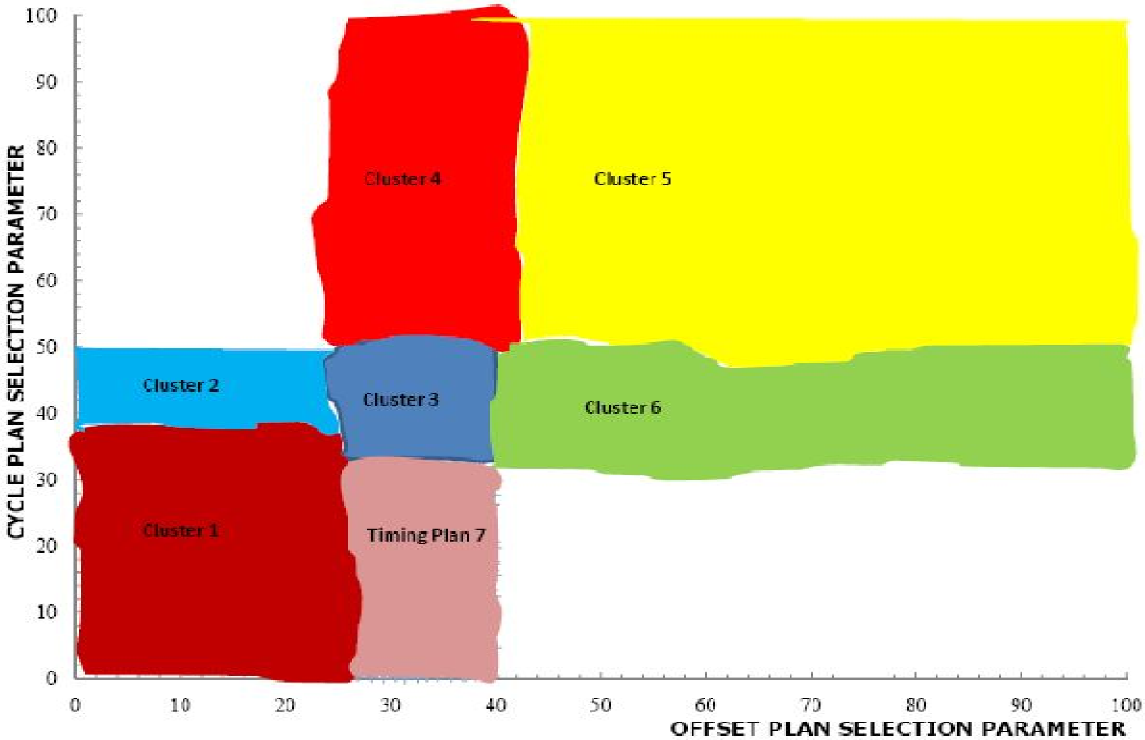


Figure 5.6 Different clusters resulted from ANN

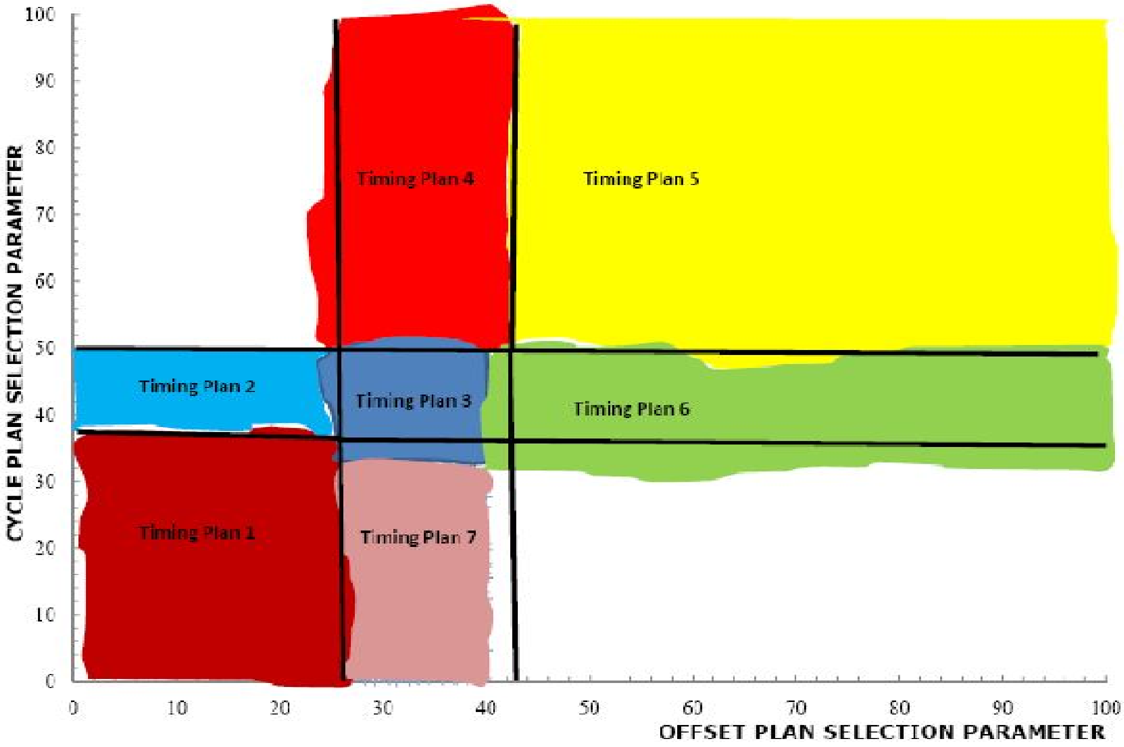


Figure 5.7 Constant thresholds separating different timing plan areas

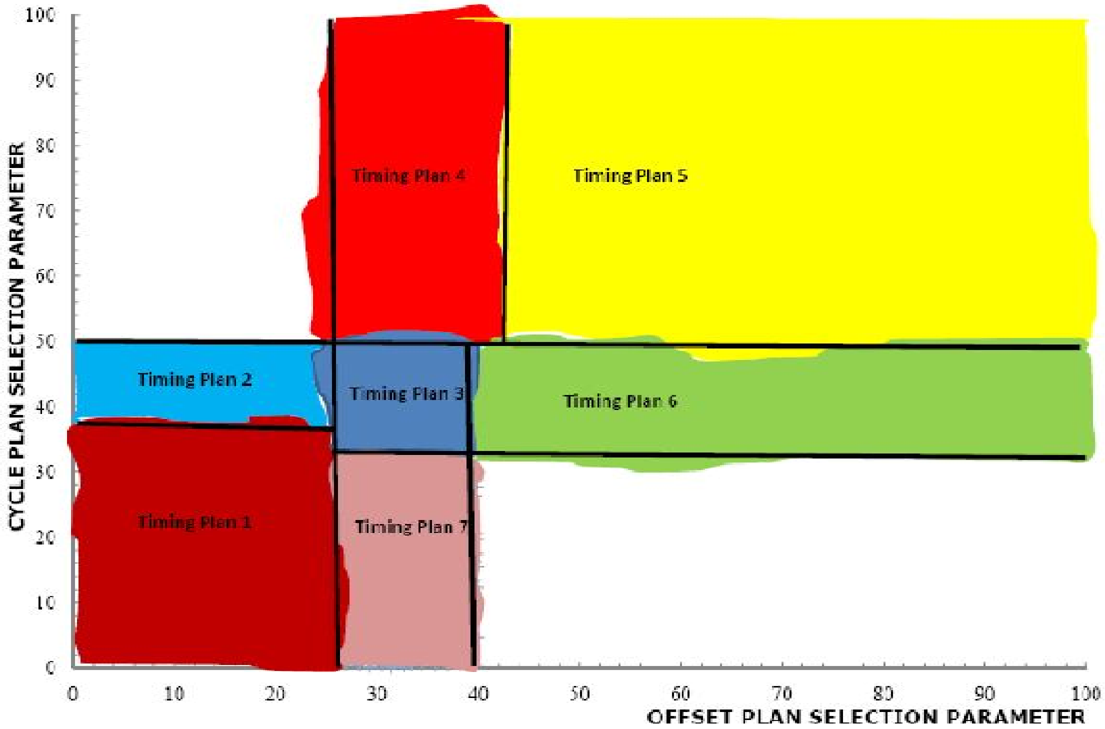


Figure 5.8 Variable thresholds give better pattern classification

5.7.3. Before and After Comparison

To test the above stipulations, seven traffic patterns were selected such that one traffic pattern belongs to each timing plan or cluster area as shown in Figure 5.9 and Figure 5.10. These traffic patterns were used with VISSIM simulation package to simulate TRPS on Reston parkway network. Table 5.1 shows different traffic movements for each pattern.

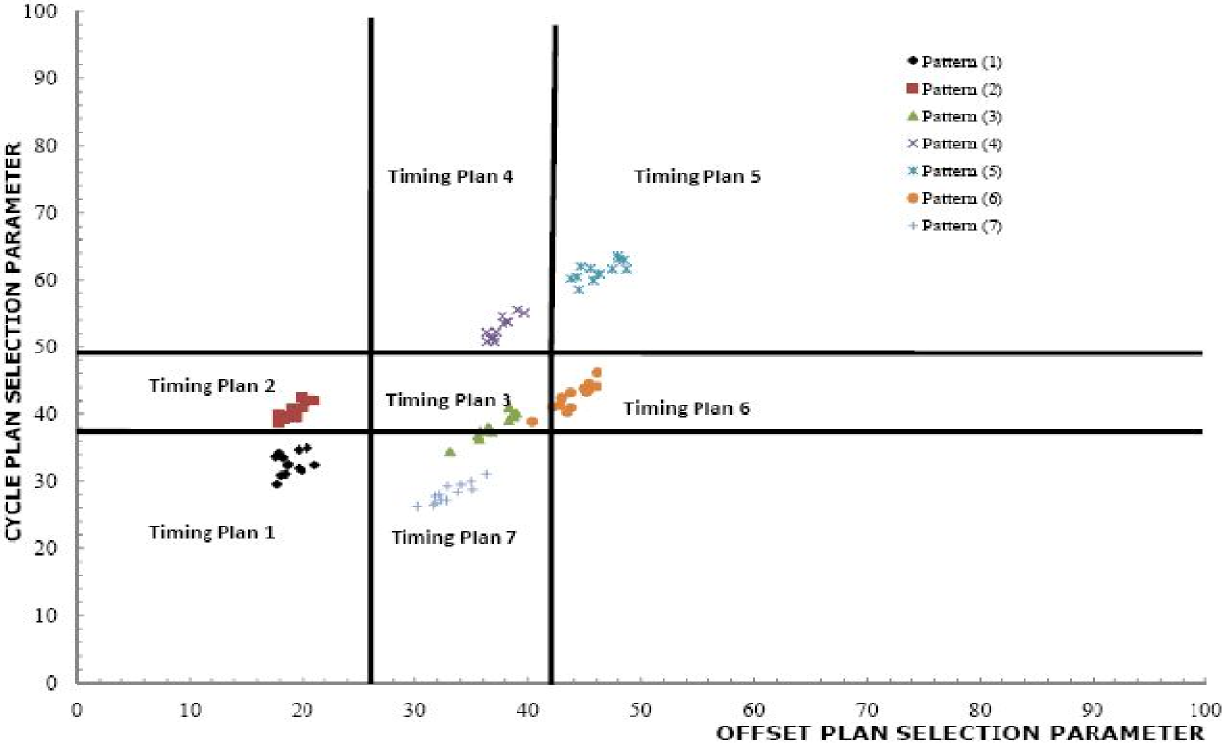


Figure 5.9 Selected traffic patterns with constant thresholds

PASSER optimization package was used to determine the optimum timing plan corresponding to each one of these traffic patterns. The seven timing plans were inserted into the VAP files to simulate all the possible plans in the entire system. Table 5.2 presents timing plans and their corresponding traffic patterns.

Two VISSIM runs were conducted for the same traffic patterns, one with constant thresholds and the other with variable thresholds. The two scenarios were run for 5 hours, in which traffic inputs to the network were changing such that all the traffic pattern were visited at least two time for 30 minutes. Counts and occupancies were collected from system detectors and were compared to these thresholds every 15 minutes.

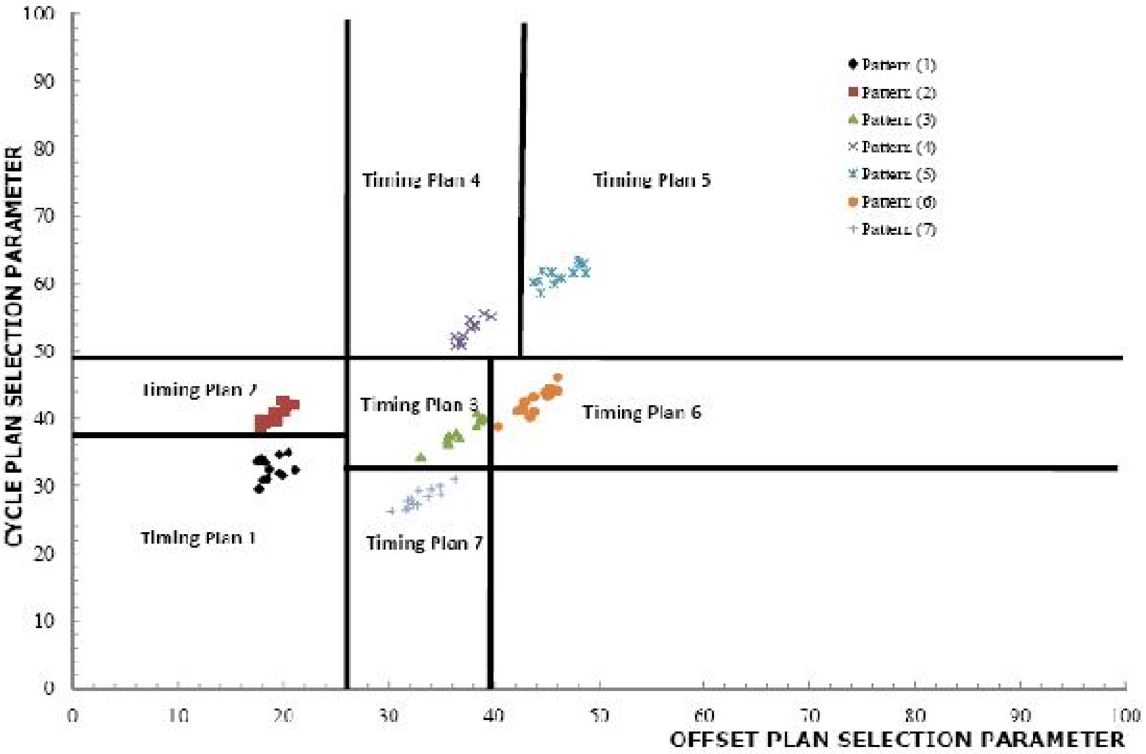
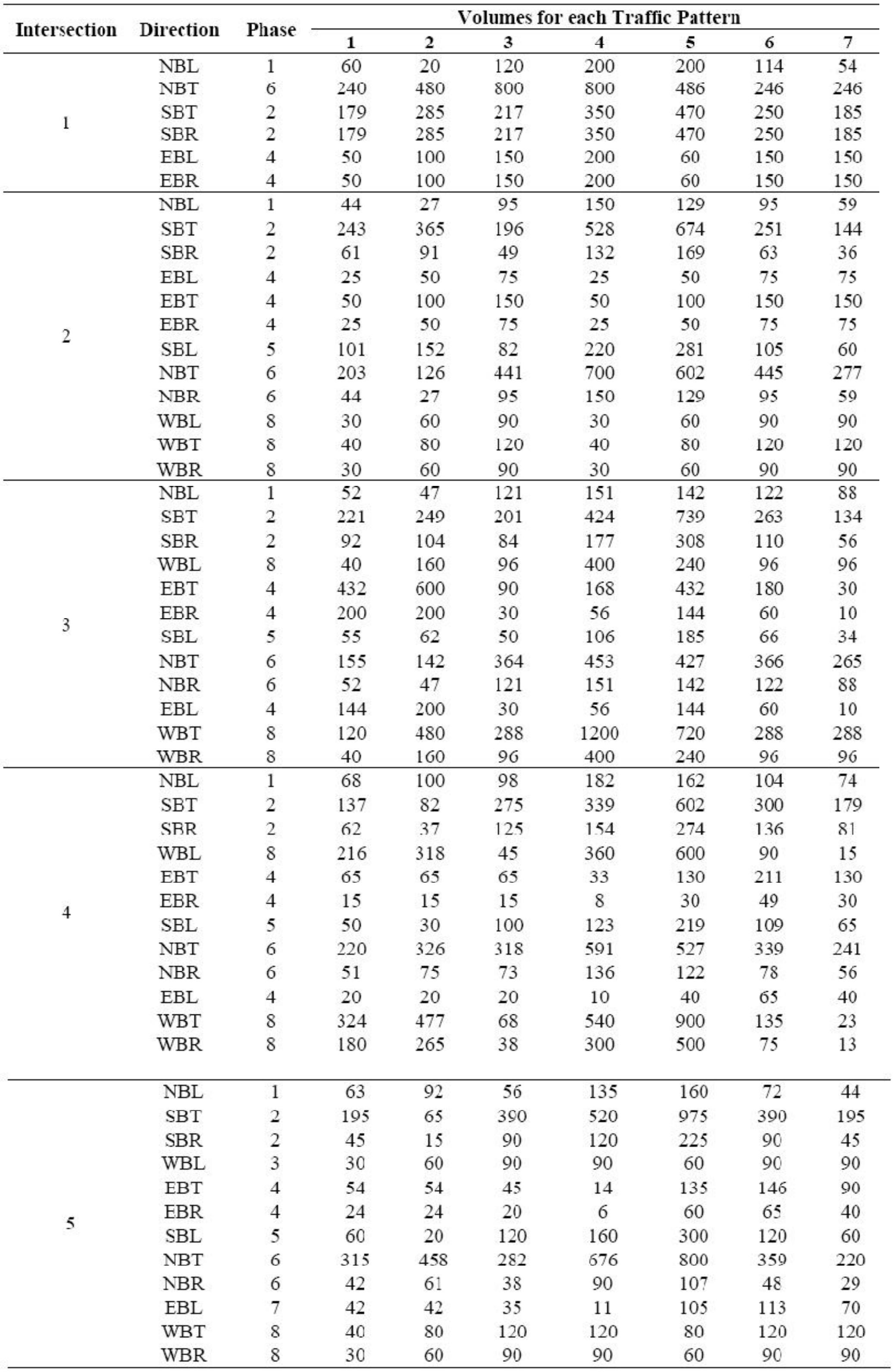


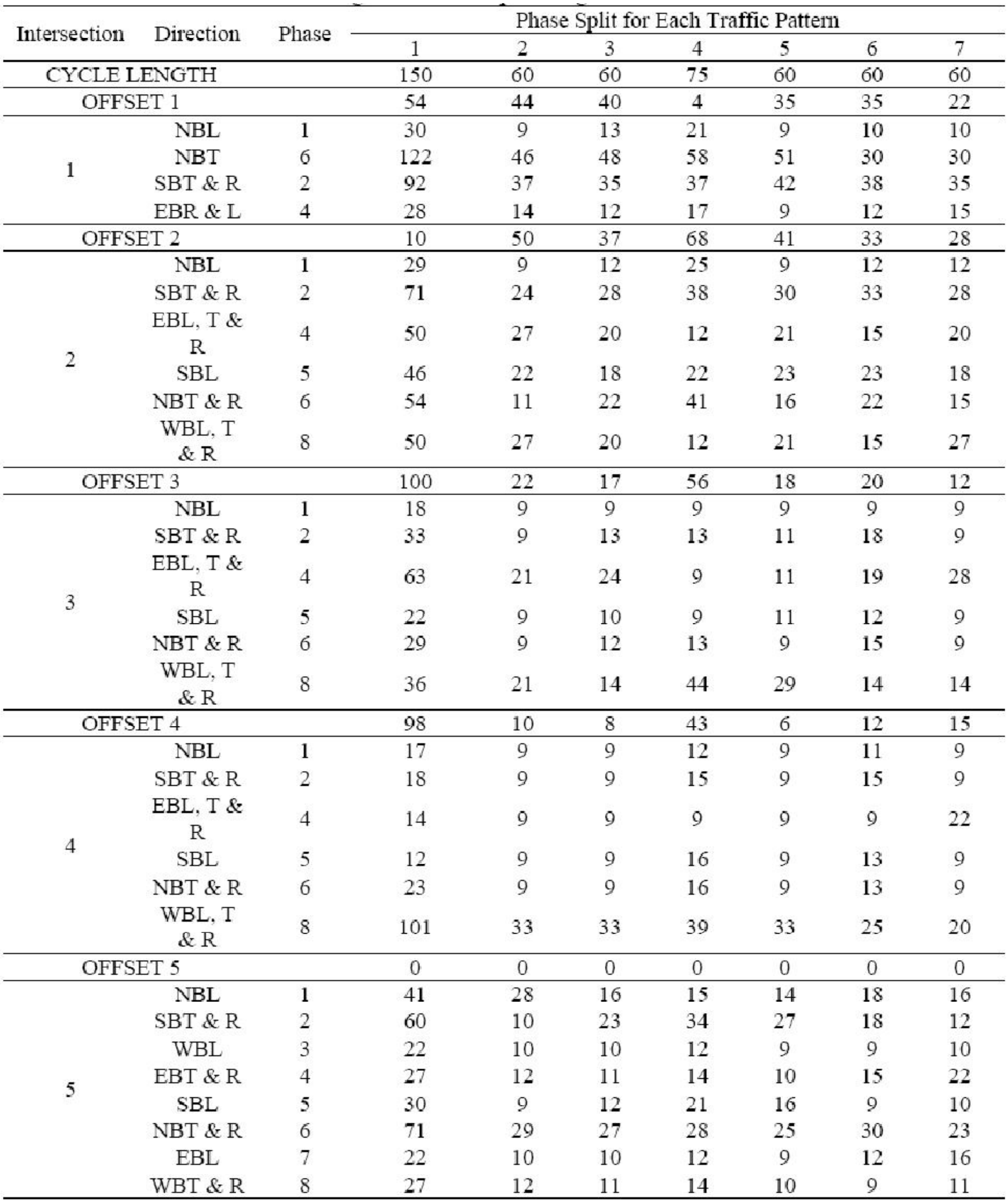
Figure 5.10 Selected traffic patterns with variable thresholds

Table 5.1 Traffic Movements for Selected Patterns at Each Intersection.



Intersection	Direction	Phase	Volumes for each Traffic Pattern						
			1	2	3	4	5	6	7
1	NBL	1	60	20	120	200	200	114	54
	NBT	6	240	480	800	800	486	246	246
	SBT	2	179	285	217	350	470	250	185
	SBR	2	179	285	217	350	470	250	185
	EBL	4	50	100	150	200	60	150	150
	EBR	4	50	100	150	200	60	150	150
2	NBL	1	44	27	95	150	129	95	59
	SBT	2	243	365	196	528	674	251	144
	SBR	2	61	91	49	132	169	63	36
	EBL	4	25	50	75	25	50	75	75
	EBT	4	50	100	150	50	100	150	150
	EBR	4	25	50	75	25	50	75	75
	SBL	5	101	152	82	220	281	105	60
	NBT	6	203	126	441	700	602	445	277
	NBR	6	44	27	95	150	129	95	59
	WBL	8	30	60	90	30	60	90	90
	WBT	8	40	80	120	40	80	120	120
	WBR	8	30	60	90	30	60	90	90
3	NBL	1	52	47	121	151	142	122	88
	SBT	2	221	249	201	424	739	263	134
	SBR	2	92	104	84	177	308	110	56
	WBL	8	40	160	96	400	240	96	96
	EBT	4	432	600	90	168	432	180	30
	EBR	4	200	200	30	56	144	60	10
	SBL	5	55	62	50	106	185	66	34
	NBT	6	155	142	364	453	427	366	265
	NBR	6	52	47	121	151	142	122	88
	EBL	4	144	200	30	56	144	60	10
	WBT	8	120	480	288	1200	720	288	288
	WBR	8	40	160	96	400	240	96	96
4	NBL	1	68	100	98	182	162	104	74
	SBT	2	137	82	275	339	602	300	179
	SBR	2	62	37	125	154	274	136	81
	WBL	8	216	318	45	360	600	90	15
	EBT	4	65	65	65	33	130	211	130
	EBR	4	15	15	15	8	30	49	30
	SBL	5	50	30	100	123	219	109	65
	NBT	6	220	326	318	591	527	339	241
	NBR	6	51	75	73	136	122	78	56
	EBL	4	20	20	20	10	40	65	40
	WBT	8	324	477	68	540	900	135	23
	WBR	8	180	265	38	300	500	75	13
5	NBL	1	63	92	56	135	160	72	44
	SBT	2	195	65	390	520	975	390	195
	SBR	2	45	15	90	120	225	90	45
	WBL	3	30	60	90	90	60	90	90
	EBT	4	54	54	45	14	135	146	90
	EBR	4	24	24	20	6	60	65	40
	SBL	5	60	20	120	160	300	120	60
	NBT	6	315	458	282	676	800	359	220
	NBR	6	42	61	38	90	107	48	29
	EBL	7	42	42	35	11	105	113	70
	WBT	8	40	80	120	120	80	120	120
	WBR	8	30	60	90	90	60	90	90

Table 5.2 Timing Plan Corresponding to Each Traffic Pattern.



Intersection	Direction	Phase	Phase Split for Each Traffic Pattern						
			1	2	3	4	5	6	7
CYCLE LENGTH			150	60	60	75	60	60	60
OFFSET 1			54	44	40	4	35	35	22
1	NBL	1	30	9	13	21	9	10	10
	NBT	6	122	46	48	58	51	30	30
	SBT & R	2	92	37	35	37	42	38	35
	EBR & L	4	28	14	12	17	9	12	15
OFFSET 2			10	50	37	68	41	33	28
2	NBL	1	29	9	12	25	9	12	12
	SBT & R	2	71	24	28	38	30	33	28
	EBL, T & R	4	50	27	20	12	21	15	20
	SBL	5	46	22	18	22	23	23	18
	NBT & R	6	54	11	22	41	16	22	15
	WBL, T & R	8	50	27	20	12	21	15	27
OFFSET 3			100	22	17	56	18	20	12
3	NBL	1	18	9	9	9	9	9	9
	SBT & R	2	33	9	13	13	11	18	9
	EBL, T & R	4	63	21	24	9	11	19	28
	SBL	5	22	9	10	9	11	12	9
	NBT & R	6	29	9	12	13	9	15	9
	WBL, T & R	8	36	21	14	44	29	14	14
OFFSET 4			98	10	8	43	6	12	15
4	NBL	1	17	9	9	12	9	11	9
	SBT & R	2	18	9	9	15	9	15	9
	EBL, T & R	4	14	9	9	9	9	9	22
	SBL	5	12	9	9	16	9	13	9
	NBT & R	6	23	9	9	16	9	13	9
	WBL, T & R	8	101	33	33	39	33	25	20
OFFSET 5			0	0	0	0	0	0	0
5	NBL	1	41	28	16	15	14	18	16
	SBT & R	2	60	10	23	34	27	18	12
	WBL	3	22	10	10	12	9	9	10
	EBT & R	4	27	12	11	14	10	15	22
	SBL	5	30	9	12	21	16	9	10
	NBT & R	6	71	29	27	28	25	30	23
	EBL	7	22	10	10	12	9	12	16
	WBT & R	8	27	12	11	14	10	9	11

5.8.Analysis Results and Discussions

It was found that variable thresholds enhance network performance by reducing both of average number of stops and average delay. For average number of stops, a reduction of 15% was achieved. While for the average delay, a reduction of 19% was achieved. Thus, using variable thresholds improves TRPS system by reducing misclassification and consequently reducing total number of stops and average delay. Figure 5.11 and Figure 5.12 show the differences in the average delay and average number of stops between using constant thresholds and variable thresholds, respectively.

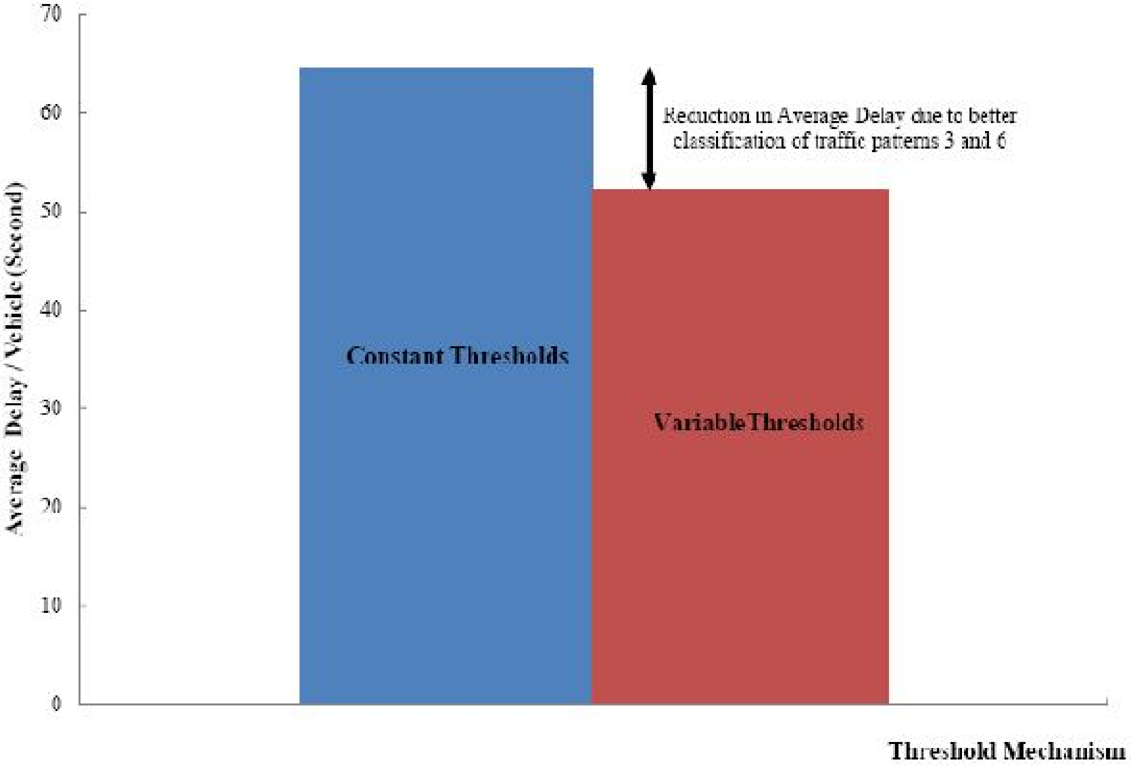


Figure 5.11 The before-after average delay for constant thresholds versus variable thresholds

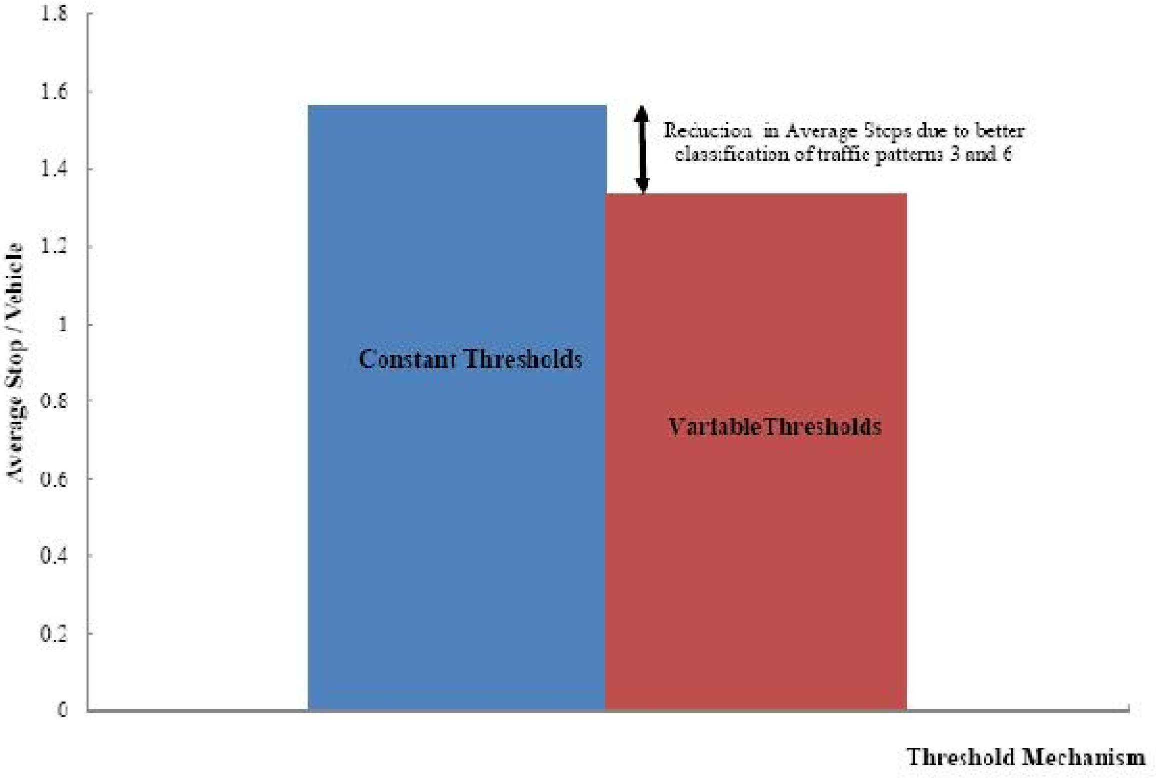


Figure 5.12 The before-after average stops for constant thresholds versus variable thresholds

This improvement in network performance was expected because it is clear that variable thresholds have more ability to classify traffic patterns efficiently. For example, there is a misclassification for traffic patterns 3 and 6 with constant thresholds. This misclassification affects the network performance negatively because it results in the system continuous switching between timing plans. This unneeded timing plan switching is the main disadvantages for any TRPS that can be reduced if the thresholds are selected properly.

Variable thresholds reduced the misclassification of patterns 3 and 6 so that it resulted in better overall network performance. Variable thresholds are expected to achieve more improvement for networks of bigger scales than this network. Also, the improvement is expected to be more for networks having large traffic variations and more timing plans.

5.9.Conclusions

TRPS performance depends on accuracy of identifying traffic patterns. It is not possible to achieve 100% classifying accuracy. The exiting classification method (i.e. constant threshold method) does not do good classification accuracy. However, it is believed from the entire analysis that the existing TRPS mechanism can be improved with the use of ANN classification techniques. This ANN classification requires implementing of ANN in the traffic controllers. Using this ANN classification technique, traffic patterns are easier to be captured and therefore classification accuracy is significantly improved. Implementing ANN in the traffic controllers might take long time, and since traffic engineers do not prefer exiting TRPS mode of operation in coordinated networks because of its low classification accuracy; a new easy method to improve this accuracy is to use simple constraint relaxation in the current threshold mechanism.

The proposed constraint relaxation depends on using variable thresholds instead of constant thresholds to separate between different traffic patterns. This relaxation is tested in the analysis and it shows average results between the existing system and the ANN classification. This suggestion does not require significant changes in traffic controllers like ANN, however it achieves better classification and identification of traffic patterns. Therefore, constraint relaxation (i.e. variable thresholds) is suggested to be implemented in traffic controllers until ANN-based controllers becoming available in the market. Using this relaxation with TRPS ability to capture traffic patterns and selecting the corresponding timing plan, TRPS is expected to be used more in coordinated networks therefore network performance increases significantly.

Chapter 6 : Pedestrian Effect on Traffic Responsive Plan Selection Control and New Pedestrian Framework

6.1.Abstract

Current Traffic Responsive Plan Selection (TRPS) control system does not provide an efficient mechanism to accommodate pedestrian movements. Pedestrian movements might have a large affect on the system if pedestrian buttons are used to serve pedestrian demands. Pedestrian buttons generally interrupt signal coordination and reduce the overall efficiency of TRPS system. In some cases where heavy pedestrian movements are present, the traffic engineer might account for these movements on the design of the timing plans in addition to vehicle demands. There are no existing guidelines on when to switch from the pedestrian button operation to timing plan accommodation. This chapter presents the result of a research on the affect of different pedestrian movement volumes on TRPS performance and recommends new framework to accommodate pedestrians with TRPS systems.

6.2.Introduction

Traffic responsive plan selection (TRPS) mode of operation is one of the control modes used to operate a system of coordinated intersections in a closed-loop system. TRPS has an advantage of selecting the timing plan based on the exiting traffic pattern by capturing the variation in traffic. Counts and occupancies of system detectors located on strategic locations on the network are collected and aggregated forming what is known as pattern selection (PS) parameters. The master controller keeps track of these PS parameters and compares them to corresponding predefined set of thresholds to activate the most appropriate stored timing plan for the existing traffic pattern.

TRPS mode of operation considers only vehicles when switching between timing plans, pedestrians' demands are not considered in decision process. However, it is understood that pedestrian might affect the overall network performance depending on the way they are considered in the controlling system. There are basically two methods to consider pedestrians: the first is by using pedestrian calls (which causes interruption to traffic signal coordination when pedestrians are present), the second is by designing the traffic phases to accommodate pedestrians in the first place (resulting in longer phase durations and hence a reduction in the traffic movement efficiency). Using any of the above methods to accommodate pedestrians in TRPS networks affects the overall network performance in a different way compared to the other method. This chapter studies the difference between these two methods for pedestrians and determines the levels up to which each one of them is considered efficient.

This chapter is divided into six sections. Section 2 presents historical background for TRPS mode of operation and pedestrians in coordinated systems. Section 3 describes the two available methods to consider pedestrians in coordinated networks. Section 4 defines the network under consideration. Section 5 includes the analysis terminology. Section 6 discusses the results obtained.

6.3.Background

Coordinating traffic networks is one of the most challenging fields in traffic engineering generally and traffic signal control specially. There are four modes to operate traffic networks free control mode, Time of Day (TOD) control mode, manual control mode, and TRPS control mode *(23)*.

Free control mode operates each intersection independently and without considering any other intersections in the network so it does not deal with coordinated systems. In TOD control mode, the most commonly used control mode, repetitive traffic patterns are assumed. Considering these repetitive patterns, different timing plans are selected and implemented at the same time every day, so the actual traffic pattern does not affect the existing timing plan. TOD requires continuous timing plans update such that the plans match the temporal distribution of traffic pattern. Manual control mode is achieved by operating all intersections under a constant plan, unless changed by the system operator *(23)*.

TRPS control mode provides functionalities similar to the TOD mode, but it has the ability of switching timing plans in response to traffic variations. This assures the application of the most appropriate timing plan for existing traffic pattern which improves the overall system performance. In order to implement TRPS mode, a set of system detectors should be spread around the network. Counts and occupancies of these system detectors are collected and aggregated to form cycle, offset, and split PS parameters. Certain number of thresholds, as well as different timing plans should be stored in the master controller. The master controller keeps track if the calculated PS parameters and continuously compares them to the predefined thresholds. If any of the new PS parameter values exceed their corresponding thresholds, the master controller selects a different timing plan from the stored library of timing plans.

The most important advantage TRPS control mode is that it provides the most optimal and snappiest operation over all other modes. This ability stems from the fact that TRPS mode switches the system's current plan to a better plan when unexpected events, incidents, or temporal changes in traffic volumes occur. In addition, TRPS control mode reduces the need for frequent redesign/update of the signal timing plans for new traffic patterns as required for TOD control mode. Several researchers studied the TRPS operation and agreed to its superiority over TOD mode *(4, 20, 22, 37, 38, and 39).*

Pedestrian are not considered in TRPS system while it is believed that they have a big effect on the overall efficiency of the system. Research has been done in pedestrian effects on different operating such as *(46, and 47)*. Pedestrian effect on TRPS is a new topic has not been studied much. This chapter attempts to fill some of this research gap.

6.4.Pedestrian in TRPS Systems

General TRPS systems consist of three levels of three different plan selection (PS) parameters cycle, offset, and split parameters. These parameters are determined using counts and occupancies collected from system detectors. These counts and occupancies are collected in the master controller that is responsible for aggregating all detector data into these three parameters only. The master controller is also responsible for tracking the change in these parameters and comparing them to a predefined set of thresholds. Based on this continuous comparison, master controller chooses the most appropriate timing plan for the existing traffic conditions.

In networks operated by TRPS mode of operation, Pedestrians crossing the main arterial have the most attention because in TRPS system, the goal is to give main arterial through movement as much green time as possible. This typically causes the assignment of a short green phase duration for the side street and longer phase duration for the main arterial. This allocation of green provides pedestrians crossing side street (crossing when the main street is green) more than enough time to cross, while for those crossing the main arterial (crossing while the main arterial phases are green) do not have enough time.

Two methods are typically used to accommodate pedestrians in networks operated by TRPS mode. The first is done by using pedestrian calls; the second is done using pedestrian phases. In the following subsections a detailed description for both ways.

6.4.1. Method 1: Pedestrian Calls

This method is generally preferred with low pedestrian demands. The method has the advantage of being implemented with relatively short cycle lengths to increase the traffic movement efficiency. However, if pedestrian call exists, the corresponding phase will be extended to allow pedestrian crossing. This in turn will cause the subject intersection to have a longer cycle length and basically being separated from the other intersections in the network. . The signal system spends some time trying to re-coordinate itself again as a result. This re-coordination is achieved by transitioning the new offset value (due to the temporary cycle extension) to the old offset value.

The drawback of this method with TRPS system is that it needs some time to make an internal transition within the currently implemented plan as well as the normal transition between different plans used in TRPS system. Making many transitions affects the overall network performance negatively. Thus, this method is considered efficient with low pedestrian volumes because the number of transitions caused by pedestrian calls is not large.

Figure 6.1 shows the effect of using pedestrian calls with TRPS systems. It appears in this figure that when pedestrians are not considered in the system, there is only one transition between different timing plans (Figure 6.1.b).

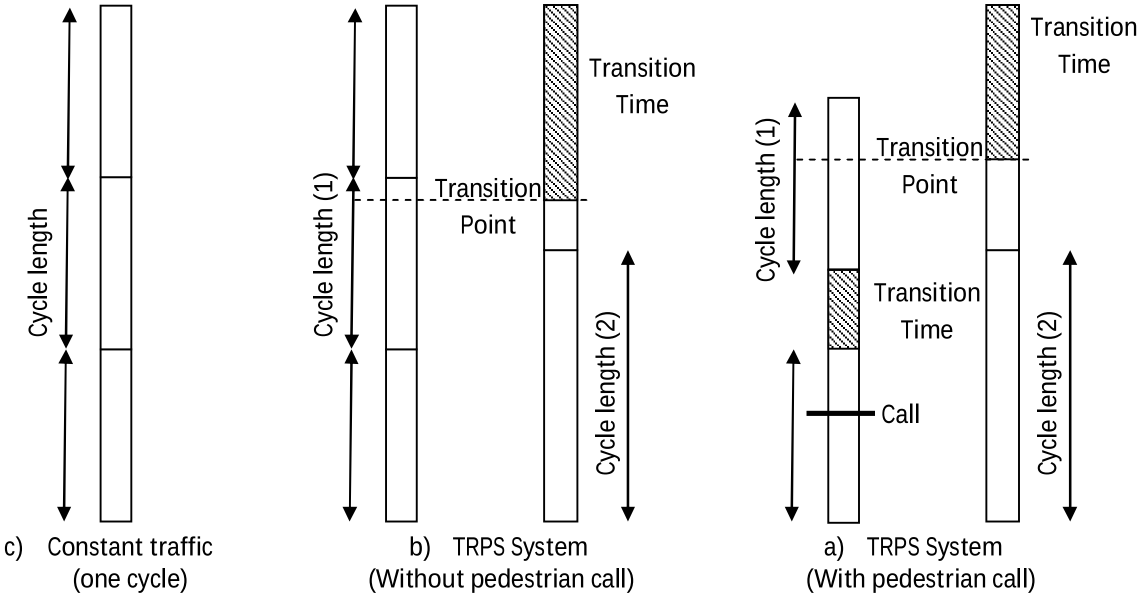


Figure 6.1 Effect of Pedestrian Calls in TRPS Systems

On the other hand, when pedestrians are considered in the system, there are two transitions one transition is within the same timing plan while the other one is the original transition between different timing plans (Figure 6.1.c). These two transitions affect the performance of the system as they required more time to achieve required offsets between different intersections.

6.4.2. Method 2: Pedestrian Phases

This method to accommodate pedestrians is preferred with medium and high pedestrian volumes. The reason for this is that this method considers pedestrian phases in the cycle length which results in long cycle lengths. These long cycle lengths increase the travel time as well as number of stops for vehicular traffic. However, with large pedestrian demands, this method tends to be more efficient than the constant transitioning associated with the first method.

The study was conducted to determine the range of pedestrian demands for each one of these methods to be more efficient. It is believed that for each network this range differs but in order to determine it with an acceptable confidence level, steps being presented here below might be followed. Also, as a result of this study, new proposed framework to consider pedestrians is suggested.

6.5.Study Network

A real traffic network is used in the analysis in this chapter. This network is on Reston Parkway Street in Northern Virginia, USA. The network consists of three intersections with spacing between each other are 824 ft and 1087 ft. The speed limit for the main arterial is 45 mph and 35 mph for the side streets. All these intersections are four legs intersections.

VISSIM simulation package is used to simulate the network accompanied with Vehicle Actuated Programming (VAP) for simulating EAGLE controllers that control these intersections. On other words, instead of using hardware in the loop simulation, software in the loop simulation is used to simulate traffic controllers. One VAP file is developed to simulate traffic controller at each.

All these intersections have a full NEMA phasing. in the design of timing plans, an all-red time of 1 seconds and 3 second yellow time are used for all phases.

System detectors are distributed in the network entrances so that traffic entered the network is detected. 16 system detectors are used in the entire network. Figure 6.2 shows the network used in the analysis.

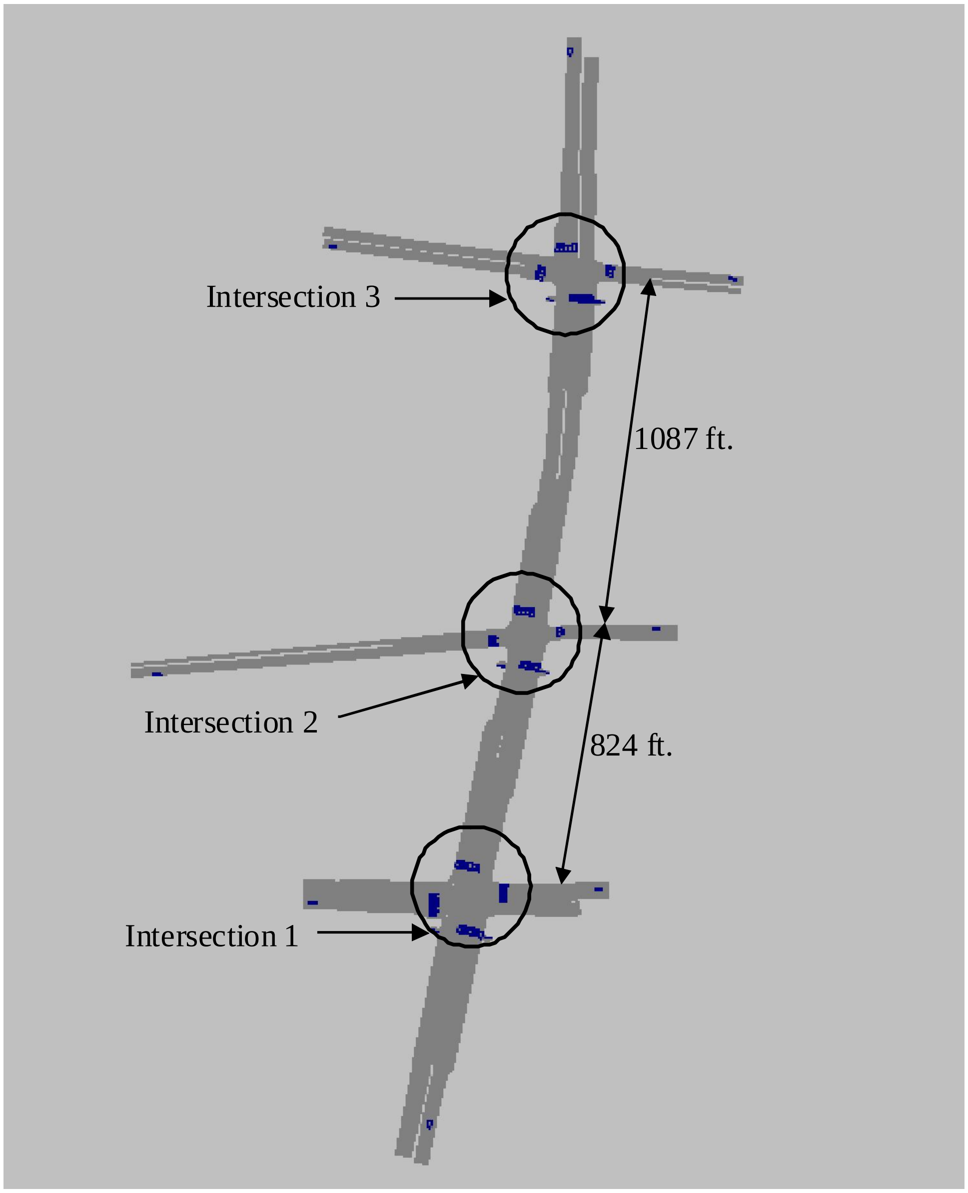


Figure 6.2 Reston Parkway Network

6.6.Analysis Terminology

The objective of this research was to determine pedestrian volumes under which each of the two methods for accommodating pedestrians should be considered in TRPS systems. Four traffic patterns were considered. Table 6.1 represents traffic patterns being considered in the analysis. The side streets in the network have low traffic volumes such that the green time required for pedestrian crossing main arterial is much greater than the required green for side-street. Providing these conditions, different runs are performed. These runs can be divided to run set for base traffic pattern (traffic pattern number 1) considering different pedestrian volumes, run set for all presented traffic patterns considering different pedestrian volumes, and the last run set is also for all presented traffic patterns considering different pedestrian volumes but with different pattern sequence and different pattern period. Each run set includes two runs; the first is for pedestrian calls while the second is for pedestrian phases.

The purpose of using the first run set is to compare TRPS system to non-TRPS system. The second run set represents TRPS systems with certain pattern sequence and pattern time range. The last run set is performed to determine if the traffic pattern sequence and timings affect the threshold between pedestrian calls and pedestrian phases or not. The first TRPS configuration is using sequence of traffic pattern 1, 2, 3, and 4 while the second TRPS configuration is performed using pattern sequence of pattern 3, 2, 1, 4. TRPS system is responsible in implementing optimum timing plan for each pattern. Table 6.2 presents optimum timing plans for each traffic pattern considering pedestrians using pedestrian calls i.e. without assigning the minimum green required for pedestrians to clear the main arterial to the side street movements. Optimum timing plan for each traffic pattern with certain pedestrian volume is determined in case of considering pedestrians using pedestrian phases. PASSER optimization program was used to obtain optimum plans. Different traffic patterns are run and the system detector counts and occupancies are collected then the cycle and offset parameters for each pattern is calculated and plotted as shown in Figure 6.3.

For pedestrian calls, the minimum green required for pedestrians to clear the main arterial is estimated using formula given in the Highway Capacity Manual *(48)*. This formula depends on the width of the intersection and hourly pedestrian volume. Thus, each intersection of the three intersections under consideration has its own minimum green for the same pedestrian volumes.

For pedestrian phases, maximum pedestrian volume expected at signalized intersections is used to determine timing plan for each traffic patterns based on the same HCM formula. Maximum pedestrian volume at signalized intersections is estimated as 250 ped/hour as described in the online *FHWA capacity Analysis of Pedestrian and Bicycle Facilities manual*. However, maximum pedestrian volume considered in the entire study is selected to be 400 ped/hour since FHWA suggestion is just the pedestrian volume causing significant increase in green time for intersections having width more than 82ft. Based on the proposed maximum pedestrian volume of 400 ped/hour, one minimum green time at each intersection is used with pedestrian phases.

Performing the proposed runs for different pedestrian volume and determining the average delay and average number of stops resulted from each run then plotting these values on the same figure, Figure 6.4 and Figure 6.5 are produced. In Figure 6.4, average delay per vehicle is plotted versus pedestrian volume for each run. Also, in Figure 6.5, average number of stops per vehicle is plotted versus pedestrian volume for each run.

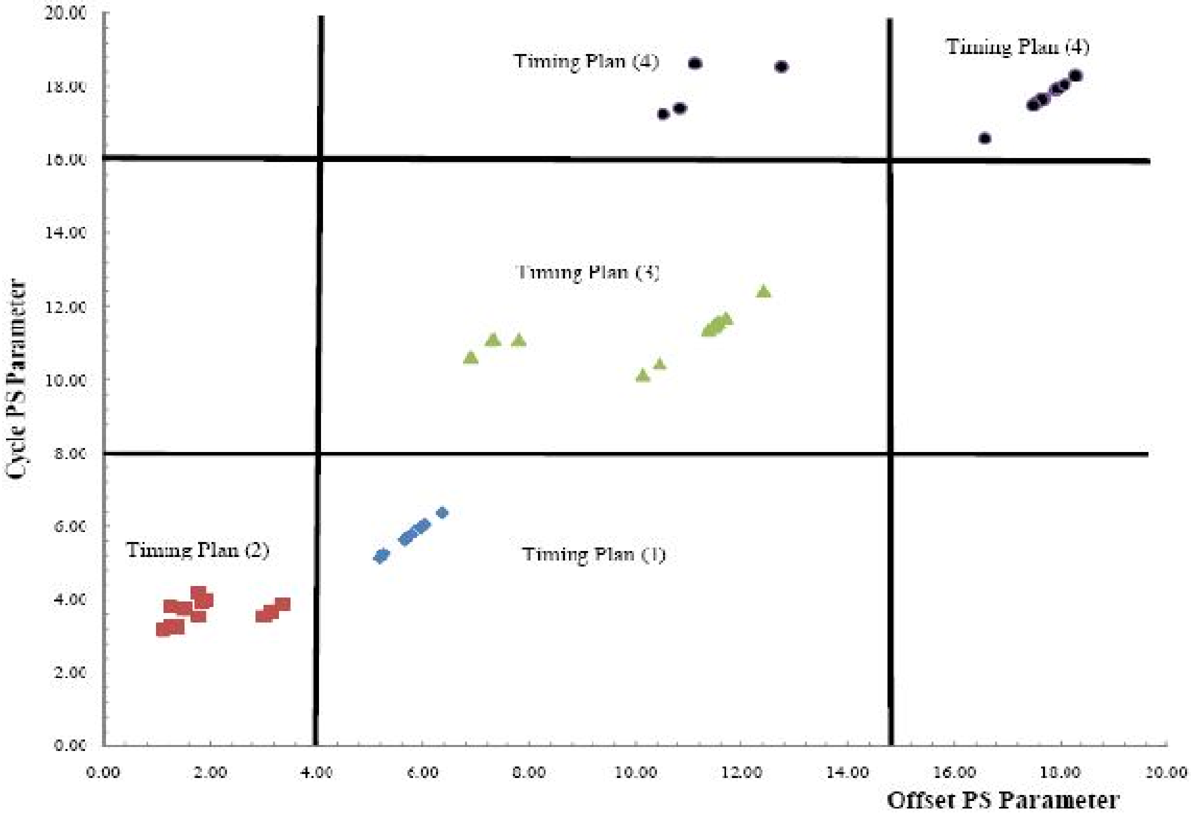


Figure 6.3 Traffic Patterns in TRPS system

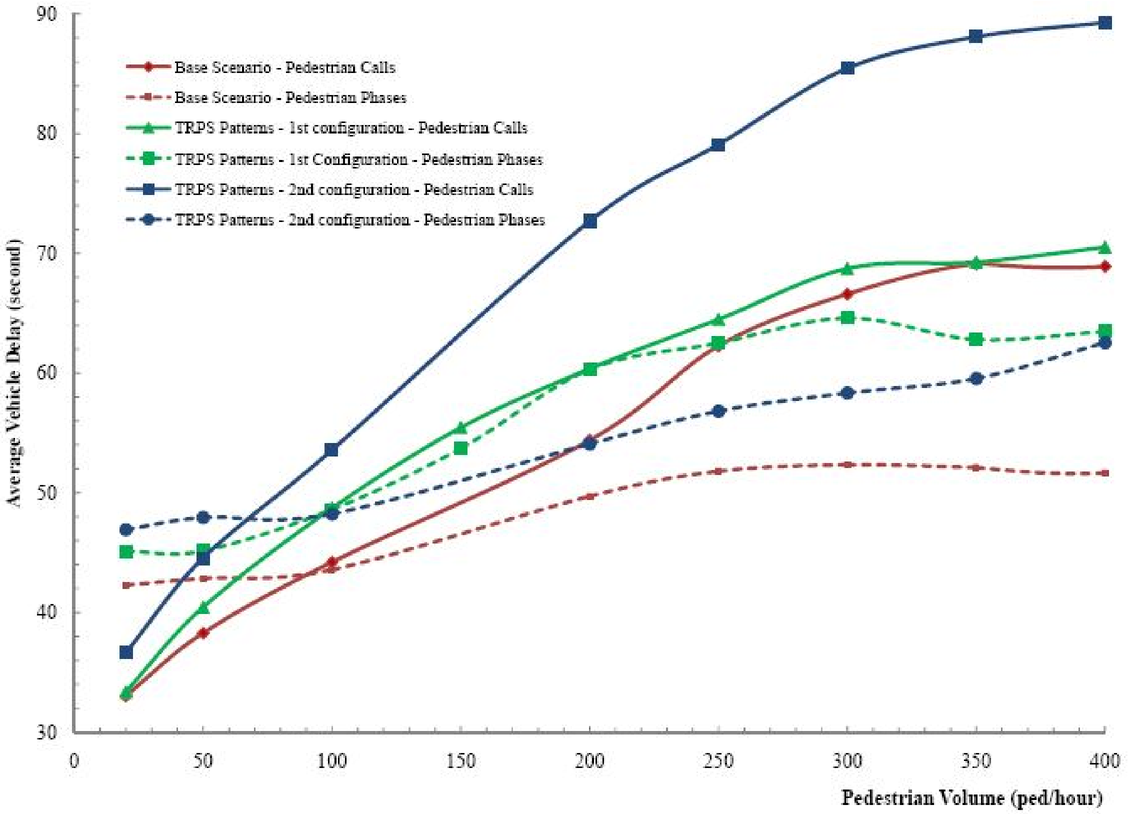


Figure 6.4 Average Delays versus Pedestrian Volume for the Two Methods with TRPS Pattern and Constant Traffic

It can be informed from these figures that pedestrian calls is efficient for very low pedestrian volumes after which it causes high delay as well as number of stops compared to pedestrian phases. It is also noticed that the threshold between pedestrian calls and pedestrian phases is not the same for both average delay and average stops. This threshold is higher if average delay is considered. The reason for this might be that with increasing pedestrian volumes more vehicles are exposed to stop either to get the green at each signal or waiting for pedestrian to clear the roadway. The average stop per vehicle depends on both stops so the threshold between pedestrian calls and pedestrian phases based on average stops is low. On the other hand, average delay depends on a huge delay increase which is expressed when vehicles are subjected to the two stops together that makes the threshold between pedestrian calls and pedestrian phases based on average delay much high because it happens at pedestrian volume causing these two stop types.

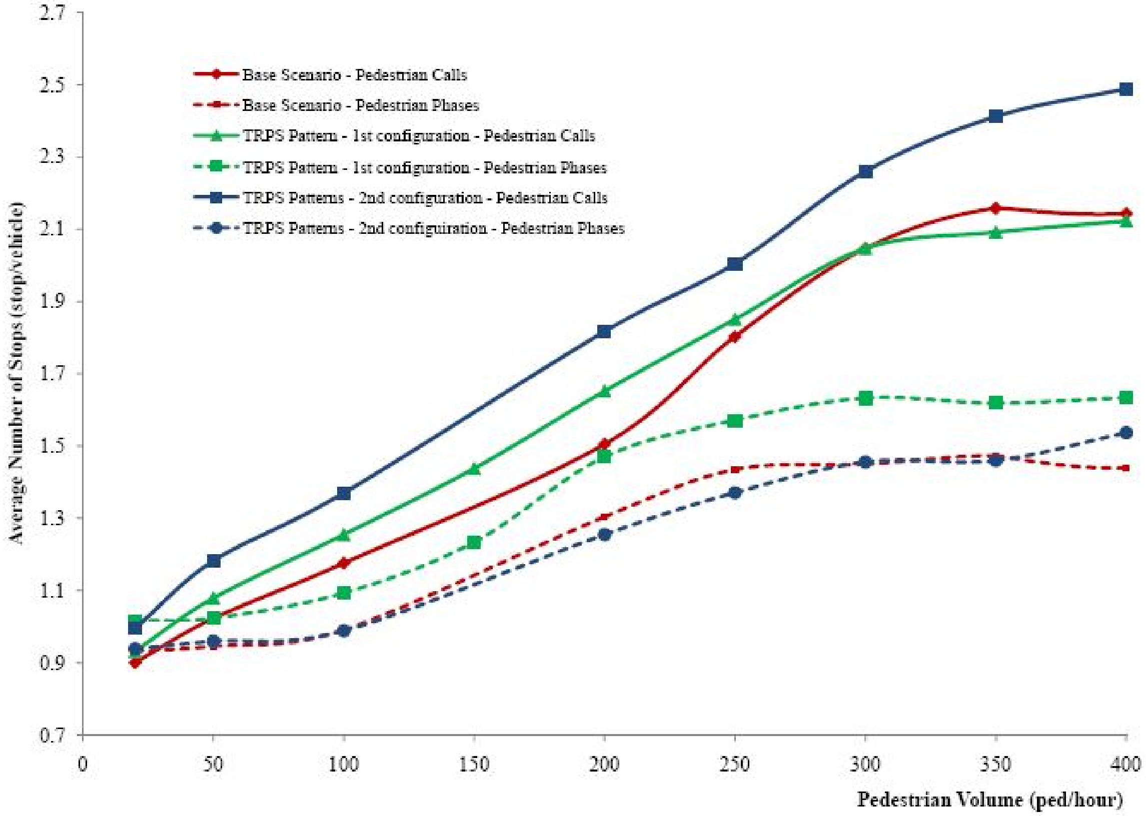


Figure 6.5 Average Stops versus Pedestrian Volume for the Two Methods with TRPS Pattern and Constant Traffic

The purpose of the last run set (which is for all traffic patterns with different pedestrian volumes using pattern configuration different than the one used in the second run set) is to determine the effect of traffic patterns on the threshold between pedestrian calls and pedestrian phases. It appears from Figure 6.4 and Figure 6.5 that as long as the pattern configuration differs, the threshold between pedestrian calls and pedestrian phases changes. On other words, this threshold is not constant with TRPS system. It subjected to traffic patterns arrangement and the period within which each pattern being implemented. For example, the thresholds between pedestrian calls and pedestrian phases for constant traffic (base scenario) and the first TRPS configuration are found to be very near to each other either for average delay or average number of stops. When the second TRPS configuration is used, it is found that the results are totally different since for average delay the threshold is almost 33% less than the first TRPS configuration while for average number of stops, threshold does not exist even for low pedestrian volumes. This missing threshold is believed to be a result of increasing number of vehicle stops with pedestrian calls due to miss-coordination between traffic signals in the TRPS system that requires long time to be corrected using transition within the same timing plan.

Table 6.1 Traffic Patterns Used in the Analysis.

Intersection	Direction	Phase	Volumes for each Traffic Pattern			
			1*	2	3	4
1	NBL	5	27	14	59	99
	SBT	6	240	120	560	960
	SBR	6	30	15	70	120
	WBL	3	3	2	5	6
	EBT	4	16	8	24	60
	EBR	4	2	1	3	8
	SBL	1	30	15	70	120
	NBT	2	216	109	476	790
	NBR	2	27	14	59	99
	EBL	7	2	1	3	8
	WBT	8	24	12	40	48
	WBR	8	3	2	5	6
2	NBL	5	33	16	73	121
	SBT	6	196	98	454	779
	SBR	6	25	12	57	97
	WBL	3	3	4	4	10
	EBT	4	40	16	48	64
	EBR	4	5	2	6	8
	SBL	1	25	12	57	97
	NBT	2	262	130	585	970
	NBR	2	33	16	73	121
	EBL	7	5	2	6	8
	WBT	8	20	32	32	80
	WBR	8	3	4	4	10
3	NBL	5	40	20	90	150
	SBT	6	163	83	372	637
	SBR	6	20	10	46	80
	WBL	3	5	1	6	4
	EBT	4	28	16	40	72
	EBR	4	4	2	5	9
	SBL	1	20	10	46	80
	NBT	2	320	160	720	1200
	NBR	2	40	20	90	150
	EBL	7	4	2	5	9
	WBT	8	36	8	48	28
	WBR	8	5	1	6	4

- * *Traffic pattern 1 is considered as the base scenario in the entire chapter.*
- * *NBL stands for North Bound Left movement, SBT stands for South Bound Through movement, SBR stands for South Bound Right movement, WBL stands for West Bound left movement, EBT stands for East Bound Through movement, EBR stands for East Bound Right movement, SBL stands for South Bound Left movement, NBT stands for North Bound Through movement, NBR stands for North Bound Right movement, EBL stands for East Bound Left movement, WET stands for West Bound Through movement, WBR stands for West Bound Right movement.*

Table 6.2 Optimum Timing Plans for Different Traffic Patterns Considered.

Intersection	Direction	Phase	Phase Split for Each Traffic Pattern			
			1	2	3	4
CYCLE LENGTH			85	60	95	145
OFFSET 1			0	0	0	0
1*	NBL	5	13	9	14	21
	SBT & R	6	52	33	63	105
	WBL	3	10	9	9	9
	EBT & R	4	10	9	9	10
	SBL	1	14	10	17	27
	NBT & R	2	51	32	60	99
	EBL	7	10	9	9	9
	WBT & R	8	10	9	9	10
OFFSET 2			12	17	12	24
2	NBL	5	21	13	26	39
	SBT & R	6	35	22	46	76
	WBL	3	10	9	9	9
	EBT & R	4	19	16	14	21
	SBL	1	15	10	19	30
	NBT & R	2	41	25	53	85
	EBL	7	10	9	9	9
	WBT & R	8	19	16	14	21
OFFSET 3			21	32	21	28
3	NBL	5	19	13	23	36
	SBT & R	6	41	29	52	90
	WBL	3	10	9	9	9
	EBT & R	4	15	9	11	10
	SBL	1	13	10	15	25
	NBT & R	2	47	32	60	101
	EBL	7	10	9	9	9
	WBT & R	8	15	9	11	10

* *Intersection number 1 is considered the master intersection having an offset of zero and all other intersections are referred to.*

This change in threshold value for TRPS system makes it much difficult to tell what range of pedestrian volume is more suitable to use pedestrian calls or phases. It is important to perform an analysis similar to the above described analysis with networks having considerable pedestrian volumes before deciding which method to use. However, it is believed that pedestrian volume is not constant and cannot be assumed constant so taking a decision to use pedestrian calls or phases is not an easy process especially if pedestrian volumes are collected in short time period. Pedestrian volumes can range from low volumes to very high volumes at any network. Thus, it is good to know how pedestrian affects the overall TRPS system performance but not easy to determine which pedestrian system should be used.

A new pedestrian framework is proposed in the following sections to be used in parallel with existing TRPS system. This framework mainly depends on determining number of pedestrian waiting at each intersection on cycle bases and based on these volumes minimum green time for each side street should be assigned. Unlike pedestrian call system, this minimum green is not constant for each cycle pedestrian calls for right of way as it depends on number of waiting pedestrians per cycle. Also unlike pedestrian phase system, this minimum green is not implemented in the system if there is no pedestrian waiting. On other words, this proposed framework is believed to have the pros of both systems.

6.7.New Proposed Pedestrian Framework

The proposed pedestrian framework depends on estimating the number of pedestrians waiting for right of way in each cycle and using the HCM formula to determine minimum side street green time required to be implemented in this cycle to serve these pedestrians. For each cycle, minimum side street green time is different based on number of waiting pedestrians. Thus, it appears that this proposed framework requires estimation for number of waiting pedestrians.

All the available pedestrian detection systems such as PUSSYCATS, TRAFFIC 2000 LIMITED, PUFFIN, NOVAX, ASIM, and Microwave Sensors do not have the ability to determine number of waiting pedestrians *(49)*. These systems are mainly used to detect the presence of pedestrians waiting without considering their number. Although, some of these systems such as microwave sensors can estimate number of pedestrians crossing the street, they cannot be used in the proposed framework since the do counting while side-street green is on. The proposed framework requires number of waiting pedestrians while side-street is still in red to decide what their minimum green is going to be.

In order to determine number of pedestrians waiting at any intersection before giving green to side-streets, a pressure sensor is proposed to be placed on the curb side with dimensions covering all the expected waiting area. This pressure sensor determines the overall weight while the side-street signal is red and based on average person weight in the area where the network under consideration locates; number of people waiting is estimated. This pressure sensor is similar to the way vehicle's weight is determined but in small scale for pedestrians. On this study an average weight of 175 lb is proposed. This average weight is based on average American weight online studies *(50)*.

After determining number of people waiting per cycle using the pre-described estimation method, minimum side-street green time is calculated for the next cycle. By implementing this green time, pedestrians are served on optimum time corresponding to their density. With high pedestrian volumes for long time periods, side-street green time is going to be the minimum green for the maximum number of people can stand on the pressure sensor. Using this concept, green time for side-streets will not take forever since it is inserted in the controller that the maximum green time for side-street is the values corresponding to maximum number of people standing on the pressure sensor. Figure 6.6 shows the proposed pedestrian framework with TRPS system.

Using this proposed framework, simulation runs for the network under consideration is performed considering different pedestrian volumes. VAP files are modified to implement the proposed framework in parallel to TRPS system. The results are compared to what has been concluded previously in the above sections. Figure 6.7 and Figure 6.8 presents results of the proposed framework compared to exiting two methods i.e. pedestrian calls and pedestrian phases.

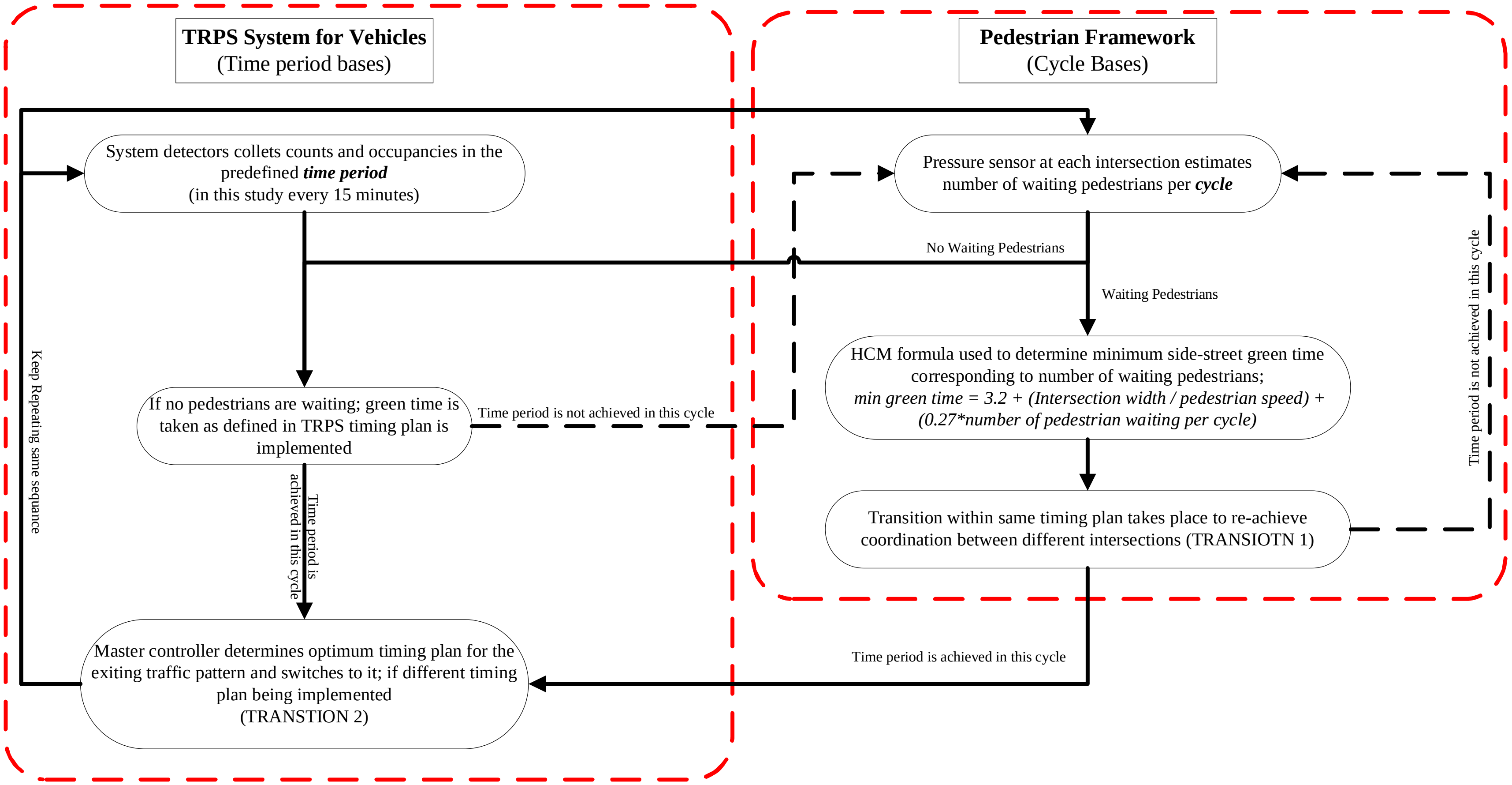


Figure 6.6 Proposed Pedestrian Framework in Parallel with Exiting TRPS System

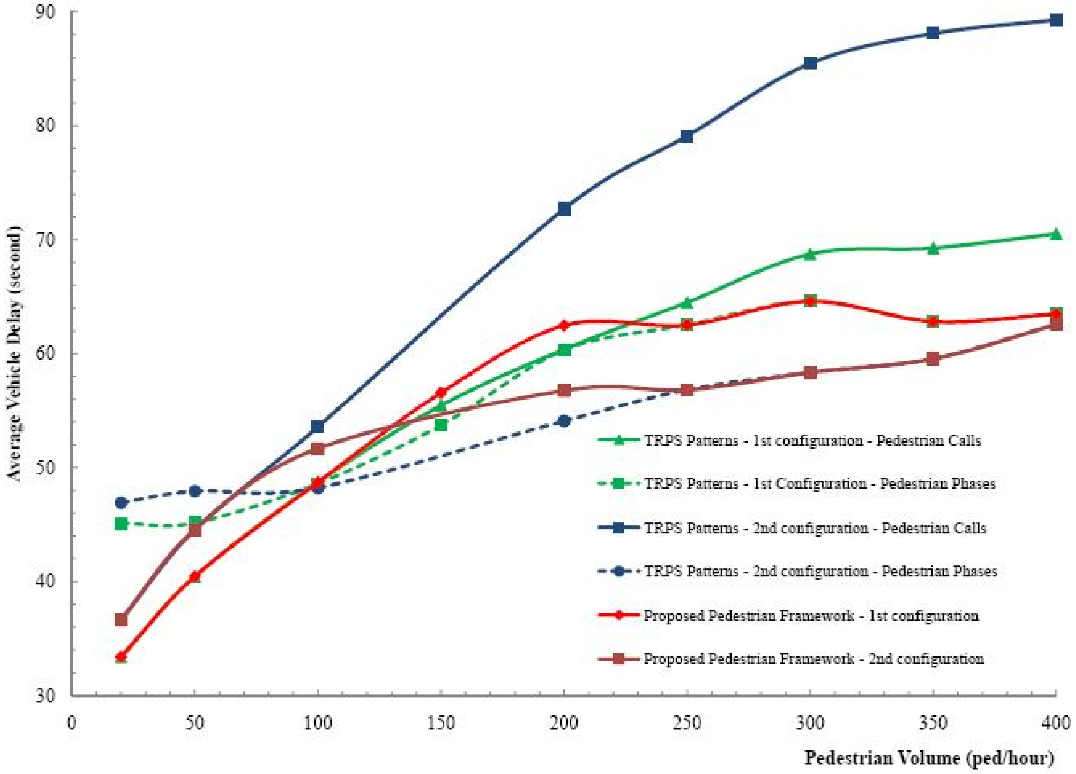


Figure 6.7 Average Delay of the Proposed Pedestrian Framework Compared to Pedestrian Calls and Pedestrian Phases

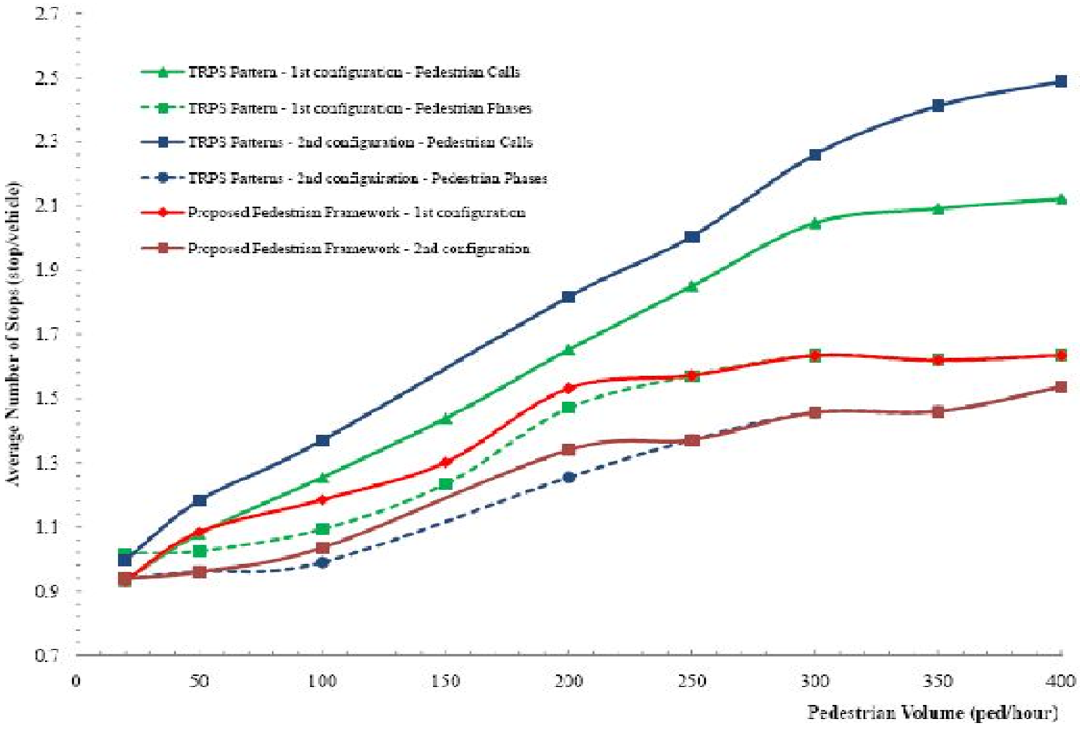


Figure 6.8 Average number of stops of the Proposed Pedestrian Framework Compared to Pedestrian Calls and Pedestrian Phases

6.8.Analysis Results and Discussions

It appears from Figure 6.7 and Figure 6.8 that the proposed framework achieves curves for average delay and/or average number of stops having mainly three parts the first part lies with the pedestrian call curve. This part is for low pedestrian volumes and in this part the proposed framework works exactly as pedestrian calls system.

The second part lies between the pedestrian call curve and pedestrian phases curve. This part of the curve is for medium pedestrian volume. The reason for lying between these two curves is believed to be the affect of cumulating transition times 1 and 2 (as appears in Figure 6.6). For medium pedestrian volumes, number of pedestrians waiting per cycle is not constant over different cycles so minimum side street green time is also not constant over cycles. This causes two transitions to happen one of them occurs every cycle and the second occurs when timing plans is being checked and switched. The accumulation of these transitions together affects the performance of the overall system since during this transition signals are not fully coordinated. The third part of the curve lies n the pedestrian phases curve. This part is for high pedestrian volumes where number of pedestrians waiting reaches the maximum number that can be read through pressure sensor.

Although, the second part of the proposed framework curve lies above the pedestrian calls curve, it is still considered the best curve since it has the ability to adjust itself with the actual pedestrian volume achieving the less delay and number of stops. Pedestrian volume cannot be expected in any traffic network so it is important to use a system like the proposed framework that can adjust itself with the pedestrian variation especially if these pedestrians have big effect on the overall network performance like the case of TRPS systems.

6.9.Conclusions

Pedestrians have a large effect on TRPS networks and should be considered in determining the operating timing plans either through pedestrian calls or pedestrian phases. Pedestrian volume threshold between these two available methods is not easy to be determined since it totally depends on the traffic patterns and their configurations. Also, it is understood that pedestrian volumes in traffic networks cannot be predicted or expected like the case with vehicle traffic volumes.

Using pedestrian calls or pedestrian phases in any network is not enough to achieve the best network performance with variation of pedestrian volumes. It is presented in this chapter that pedestrian calls is only efficient for low pedestrian volumes while pedestrian phase is efficient for high pedestrian volumes. Since, pedestrian volume is not predicted; using one system is not efficient for all pedestrian volume ranges.

New proposed pedestrian framework is suggested to be used in parallel to the existing TRPS system. This framework has the ability to adjust itself with the variation in pedestrian volume. The proposed framework proposes using new pressure sensor to estimate number of pedestrians waiting for right of way per cycle. Based on this number, minimum green time for side-streets is estimated and assigned in the next cycle.

This proposed framework is tested in the analysis done in this chapter and shows great results with different pedestrian volumes except for medium pedestrian volumes. However, this pedestrian framework is considered the more reliable and efficient way to deal with pedestrians in networks operated with TRPS system that is very sensate to pedestrians.

Chapter 7 : Conclusions and Recommendations for Future Research

7.1.Thesis Conclusions

It is concluded from the research done in this thesis that:

1. Using the new introduced concept of significant critical movements helps to generate more realistic traffic scenarios. These scenarios can be used for different applications in traffic engineering. This new approach will help traffic engineers to focus on the main analysis they are performing rather than looking for generating traffic patterns.

2. Implementing traffic responsive control mode of operation in large networks improves the overall system performance by reducing total number of stops as well as total delay.

3. The proposed approach for implementing pattern matching mechanism for traffic responsive control mode produces good system parameters which consequently achieve good traffic responsive system. This approach can be followed for any network rather than larger networks.

4. Relaxation of constrains for threshold mechanism helps to improve the entire system performance. It achieves better pattern classification which consequently implements the most appropriate timing plan for each traffic scenarios. It is recommended to controller manufacturers to implement this relaxation in their controllers.

5. Pedestrians have a great effect on traffic responsive control mode of operation either it follows threshold mechanism or pattern matching mechanism. This effect depends on pedestrian volumes as well as the method being used to deal with pedestrians (either pedestrian calls or pedestrian phases).

6. Pedestrian call system is found to perform better with low pedestrian volumes while pedestrian phases perform better with high pedestrian volumes.

7. The new pedestrian framework shows a great improve in networks having wide range of pedestrians. It has the advantage of working as pedestrian call system for low pedestrian volumes and at the same time, it works as pedestrian phases for high pedestrian volumes.

7.2.Recommendations for Future Researches

The following points are believed to be good potentials for new researches regarding traffic responsive control mode of operation:

1. It is required to perform a study comparing the threshold mechanism and pattern matching mechanism. It is believed to have one system performs better than the other. Limited studies were conducted to show which system is better. This will help to implement the best mechanism in traffic controllers.

2. All the research performed studying traffic responsive control mode including the work presented in this thesis consider only arterial networks. It is required to have a study concerning about implementing traffic responsive control mode of operation on system networks.

3. More detailed study for the proposed pedestrian framework is recommended. In this thesis, the lack of information does not help to go into deep details. This system is expected to have a great effect on pedestrian safety as well as overall system performance.

REFERENCES

1. *An Approximate Dynamic Programming Strategy for Responsive Traffic Signal Control.* s.l. : Strategy for Responsive Traffic Signal Control Dynamic Programming and Reinforcement Learning, 2007.
2. *SCOOT - a Traffic Responsive Method of Coordinating Signals.* Hunt, P. B., et al. s.l. : TRRL Laboratory Report 1014, 1981.
3. *SCATS. Splits and offsets simplified (SOS).* Sims, A. G. and Finlay, A. B. 4, s.l. : ARRB Proceedings, 1984, Vol. 12.
4. *Methodology for Determination of Optimal Traffic Responsive Plan Selection Control Parameters.* Abbas, Montasir M., et al. s.l. : Texas Department of Transportation and the U.S. Department of Transportation, Federal Highway Administration, 2004, p. 84. FHWA/TX-04/0-4421-1.
5. *Locating Detectors for Advanced Traffic Control Strategies: Handbook.* Kay, J., Henry, R. and Smith, S. s.l. : FHWA, U.S. Department of Transportation, 1975. Report No. FHWA-RD-75-91.
6. *National Transportation Communications for ITS Protocol: Field Management Stations Draft. NTCIP 1210.* Rosslyn, Va. : National Electrical Manufacturers Association, 2004.
7. *Master Controller Software.* Sugarland, Texas : Naztec, Inc., 2002.
8. *ASC/2M-1000 Zone Master Programming Manual.* Anaheim, California : Econolite Control Products, Inc., 1996.
9. *MARC 300 Series Master Controller.* Austin, Texas : Automatic Signal/Eagle Signal, 1997.
10. *TRPS Implementation and Evaluation.* s.l. : Virginia Department of Transportation, 2001.
11. *An Approximate Dynamic Programming Strategy for Responsive Traffic Signal Control.* Cai, Chen. s.l. : Proceedings of the 2007 IEEE Symposium on Approximate Dynamic Programming and Reinforcement Learning, 2007, pp. 303 - 310. 1-4244-0706-0.
12. *Traffic-Responsive Signalling Control Through a Modular/Switching Model Represented via DTPN.* Di Febbraro, Angela and Giglio, Davide. Toronto, Canada : Proceedings of the IEEE ITSC 2006, 2006, pp. 1430 -1435. 1-4244-0094-5.
13. *Traffic Responsive Signal Control Using Fuzzy Logic- A Practical Modular Approach.* Sayers, Tessa, et al. Savoy Place, London : The Institution of Electrical Engineers IEE, 1996.

14. *Improving the Traffic Responsiveness of Signal Controllers Using Fuzzy-Logic.* Sayers, Tessa, et al. s.l. : The Institution of Electrical Engineers IEE, 1995.
15. *Applied Discriminant Analysis.* Huiberty, C.J. s.l. : John Wiley & Sons, Inc., 1994.
16. *The Nature ofStatistical Learning Theory.* Vapnik, V.,. s.l. : Springer, 1995.
17. *Minimal Consistent Set (MCS) Identification for Optimal Nearest Neighbor Decision Systems Design.* Dasarathy, B.V. 3, s.l. : IEEE Transactions on Systems, Man, and Cybernetics, 1994, Vol. 24.
18. *Traffic State Classification in Condition-Responsive Traffic Control.* Pesti, Geza, Abbas, Montasir M. and Chaudhary, Nadeem. s.l. : IEEE, 2007. 1-4244-1148-3.
19. *Configuration Methodology for Traffic-Responsive Plan Selection.* Abbas, Montasir M., et al. Washington : Transportation Research Board of the National Academies, 2005, Transportation Research Record: Journal of the Transportation Research Board, Vol. 1925, pp. 195–204.
20. *A Traffic-Responsive Control Method for Small Networks.* Wilson, A. Seoul, Korea : Proceedings of the 5th World Congress on Intelligent Transportation System, 1998.
21. *Methodology of Evaluating the Effectiveness of Traffic-Responsive System on Intersection Congestion and Traffic Safety.* Hanbali, R. and Fornal, C. s.l. : TRB, National Research Council, 1997, Transportation Research Record, Vol. 1603, pp. 137 - 149.
22. Nelson, E., et al. *Development of Closed-Loop System Evaluation Procedures.* McLean, Virginia : FHWA/IN/JTRP, 2000.
23. Abbas, Montasir M., et al. *Guidelines for Determination of Optimal Traffic Responsive Plan Selection Control Parameters.* s.l. : Texas Department of Transportation and the Federal Highway Administration, 2005. FHWA/TX-05/0-4421-2.
24. *A Dynamic Traffic Analysis with Static Data Guidelines with Application to Paris.* Marchal, F., and De Palma, A. Washington, D.C. : Transportation Research Record, 2001, Vol. 1752.
25. *Toward a Class of Link Travel Time Functions for Dynamic Assignment Models on Signalized Networks.* Ran, B., N. M. Rouphail, A. Tarko, abd D. E. Boyce. 4, s.l. : Transportation Research, 1997, Vol. B31.
26. *Estimation of Time-Varying Origin-Destination Distributions with Dynamic Screen line Flows.* Wu, J., and G.-L. Chang. 4, s.l. : Transportation Research Part B, 1996, Vol. 30.

27. *Examining the Quality of Synthetic Origin-Destination Trip Table Estimated by Path Flow Estimator.* Chen, A., Chootinan, P., and Recker, W. W. 7, s.l. : American Society of Civil Engineering, 2005, Journal of Transportation Engineering, Vol. 131.
28. *Dynamic Origin-Destination Matrix Estimation and Prediction for Real-Time Management Systems.* Ashok, k., and Ben-Akiva, M. E. Berkeley : Proc., 12th International Symp. on Transportation and Traffic Theory, 1990.
29. *Estimation and Prediction of Time-Dependent Origin-Destination Flows with a Stochastic Mapping to Path Flows and Link Flows.* Ashok, K., and Ben-Akiva, M. E. 2, s.l. : Transportation Sci, 2002, Vol. 36.
30. *MATLAB 14 version 7.0.1.* s.l. : Mathworks, Inc, 2004.
31. *SAS 9.1.2 Qualification Tools User's Guide.* Cary, NC, USA : SAS Institute Inc., 2004.
32. *QUEENSOD Ref 2.10 - User Guide: Estimating Orign-Destination Traffic Demands from Link Flow Counts.* Kingston, Ontario, Canada : M. Van Aerde & Assoc., Ltd, 2007.
33. Institute, Taxes Transportation. *PASSER V-07, version 1.02-Beta.* s.l. : Taxes Department of Transportation (TDOT), 2007.
34. ITT Industries, lnc., Systems Division. *CORSIM User's Guide: Traffic Software Integerated System version 5.1.* s.l. : FHWA Office of Operation Research and Development, 2003.
35. *VISSIM 4.30 02.* Karlsruhe, Germany : PTV Planung Transport Verkehr AG, 2007.
36. *VisVAP - version 2.16.* Karlsruhe, Germany : PTV AG, 2007.
37. *A Toolbox for Alleviating Traffic Congestion and Enhancing Mobility.* Meyer, M. s.l. : Institute of Transportation Engineers, 1997.
38. Balke, K.N., R.S. Keithireddipalli, and C.L. Brehmer. *Guidelines for Implementing Traffic Responsive Mode in TxDOT Closed-Loop Traffic Signal Systems.* Texas : Texas Transportation Institute, The Texas A&M University System, College Station, 1997. Research Report 2929-3F. Project No. 7-2929.
39. *Methodology of Evaluating the Effectiveness of Traffic Responsive System on Intersection Congestion and Traffic Safety.* Hanbali, R., and Fornal, C. s.l. : Transportation Research Record, 1997, Vol. 1603.
40. Sharma, A. *Determination of Traffic Responsive Plan Selection Factors and Thresholds Using Artificial Neural Networks (Master's Thesis).* s.l. : Texas A&M University, College Station, Texas, 2004.

41. *A Grsphical Aid to the Interpretation and Validation of Cluster Analysis.* Rousseeuw, P.J. Silhouettes. s.l. : Journal of Computational and Applied Mathematics, 1987, Vol. 20.
42. *Neural Networks for Pattern Recognition.* Bishop, C.C. Oxford : Clarendon Press, 1995.
43. *Pattern Recognition Concepts, Methods and Applications.* Marques, de Sa J.P. New York : Springer, 2001.
44. *Clustering Algorithms.* Hartigan, J.A. New York : John Wiley & Sons Inc. , 1974.
45. *Finding Groups in Data An Introduction to Cluster Analysis.* Kaufman, L., and Rousseeuw, P. J. New York : John Wiley & Sons Inc., 1990.
46. *Pedestrian Violations at Signalized Crossing Facilities.* Barker, C.J., Wang, W.Y., and Yue, W.L. s.l. : Australian road research, 1991.
47. *Arterial Interchange.* Eyler, D.R. s.l. : Transportation Research Board, 2005.
48. *Chapter 11: Pedestrian and Bicycle Concepts.* s.l. : Highway Capacity Manual, HCM manual , 2000.
49. *Bicycle and Pedestrian Detection.* s.l. : SRF Consulting Group Report, 2003.
50. *www.americansportsdata.com.* [Online] [Cited: December 7, 2007.]

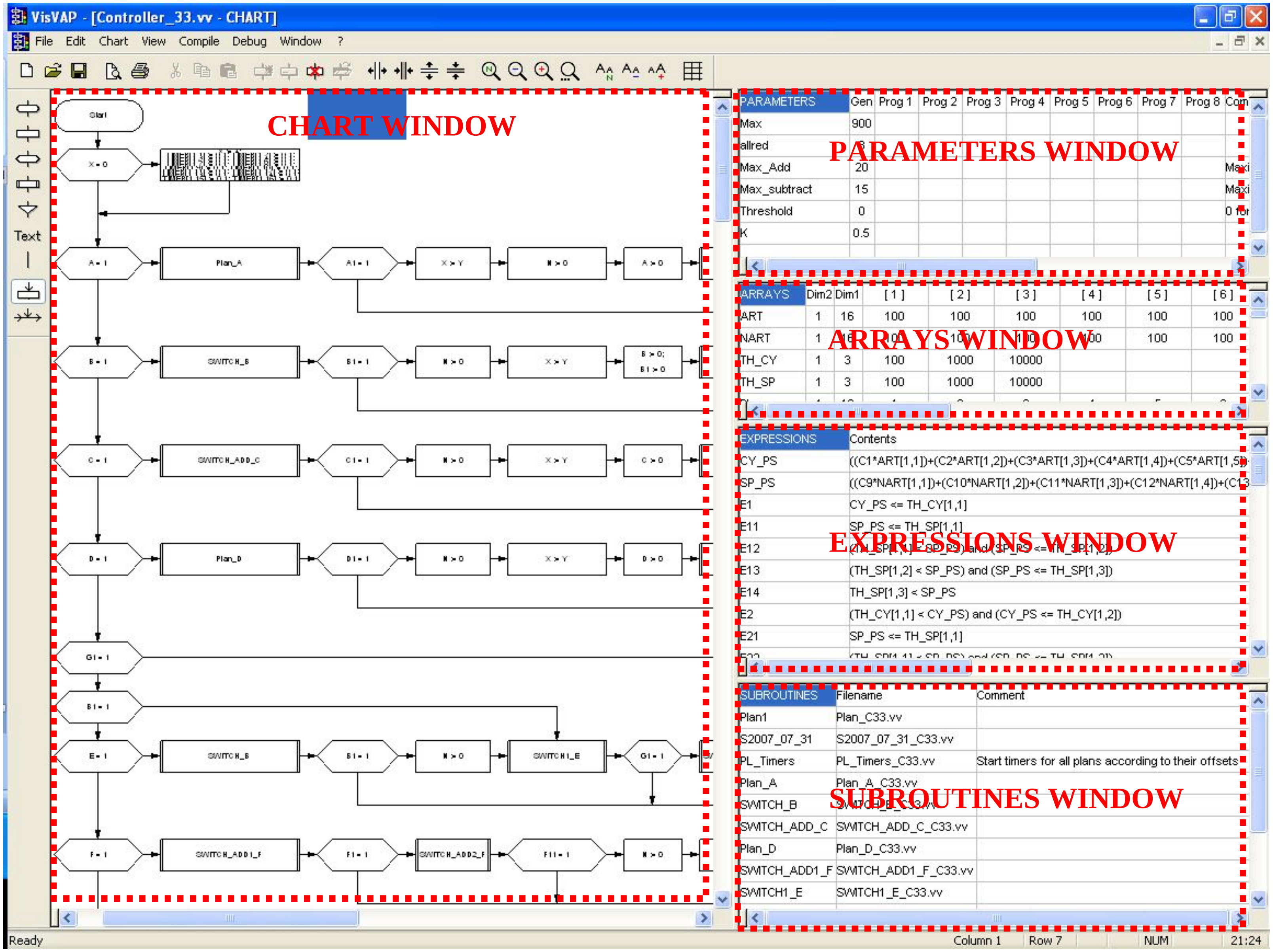
Appendix A : Vehicle Actuated Programming (VAP) Files for Traffic Responsive Control Mode

This appendix includes a detailed description for the VAP file used in this thesis. This VAP file supports the traffic responsive control mode of operation with its two mechanisms, threshold mechanism and pattern matching mechanism. This file also supports time of day mode of operation.

VisVAP is used to draw the flow chart for these controlling modes and then it is compiled to generate the required VAP file. Different subroutines within the main code are used to do different controlling issues such as switching between different timing plans.

Different VAP file is generated for each intersection in Reston Parkway network. The following sections consider only an example for one intersection; between Reston Parkway arterial and Glade Drive Street. This intersection is selected because it has full NEMA phases. Figure A.1 shows a screen shot for VisVAP interface. As shown in this figure, there are five different windows; chart window, parameter window, array window, expression window, and subroutines window.

The chart window is the place where flowchart for the code is drawn. Different parameters are inserted in the parameter widow. All the values for the arrays used in the code are inserted in the array window. Expressions window includes all the functions or expressions used in the entire network. Subroutines window shows the name of subroutine files used in the coding. The main code as well as each subroutine has all these windows.



PARAMETERS	Gen	Prog 1	Prog 2	Prog 3	Prog 4	Prog 5	Prog 6	Prog 7	Prog 8	Com
Max	900									
allred	3									
Max_Add	20									Maxi
Max_subtract	15									Maxi
Threshold	0									0 for
K	0.5									

ARRAYS	Dim2	Dim1	[1]	[2]	[3]	[4]	[5]	[6]
ART	1	16	100	100	100	100	100	100
NART	1	16	100	100	100	100	100	100
TH_CY	1	3	100	1000	10000			
TH_SP	1	3	100	1000	10000			

EXPRESSIONS	Contents
CY_PS	((C1*ART[1,1])+(C2*ART[1,2])+(C3*ART[1,3])+(C4*ART[1,4])+(C5*ART[1,5])
SP_PS	((C9*NART[1,1])+(C10*NART[1,2])+(C11*NART[1,3])+(C12*NART[1,4])+(C13
E1	CY_PS <= TH_CY[1,1]
E11	SP_PS <= TH_SP[1,1]
E12	(TH_SP[1,1] < SP_PS) and (SP_PS <= TH_SP[1,2])
E13	(TH_SP[1,2] < SP_PS) and (SP_PS <= TH_SP[1,3])
E14	TH_SP[1,3] < SP_PS
E2	(TH_CY[1,1] < CY_PS) and (CY_PS <= TH_CY[1,2])
E21	SP_PS <= TH_SP[1,1]

SUBROUTINES	Filename	Comment
Plan1	Plan_C33.vv	
S2007_07_31	S2007_07_31_C33.vv	
PL_Timers	PL_Timers_C33.vv	Start timers for all plans according to their offsets
Plan_A	Plan_A_C33.vv	
SWITCH_B	SWITCH_B_C33.vv	
SWITCH_ADD_C	SWITCH_ADD_C_C33.vv	
Plan_D	Plan_D_C33.vv	
SWITCH_ADD1_F	SWITCH_ADD1_F_C33.vv	
SWITCH1_E	SWITCH1_E_C33.vv	

Figure A.1 VisVAP Screen Shot

Main Code

The main code is the original file that controls when each subroutine should be activated. All the input data for the two controlling modes as well as different mechanisms are to be inserted in the main code. Figure A.2 through Figure A.11 shows the chart window of the main code used for this intersection.

Figure A.12 shows the parameters window used in the main code. It shows six different parameters named as Max, allred, Max_add, Max_subtract, Threshold, and K. these parameters are described as:

- ***Max*** is the maximum time period in seconds after which the master controller perform its check for switching timing plan or not,

- ***Allred*** is the all red time in seconds for all phases at the intersection being considered. It is assumed to be constant for all phases,

- ***Max_add*** is the maximum adding percentage by which the cycle length of plan (i) is increased during switching to another plan. Typically, this percentage is 20%,

- ***Max_subtract*** is the maximum subtracting percentage by which the cycle length of plan (i) is decreased during switching to another plan. Typically this percentage is 15%,

- ***Threshold*** is a parameter that determines which controlling mode is going to be used. 0 is for pattern matching traffic responsive control mechanism, 1 is for threshold traffic responsive control mode of operation, and 2 is for time of day mode of operation.

- ***K*** is the global factor used in pattern matching traffic control mode of operation.

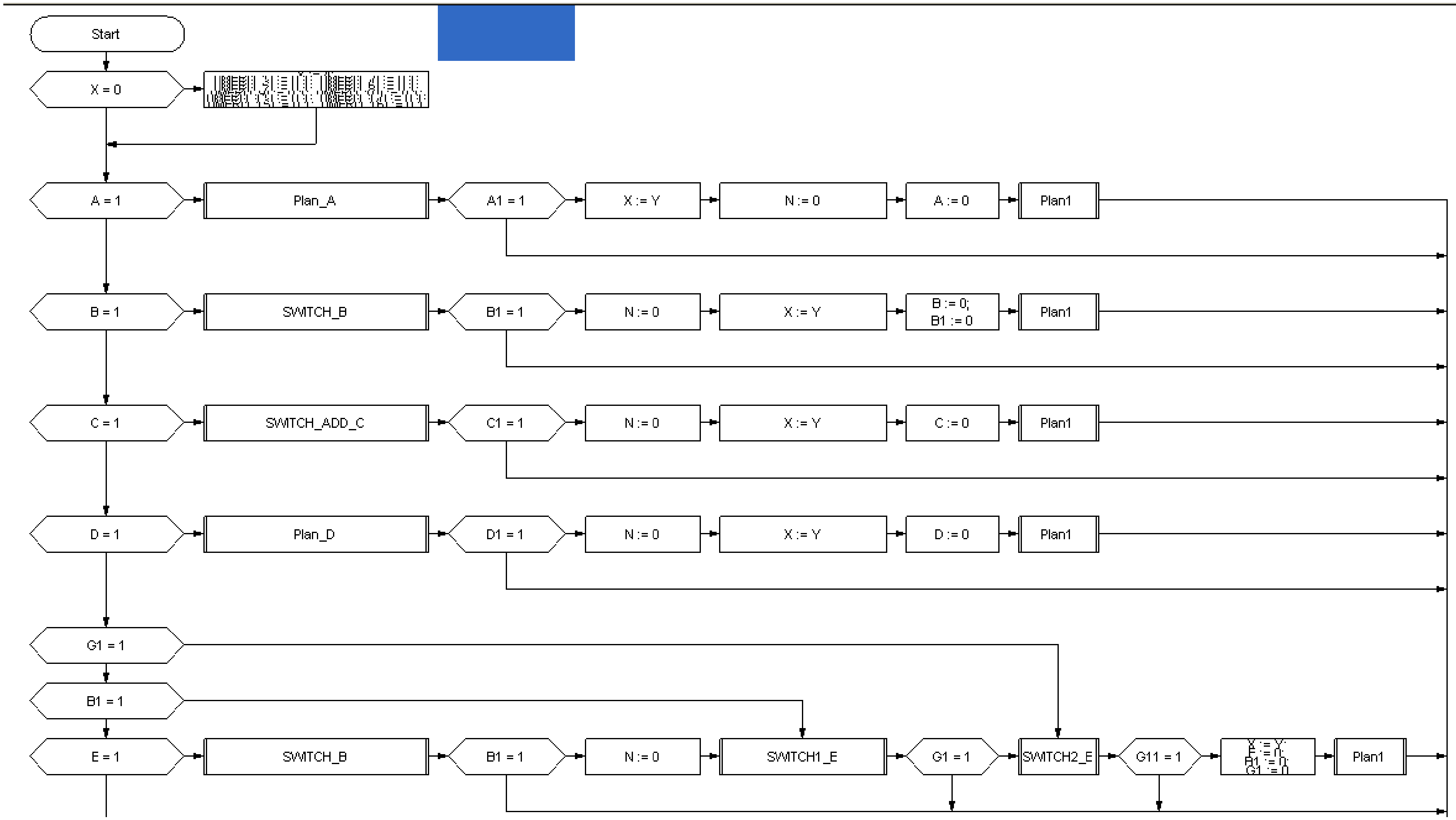


Figure A.2 Main Code Part 1

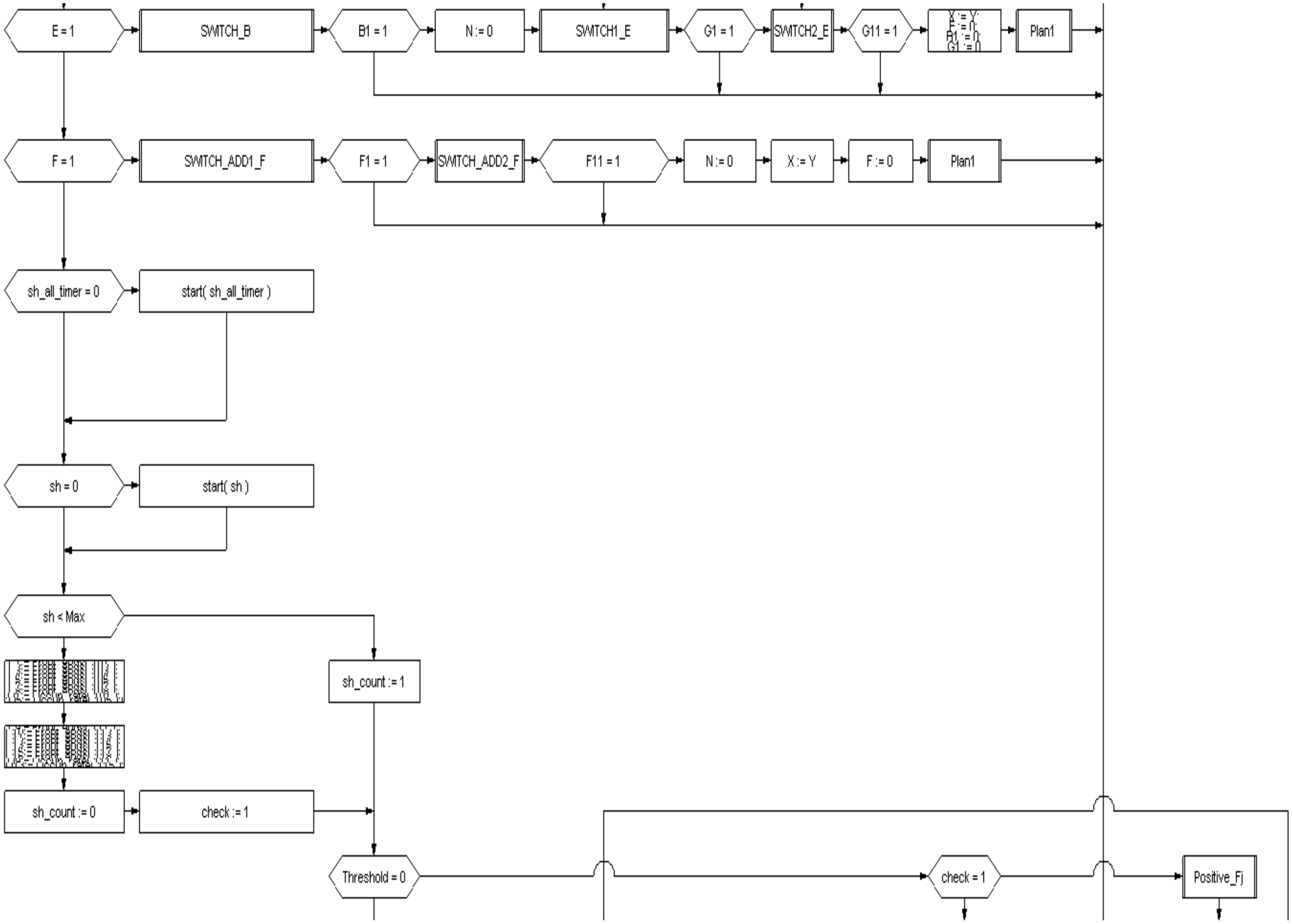


Figure A.3 Main Code Part 2

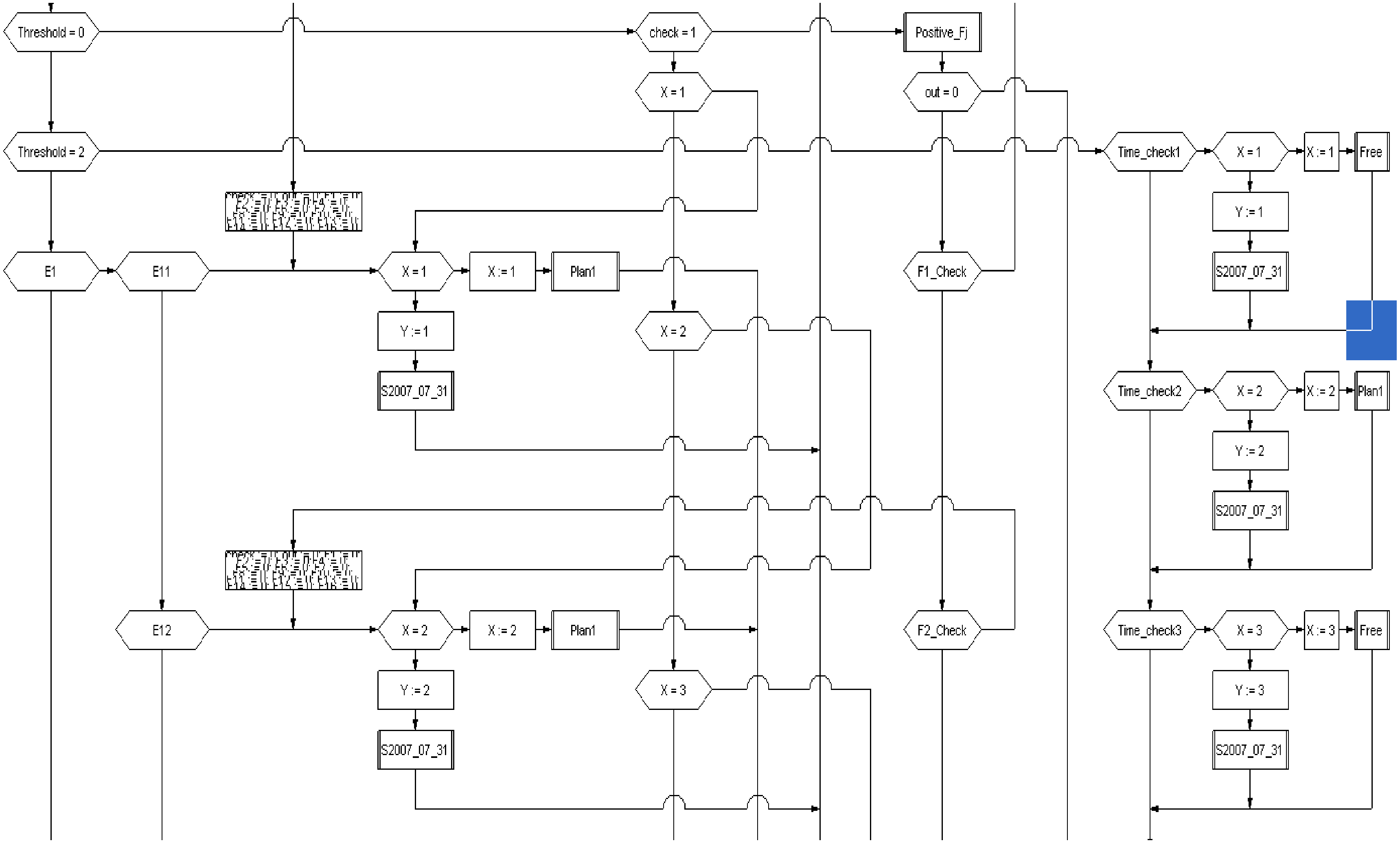


Figure A.4 Main Code Part 3

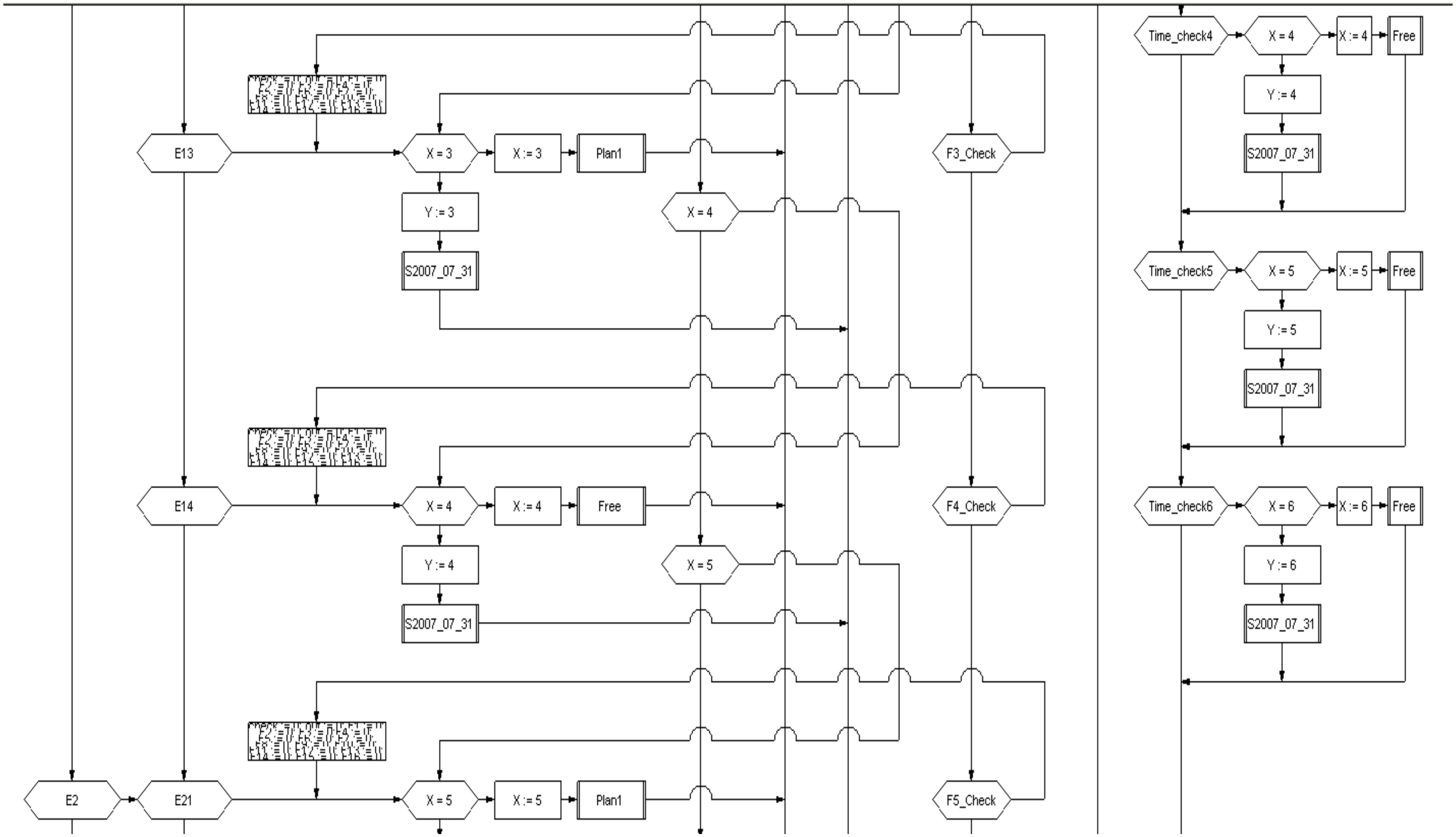


Figure A.5 Main Code Part 4

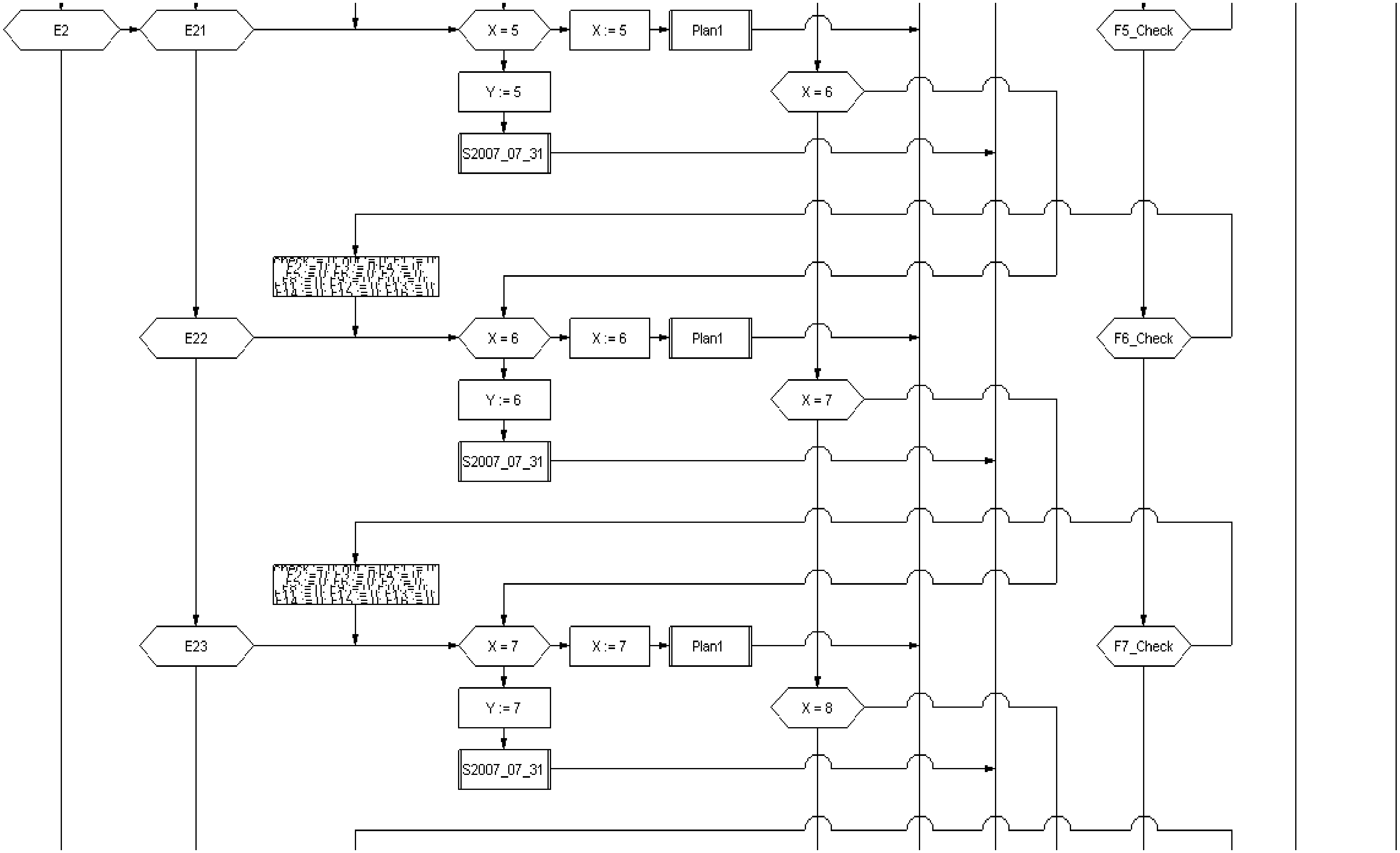


Figure A.6 Main Code Part 5

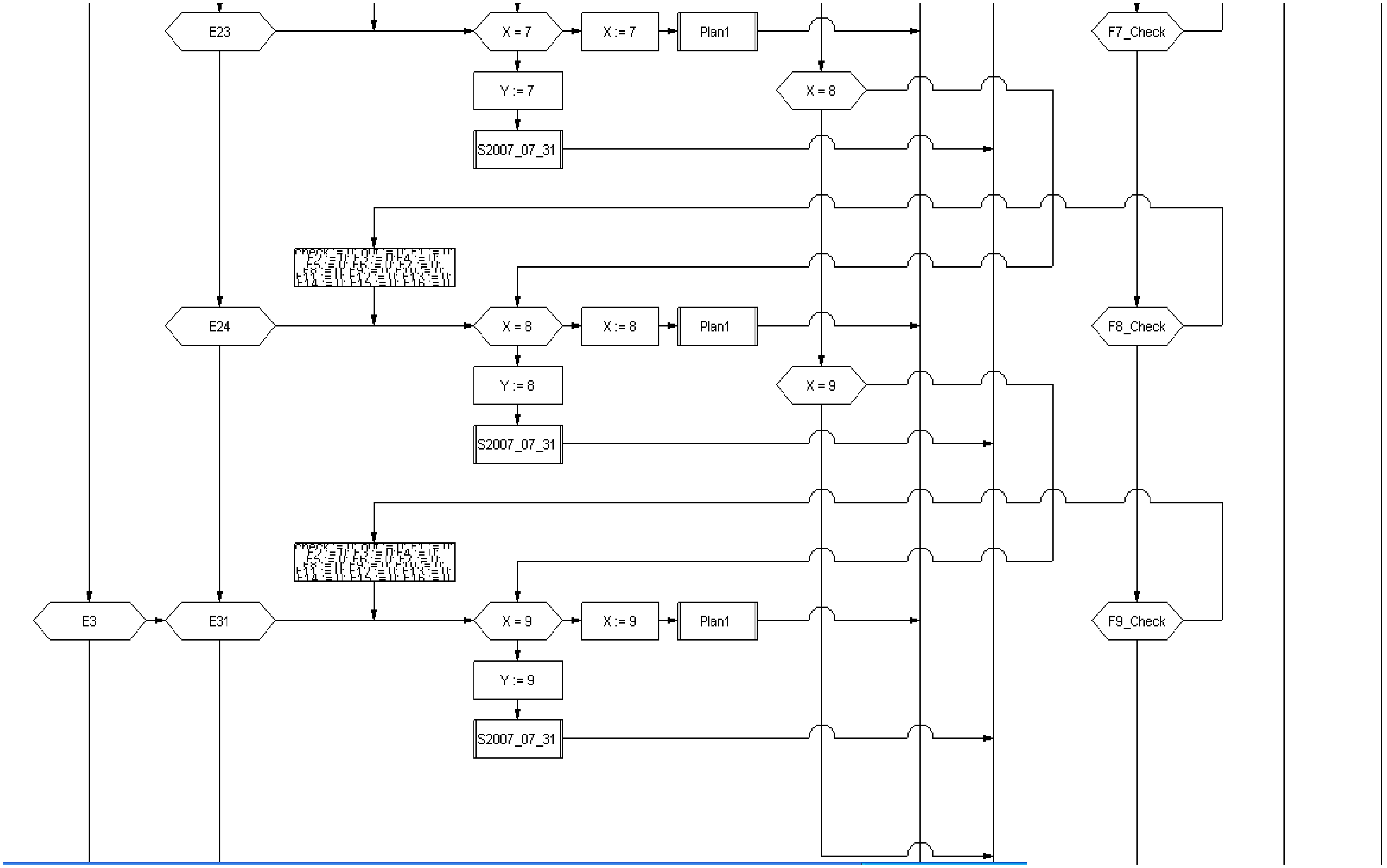


Figure A.7 Main Code Part 6

Figure A.8 Main Code Part 7

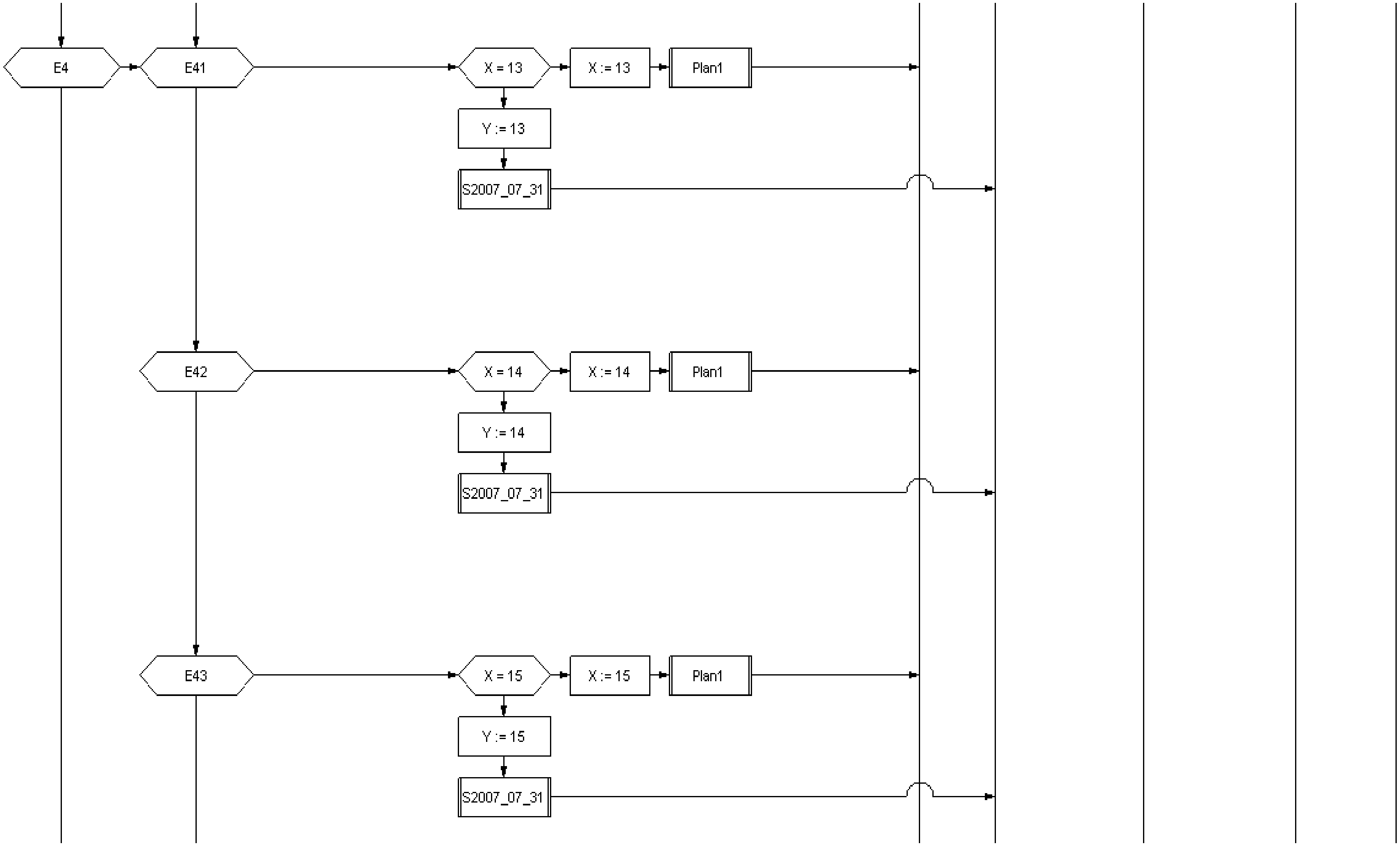


Figure A.9 Main Code Part 8

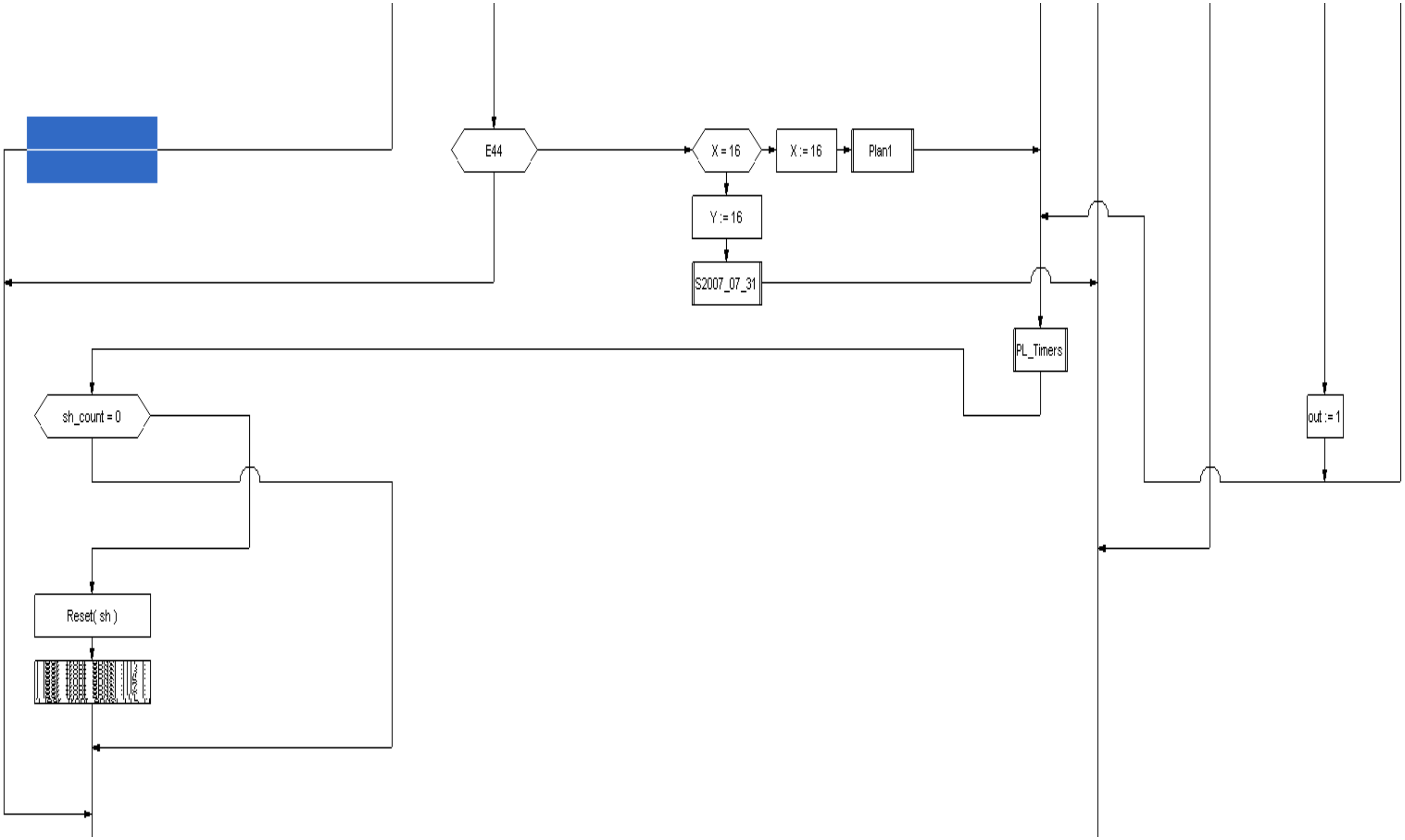


Figure A.10 Main Code Part 9

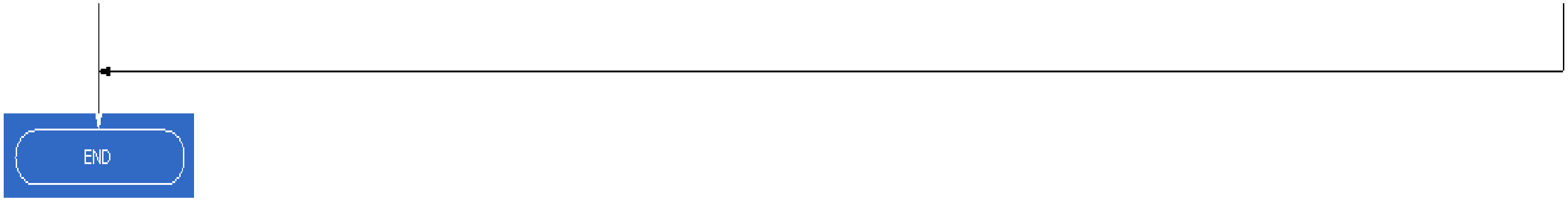
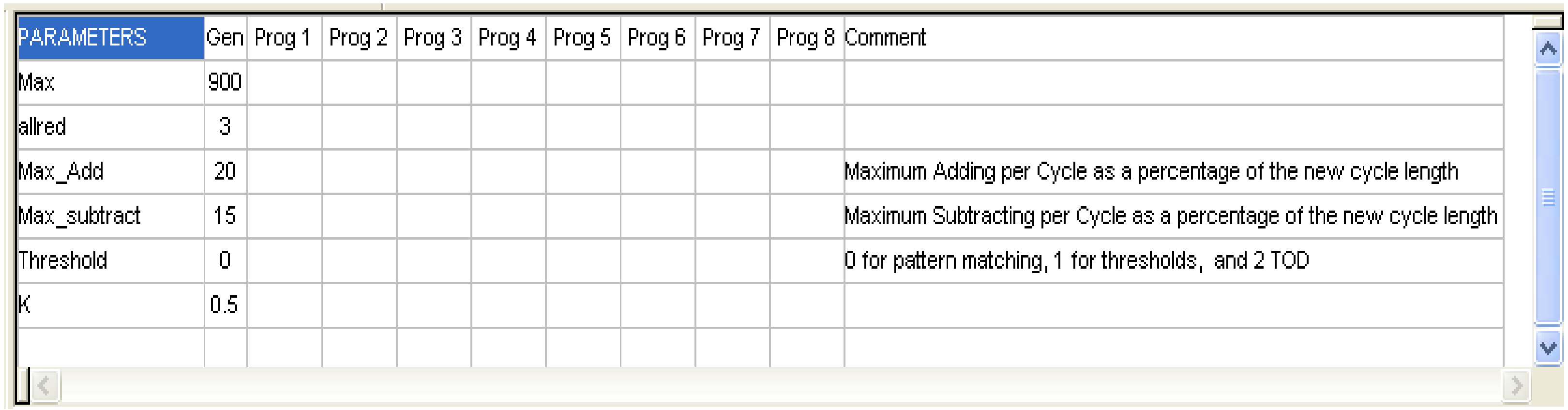


Figure A.11 Main Code Part 10



PARAMETERS	Gen	Prog 1	Prog 2	Prog 3	Prog 4	Prog 5	Prog 6	Prog 7	Prog 8	Comment
Max	900									
allred	3									
Max_Add	20									Maximum Adding per Cycle as a percentage of the new cycle length
Max_subtract	15									Maximum Subtracting per Cycle as a percentage of the new cycle length
Threshold	0									0 for pattern matching, 1 for thresholds, and 2 TOD
K	0.5									

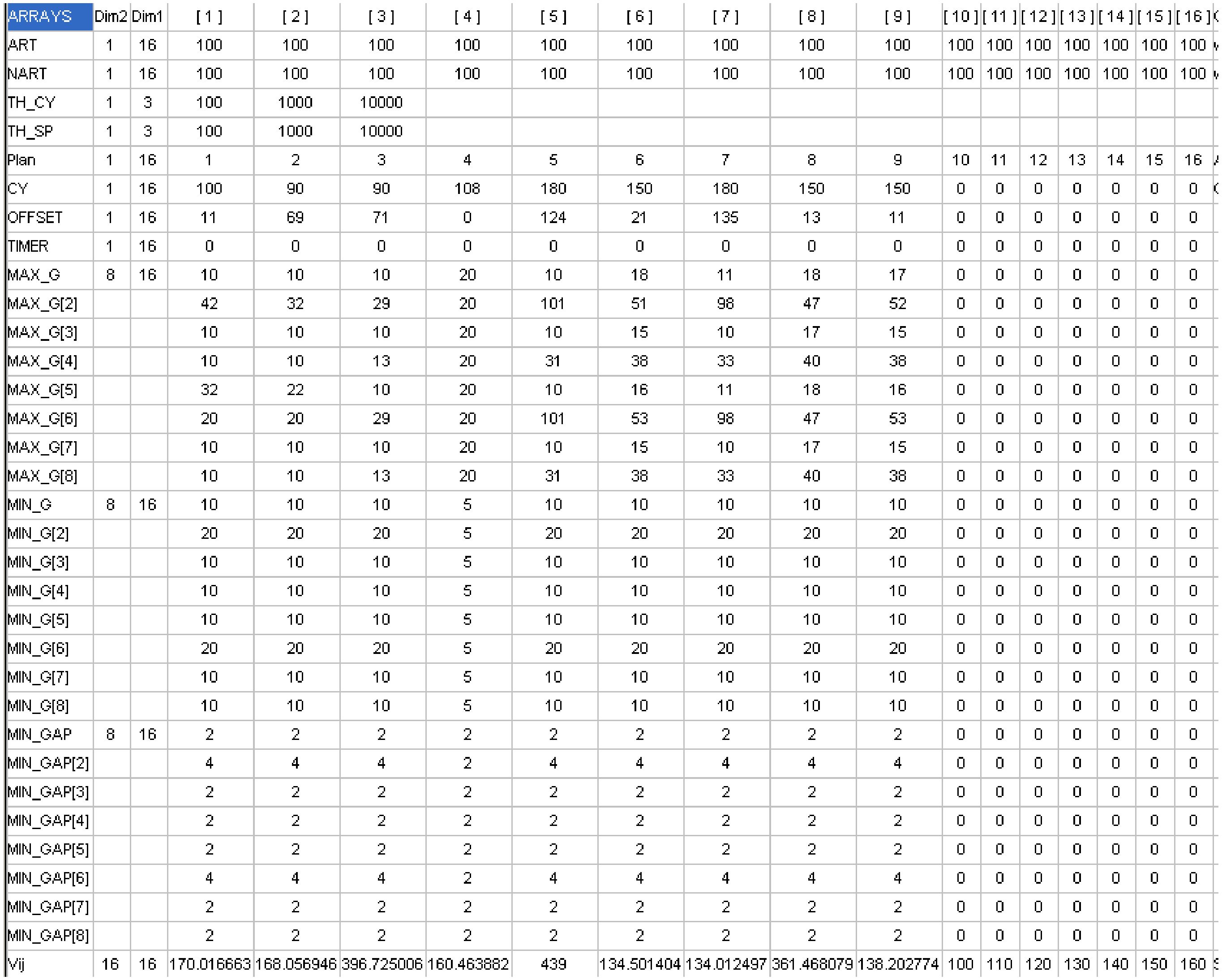
Figure A.12 Parameters Window for Main Code

Figure A.13 through Figure A.15 shows all arrays used in the coding for all control modes considered in this VAP coding. The first four arrays, i.e. ART, NART, TH_CY, and TH_SP, are used with threshold traffic responsive mechanism. ART and NART are the computational channels for Eagle controllers, while TH_CY and TH_SP are the cycle and split thresholds respectively.

The next seven arrays, i.e. Plan, CY, OFFSET, TIMER, MAX_G, MIN_G, and MIN_GAP are the timing plans themselves. They are being used for any mode of operation or mechanism. This VAP code supports up to 16 different timing plans as appears in the first row in arrays window. For the intersection considered, only nine plans are being used. Plan array is just to show plan number but it does not have any effect on the code itself. CY and OFFSET arrays are the cycle length and offset, respectively, in seconds for each plan. TIMER array is used for switching plans. The values in this array are being calculated during the simulation thus it is recommended not to change this array. MAX_G and MIN_G are the force off and minimum green for each phase in each timing plan respectively.

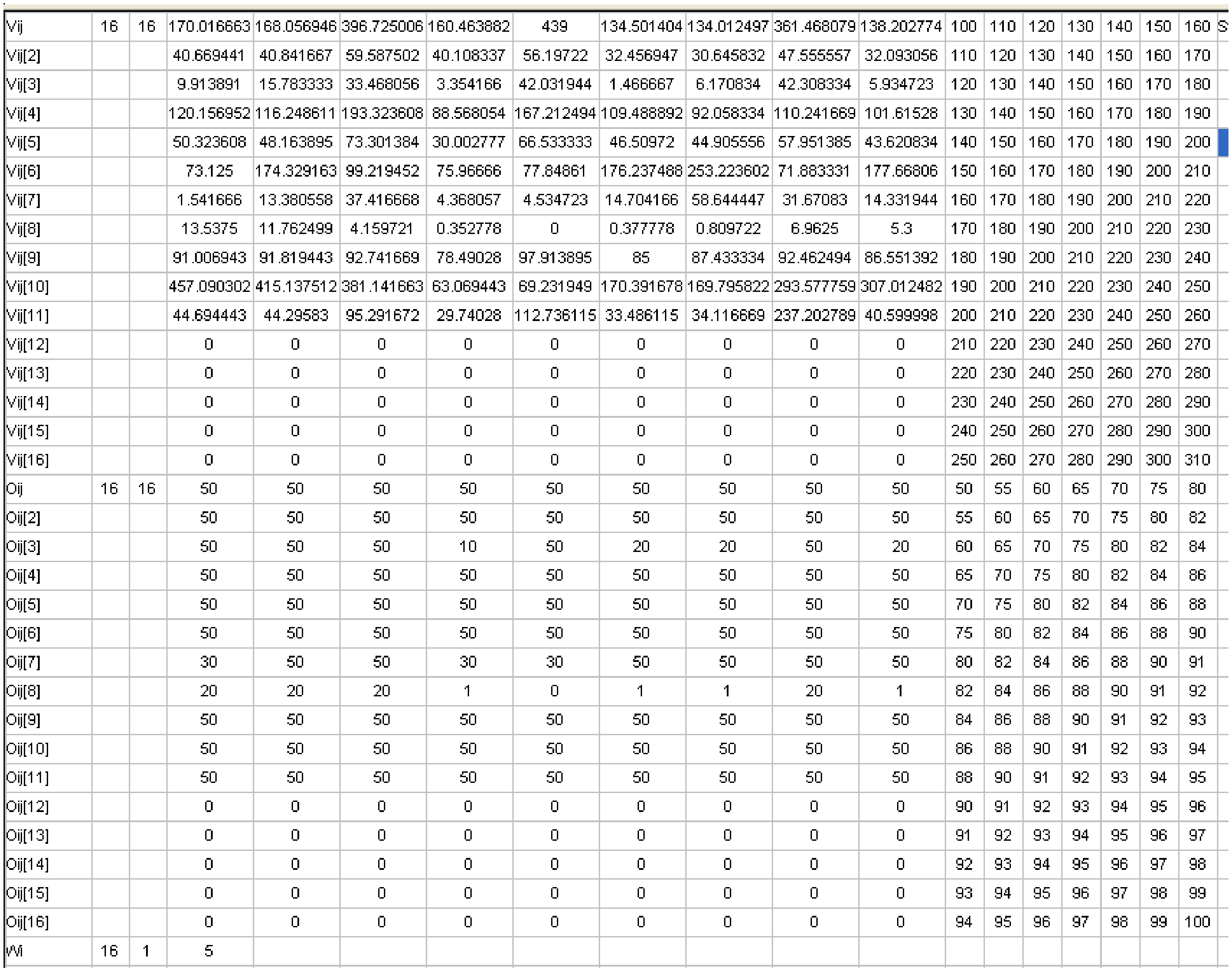
The next four arrays, i.e. Vij, Oij, Wi, and Fij, are related to the pattern matching traffic responsive mechanism. Vij and Oij arrays include all the counts, and occupancies values for different system detectors accompanied with each timing plan respectively. Wi array include the weighting factor of each system detector in the network. It is clear that this code can support up to 16 different system detectors. In VISSIM file, the name of these system detectors should be either in the range from 101 to 108 or form 111 to 118. If threshold mechanism is considered, detectors used to collect data for cycle threshold should be in the former range while the later range is for detectors used to collect data for split threshold. Fij array includes all the F values for different plans. This array is calculated during the simulation thus its values should not be changed.

The last array is for the time of day operation. The values in the array represent the time in seconds at which timing plan in being switched from pan (i) to plan (j). It is clear that this code supports up to 6 switching between plans.



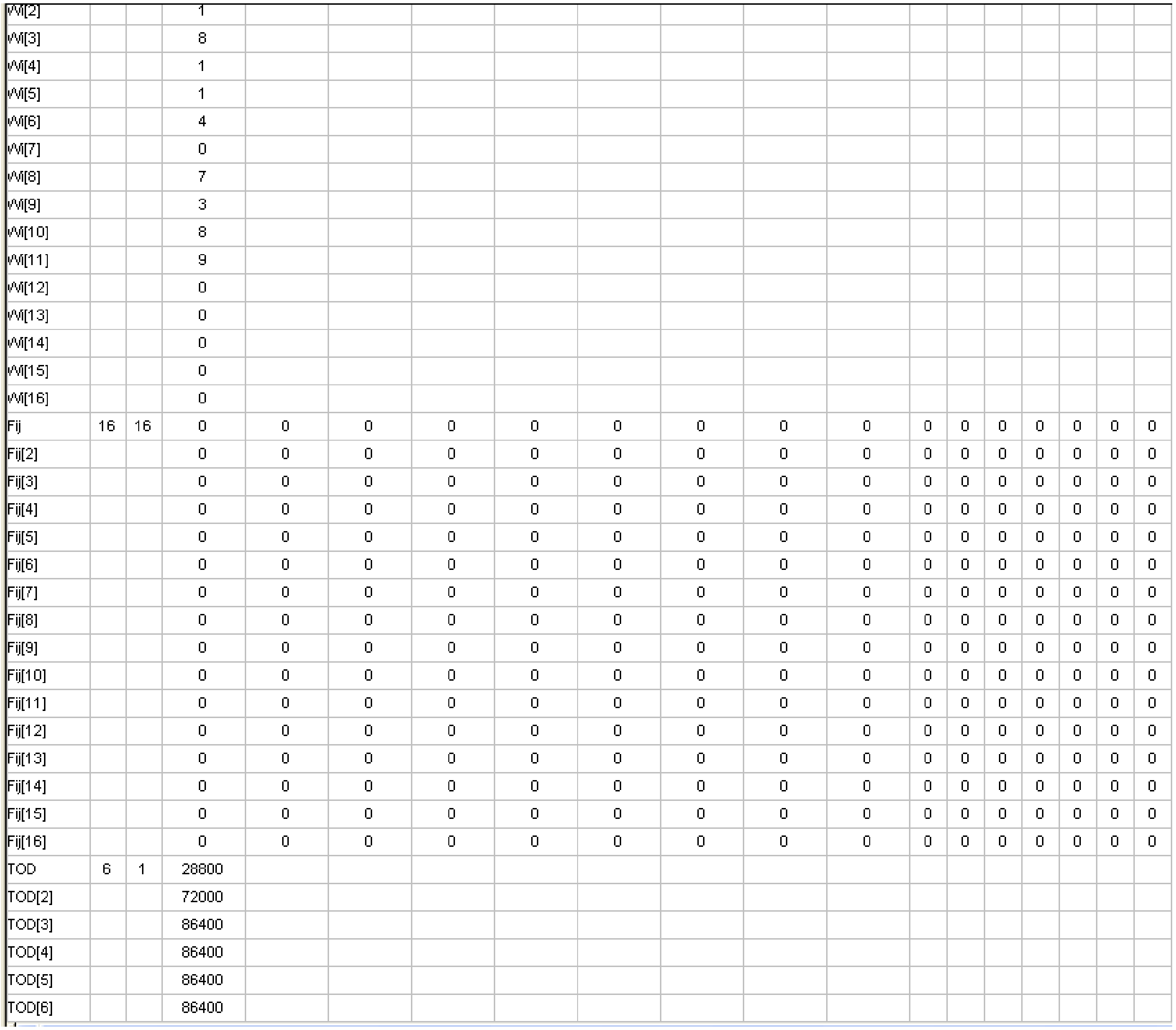
ARRAYS	Dim2	Dim1	[1]	[2]	[3]	[4]	[5]	[6]	[7]	[8]	[9]	[10]	[11]	[12]	[13]	[14]	[15]	[16]
ART	1	16	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100
NART	1	16	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100
TH_CY	1	3	100	1000	10000													
TH_SP	1	3	100	1000	10000													
Plan	1	16	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16
CY	1	16	100	90	90	108	180	150	180	150	150	0	0	0	0	0	0	0
OFFSET	1	16	11	69	71	0	124	21	135	13	11	0	0	0	0	0	0	0
TIMER	1	16	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
MAX_G	8	16	10	10	10	20	10	18	11	18	17	0	0	0	0	0	0	0
MAX_G[2]			42	32	29	20	101	51	98	47	52	0	0	0	0	0	0	0
MAX_G[3]			10	10	10	20	10	15	10	17	15	0	0	0	0	0	0	0
MAX_G[4]			10	10	13	20	31	38	33	40	38	0	0	0	0	0	0	0
MAX_G[5]			32	22	10	20	10	16	11	18	16	0	0	0	0	0	0	0
MAX_G[6]			20	20	29	20	101	53	98	47	53	0	0	0	0	0	0	0
MAX_G[7]			10	10	10	20	10	15	10	17	15	0	0	0	0	0	0	0
MAX_G[8]			10	10	13	20	31	38	33	40	38	0	0	0	0	0	0	0
MIN_G	8	16	10	10	10	5	10	10	10	10	10	0	0	0	0	0	0	0
MIN_G[2]			20	20	20	5	20	20	20	20	20	0	0	0	0	0	0	0
MIN_G[3]			10	10	10	5	10	10	10	10	10	0	0	0	0	0	0	0
MIN_G[4]			10	10	10	5	10	10	10	10	10	0	0	0	0	0	0	0
MIN_G[5]			10	10	10	5	10	10	10	10	10	0	0	0	0	0	0	0
MIN_G[6]			20	20	20	5	20	20	20	20	20	0	0	0	0	0	0	0
MIN_G[7]			10	10	10	5	10	10	10	10	10	0	0	0	0	0	0	0
MIN_G[8]			10	10	10	5	10	10	10	10	10	0	0	0	0	0	0	0
MIN_GAP	8	16	2	2	2	2	2	2	2	2	2	0	0	0	0	0	0	0
MIN_GAP[2]			4	4	4	2	4	4	4	4	4	0	0	0	0	0	0	0
MIN_GAP[3]			2	2	2	2	2	2	2	2	2	0	0	0	0	0	0	0
MIN_GAP[4]			2	2	2	2	2	2	2	2	2	0	0	0	0	0	0	0
MIN_GAP[5]			2	2	2	2	2	2	2	2	2	0	0	0	0	0	0	0
MIN_GAP[6]			4	4	4	2	4	4	4	4	4	0	0	0	0	0	0	0
MIN_GAP[7]			2	2	2	2	2	2	2	2	2	0	0	0	0	0	0	0
MIN_GAP[8]			2	2	2	2	2	2	2	2	2	0	0	0	0	0	0	0
Vij	16	16	170.016663	168.056946	396.725006	160.463882	439	134.501404	134.012497	361.468079	138.202774	100	110	120	130	140	150	160

Figure A.13 Arrays Widow for Main Code Part 1



Vij	16	16	170.016663	168.056946	396.725006	160.463882	439	134.501404	134.012497	361.468079	138.202774	100	110	120	130	140	150	160	S
Vij[2]			40.669441	40.841667	59.587502	40.108337	56.19722	32.456947	30.645832	47.555557	32.093056	110	120	130	140	150	160	170	
Vij[3]			9.913891	15.783333	33.468056	3.354166	42.031944	1.466667	6.170834	42.308334	5.934723	120	130	140	150	160	170	180	
Vij[4]			120.156952	116.248611	193.323608	88.568054	167.212494	109.488892	92.058334	110.241669	101.61528	130	140	150	160	170	180	190	
Vij[5]			50.323608	48.163895	73.301384	30.002777	66.533333	46.50972	44.905556	57.951385	43.620834	140	150	160	170	180	190	200	
Vij[6]			73.125	174.329163	99.219452	75.96666	77.84861	176.237488	253.223602	71.883331	177.66806	150	160	170	180	190	200	210	
Vij[7]			1.541666	13.380558	37.416668	4.368057	4.534723	14.704166	58.644447	31.67083	14.331944	160	170	180	190	200	210	220	
Vij[8]			13.5375	11.762499	4.159721	0.352778	0	0.377778	0.809722	6.9625	5.3	170	180	190	200	210	220	230	
Vij[9]			91.006943	91.819443	92.741669	78.49028	97.913895	85	87.433334	92.462494	86.551392	180	190	200	210	220	230	240	
Vij[10]			457.090302	415.137512	381.141663	63.069443	69.231949	170.391678	169.795822	293.577759	307.012482	190	200	210	220	230	240	250	
Vij[11]			44.694443	44.29583	95.291672	29.74028	112.736115	33.486115	34.116669	237.202789	40.599998	200	210	220	230	240	250	260	
Vij[12]			0	0	0	0	0	0	0	0	0	210	220	230	240	250	260	270	
Vij[13]			0	0	0	0	0	0	0	0	0	220	230	240	250	260	270	280	
Vij[14]			0	0	0	0	0	0	0	0	0	230	240	250	260	270	280	290	
Vij[15]			0	0	0	0	0	0	0	0	0	240	250	260	270	280	290	300	
Vij[16]			0	0	0	0	0	0	0	0	0	250	260	270	280	290	300	310	
Oij	16	16	50	50	50	50	50	50	50	50	50	50	55	60	65	70	75	80	
Oij[2]			50	50	50	50	50	50	50	50	50	55	60	65	70	75	80	82	
Oij[3]			50	50	50	10	50	20	20	50	20	60	65	70	75	80	82	84	
Oij[4]			50	50	50	50	50	50	50	50	50	65	70	75	80	82	84	86	
Oij[5]			50	50	50	50	50	50	50	50	50	70	75	80	82	84	86	88	
Oij[6]			50	50	50	50	50	50	50	50	50	75	80	82	84	86	88	90	
Oij[7]			30	50	50	30	30	50	50	50	50	80	82	84	86	88	90	91	
Oij[8]			20	20	20	1	0	1	1	20	1	82	84	86	88	90	91	92	
Oij[9]			50	50	50	50	50	50	50	50	50	84	86	88	90	91	92	93	
Oij[10]			50	50	50	50	50	50	50	50	50	86	88	90	91	92	93	94	
Oij[11]			50	50	50	50	50	50	50	50	50	88	90	91	92	93	94	95	
Oij[12]			0	0	0	0	0	0	0	0	0	90	91	92	93	94	95	96	
Oij[13]			0	0	0	0	0	0	0	0	0	91	92	93	94	95	96	97	
Oij[14]			0	0	0	0	0	0	0	0	0	92	93	94	95	96	97	98	
Oij[15]			0	0	0	0	0	0	0	0	0	93	94	95	96	97	98	99	
Oij[16]			0	0	0	0	0	0	0	0	0	94	95	96	97	98	99	100	
Wi	16	1	5																

Figure A.14 Arrays Window for Main Code Part 2



Wi[2]			1															
Wi[3]			8															
Wi[4]			1															
Wi[5]			1															
Wi[6]			4															
Wi[7]			0															
Wi[8]			7															
Wi[9]			3															
Wi[10]			8															
Wi[11]			9															
Wi[12]			0															
Wi[13]			0															
Wi[14]			0															
Wi[15]			0															
Wi[16]			0															
Fij	16	16	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Fij[2]			0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Fij[3]			0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Fij[4]			0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Fij[5]			0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Fij[6]			0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Fij[7]			0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Fij[8]			0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Fij[9]			0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Fij[10]			0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Fij[11]			0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Fij[12]			0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Fij[13]			0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Fij[14]			0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Fij[15]			0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Fij[16]			0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
TOD	6	1	28800															
TOD[2]			72000															
TOD[3]			86400															
TOD[4]			86400															
TOD[5]			86400															
TOD[6]			86400															

Figure A.15 Arrays Window for Main Code Part 3

Figure A.16 and Figure A.17 show the expression widow including all the expressions used in the main code as well as the subroutines. The first 22 expressions are used for the thresholds mechanism. The last 6 expressions are used for time of day mode of operation. The remaining expressions are for pattern matching mechanism. These expressions should not be changed as the code just uses them to implement the required mode of operation.

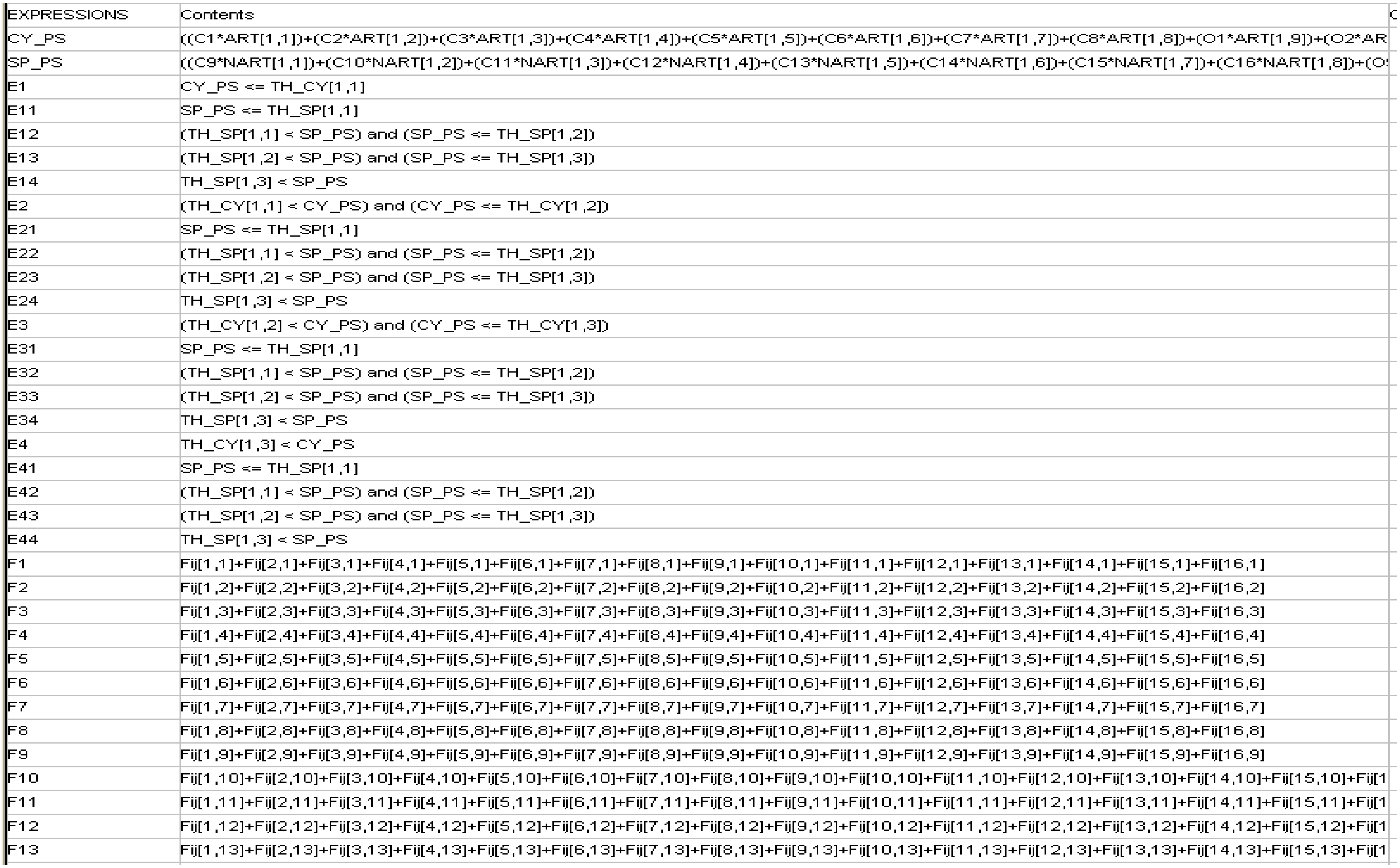
Figure A.18 shows the subroutines used in the code. The description for what each subroutine does is here below:

- ***Plan1*** controls the traffic signal regularly,

- ***S2007_07_31, PL_Timers, Plan_A, SWITCH_B, SWITCH_ADD_C, Plan_D, SWITCH_ADD1_F, SWITCH1_E, SWITCH2_E, SWITCH_ADD2_F, and Positive_Fj*** are all used to perform the switching between different timing plans either by adding or subtracting.

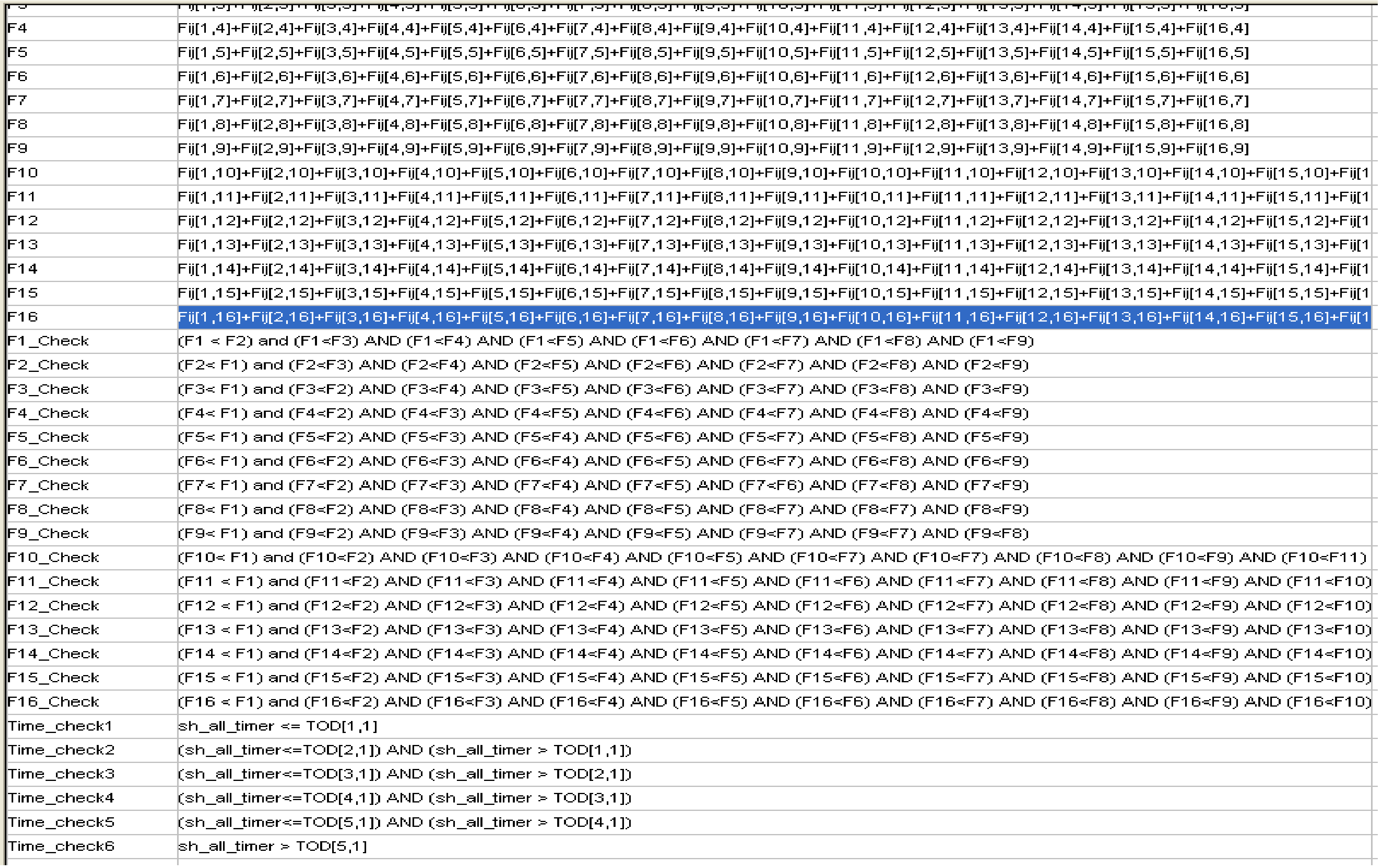
- ***FREE*** is the free control code.

Figure A.19 to Figure A.38 show chart windows for examples of the described subroutines.



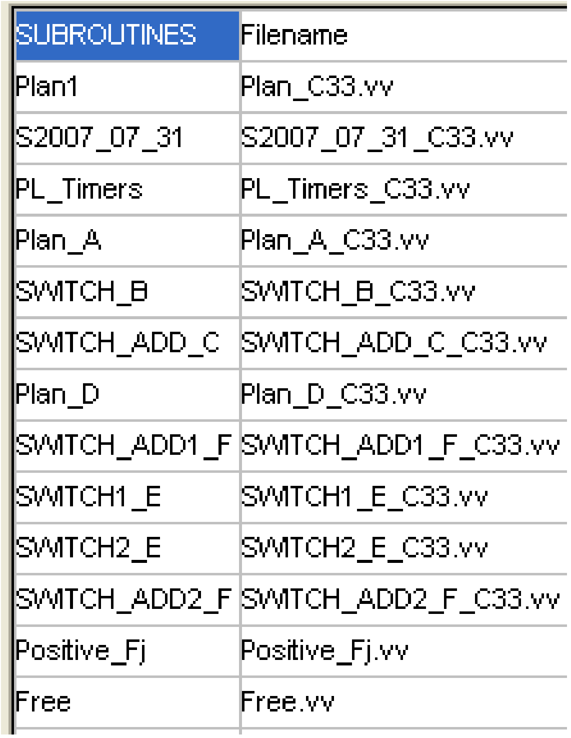
EXPRESSIONS	Contents
CY_PS	((C1*ART[1,1])+(C2*ART[1,2])+(C3*ART[1,3])+(C4*ART[1,4])+(C5*ART[1,5])+(C6*ART[1,6])+(C7*ART[1,7])+(C8*ART[1,8])+(O1*ART[1,9])+(O2*AR
SP_PS	((C9*NART[1,1])+(C10*NART[1,2])+(C11*NART[1,3])+(C12*NART[1,4])+(C13*NART[1,5])+(C14*NART[1,6])+(C15*NART[1,7])+(C16*NART[1,8])+(O
E1	CY_PS <= TH_CY[1,1]
E11	SP_PS <= TH_SP[1,1]
E12	(TH_SP[1,1] < SP_PS) and (SP_PS <= TH_SP[1,2])
E13	(TH_SP[1,2] < SP_PS) and (SP_PS <= TH_SP[1,3])
E14	TH_SP[1,3] < SP_PS
E2	(TH_CY[1,1] < CY_PS) and (CY_PS <= TH_CY[1,2])
E21	SP_PS <= TH_SP[1,1]
E22	(TH_SP[1,1] < SP_PS) and (SP_PS <= TH_SP[1,2])
E23	(TH_SP[1,2] < SP_PS) and (SP_PS <= TH_SP[1,3])
E24	TH_SP[1,3] < SP_PS
E3	(TH_CY[1,2] < CY_PS) and (CY_PS <= TH_CY[1,3])
E31	SP_PS <= TH_SP[1,1]
E32	(TH_SP[1,1] < SP_PS) and (SP_PS <= TH_SP[1,2])
E33	(TH_SP[1,2] < SP_PS) and (SP_PS <= TH_SP[1,3])
E34	TH_SP[1,3] < SP_PS
E4	TH_CY[1,3] < CY_PS
E41	SP_PS <= TH_SP[1,1]
E42	(TH_SP[1,1] < SP_PS) and (SP_PS <= TH_SP[1,2])
E43	(TH_SP[1,2] < SP_PS) and (SP_PS <= TH_SP[1,3])
E44	TH_SP[1,3] < SP_PS
F1	Fij[1,1]+Fij[2,1]+Fij[3,1]+Fij[4,1]+Fij[5,1]+Fij[6,1]+Fij[7,1]+Fij[8,1]+Fij[9,1]+Fij[10,1]+Fij[11,1]+Fij[12,1]+Fij[13,1]+Fij[14,1]+Fij[15,1]+Fij[16,1]
F2	Fij[1,2]+Fij[2,2]+Fij[3,2]+Fij[4,2]+Fij[5,2]+Fij[6,2]+Fij[7,2]+Fij[8,2]+Fij[9,2]+Fij[10,2]+Fij[11,2]+Fij[12,2]+Fij[13,2]+Fij[14,2]+Fij[15,2]+Fij[16,2]
F3	Fij[1,3]+Fij[2,3]+Fij[3,3]+Fij[4,3]+Fij[5,3]+Fij[6,3]+Fij[7,3]+Fij[8,3]+Fij[9,3]+Fij[10,3]+Fij[11,3]+Fij[12,3]+Fij[13,3]+Fij[14,3]+Fij[15,3]+Fij[16,3]
F4	Fij[1,4]+Fij[2,4]+Fij[3,4]+Fij[4,4]+Fij[5,4]+Fij[6,4]+Fij[7,4]+Fij[8,4]+Fij[9,4]+Fij[10,4]+Fij[11,4]+Fij[12,4]+Fij[13,4]+Fij[14,4]+Fij[15,4]+Fij[16,4]
F5	Fij[1,5]+Fij[2,5]+Fij[3,5]+Fij[4,5]+Fij[5,5]+Fij[6,5]+Fij[7,5]+Fij[8,5]+Fij[9,5]+Fij[10,5]+Fij[11,5]+Fij[12,5]+Fij[13,5]+Fij[14,5]+Fij[15,5]+Fij[16,5]
F6	Fij[1,6]+Fij[2,6]+Fij[3,6]+Fij[4,6]+Fij[5,6]+Fij[6,6]+Fij[7,6]+Fij[8,6]+Fij[9,6]+Fij[10,6]+Fij[11,6]+Fij[12,6]+Fij[13,6]+Fij[14,6]+Fij[15,6]+Fij[16,6]
F7	Fij[1,7]+Fij[2,7]+Fij[3,7]+Fij[4,7]+Fij[5,7]+Fij[6,7]+Fij[7,7]+Fij[8,7]+Fij[9,7]+Fij[10,7]+Fij[11,7]+Fij[12,7]+Fij[13,7]+Fij[14,7]+Fij[15,7]+Fij[16,7]
F8	Fij[1,8]+Fij[2,8]+Fij[3,8]+Fij[4,8]+Fij[5,8]+Fij[6,8]+Fij[7,8]+Fij[8,8]+Fij[9,8]+Fij[10,8]+Fij[11,8]+Fij[12,8]+Fij[13,8]+Fij[14,8]+Fij[15,8]+Fij[16,8]
F9	Fij[1,9]+Fij[2,9]+Fij[3,9]+Fij[4,9]+Fij[5,9]+Fij[6,9]+Fij[7,9]+Fij[8,9]+Fij[9,9]+Fij[10,9]+Fij[11,9]+Fij[12,9]+Fij[13,9]+Fij[14,9]+Fij[15,9]+Fij[16,9]
F10	Fij[1,10]+Fij[2,10]+Fij[3,10]+Fij[4,10]+Fij[5,10]+Fij[6,10]+Fij[7,10]+Fij[8,10]+Fij[9,10]+Fij[10,10]+Fij[11,10]+Fij[12,10]+Fij[13,10]+Fij[14,10]+Fij[15,10]+Fij[1
F11	Fij[1,11]+Fij[2,11]+Fij[3,11]+Fij[4,11]+Fij[5,11]+Fij[6,11]+Fij[7,11]+Fij[8,11]+Fij[9,11]+Fij[10,11]+Fij[11,11]+Fij[12,11]+Fij[13,11]+Fij[14,11]+Fij[15,11]+Fij[1
F12	Fij[1,12]+Fij[2,12]+Fij[3,12]+Fij[4,12]+Fij[5,12]+Fij[6,12]+Fij[7,12]+Fij[8,12]+Fij[9,12]+Fij[10,12]+Fij[11,12]+Fij[12,12]+Fij[13,12]+Fij[14,12]+Fij[15,12]+Fij[1
F13	Fij[1,13]+Fij[2,13]+Fij[3,13]+Fij[4,13]+Fij[5,13]+Fij[6,13]+Fij[7,13]+Fij[8,13]+Fij[9,13]+Fij[10,13]+Fij[11,13]+Fij[12,13]+Fij[13,13]+Fij[14,13]+Fij[15,13]+Fij[1

Figure A.16 Expressions Window for Main Code Part 1



F4	Fij[1,4]+Fij[2,4]+Fij[3,4]+Fij[4,4]+Fij[5,4]+Fij[6,4]+Fij[7,4]+Fij[8,4]+Fij[9,4]+Fij[10,4]+Fij[11,4]+Fij[12,4]+Fij[13,4]+Fij[14,4]+Fij[15,4]+Fij[16,4]
F5	Fij[1,5]+Fij[2,5]+Fij[3,5]+Fij[4,5]+Fij[5,5]+Fij[6,5]+Fij[7,5]+Fij[8,5]+Fij[9,5]+Fij[10,5]+Fij[11,5]+Fij[12,5]+Fij[13,5]+Fij[14,5]+Fij[15,5]+Fij[16,5]
F6	Fij[1,6]+Fij[2,6]+Fij[3,6]+Fij[4,6]+Fij[5,6]+Fij[6,6]+Fij[7,6]+Fij[8,6]+Fij[9,6]+Fij[10,6]+Fij[11,6]+Fij[12,6]+Fij[13,6]+Fij[14,6]+Fij[15,6]+Fij[16,6]
F7	Fij[1,7]+Fij[2,7]+Fij[3,7]+Fij[4,7]+Fij[5,7]+Fij[6,7]+Fij[7,7]+Fij[8,7]+Fij[9,7]+Fij[10,7]+Fij[11,7]+Fij[12,7]+Fij[13,7]+Fij[14,7]+Fij[15,7]+Fij[16,7]
F8	Fij[1,8]+Fij[2,8]+Fij[3,8]+Fij[4,8]+Fij[5,8]+Fij[6,8]+Fij[7,8]+Fij[8,8]+Fij[9,8]+Fij[10,8]+Fij[11,8]+Fij[12,8]+Fij[13,8]+Fij[14,8]+Fij[15,8]+Fij[16,8]
F9	Fij[1,9]+Fij[2,9]+Fij[3,9]+Fij[4,9]+Fij[5,9]+Fij[6,9]+Fij[7,9]+Fij[8,9]+Fij[9,9]+Fij[10,9]+Fij[11,9]+Fij[12,9]+Fij[13,9]+Fij[14,9]+Fij[15,9]+Fij[16,9]
F10	Fij[1,10]+Fij[2,10]+Fij[3,10]+Fij[4,10]+Fij[5,10]+Fij[6,10]+Fij[7,10]+Fij[8,10]+Fij[9,10]+Fij[10,10]+Fij[11,10]+Fij[12,10]+Fij[13,10]+Fij[14,10]+Fij[15,10]+Fij[1
F11	Fij[1,11]+Fij[2,11]+Fij[3,11]+Fij[4,11]+Fij[5,11]+Fij[6,11]+Fij[7,11]+Fij[8,11]+Fij[9,11]+Fij[10,11]+Fij[11,11]+Fij[12,11]+Fij[13,11]+Fij[14,11]+Fij[15,11]+Fij[1
F12	Fij[1,12]+Fij[2,12]+Fij[3,12]+Fij[4,12]+Fij[5,12]+Fij[6,12]+Fij[7,12]+Fij[8,12]+Fij[9,12]+Fij[10,12]+Fij[11,12]+Fij[12,12]+Fij[13,12]+Fij[14,12]+Fij[15,12]+Fij[1
F13	Fij[1,13]+Fij[2,13]+Fij[3,13]+Fij[4,13]+Fij[5,13]+Fij[6,13]+Fij[7,13]+Fij[8,13]+Fij[9,13]+Fij[10,13]+Fij[11,13]+Fij[12,13]+Fij[13,13]+Fij[14,13]+Fij[15,13]+Fij[1
F14	Fij[1,14]+Fij[2,14]+Fij[3,14]+Fij[4,14]+Fij[5,14]+Fij[6,14]+Fij[7,14]+Fij[8,14]+Fij[9,14]+Fij[10,14]+Fij[11,14]+Fij[12,14]+Fij[13,14]+Fij[14,14]+Fij[15,14]+Fij[1
F15	Fij[1,15]+Fij[2,15]+Fij[3,15]+Fij[4,15]+Fij[5,15]+Fij[6,15]+Fij[7,15]+Fij[8,15]+Fij[9,15]+Fij[10,15]+Fij[11,15]+Fij[12,15]+Fij[13,15]+Fij[14,15]+Fij[15,15]+Fij[1
F16	Fij[1,16]+Fij[2,16]+Fij[3,16]+Fij[4,16]+Fij[5,16]+Fij[6,16]+Fij[7,16]+Fij[8,16]+Fij[9,16]+Fij[10,16]+Fij[11,16]+Fij[12,16]+Fij[13,16]+Fij[14,16]+Fij[15,16]+Fij[1
F1_Check	(F1 < F2) and (F1<F3) AND (F1<F4) AND (F1<F5) AND (F1<F6) AND (F1<F7) AND (F1<F8) AND (F1<F9)
F2_Check	(F2< F1) and (F2<F3) AND (F2<F4) AND (F2<F5) AND (F2<F6) AND (F2<F7) AND (F2<F8) AND (F2<F9)
F3_Check	(F3< F1) and (F3<F2) AND (F3<F4) AND (F3<F5) AND (F3<F6) AND (F3<F7) AND (F3<F8) AND (F3<F9)
F4_Check	(F4< F1) and (F4<F2) AND (F4<F3) AND (F4<F5) AND (F4<F6) AND (F4<F7) AND (F4<F8) AND (F4<F9)
F5_Check	(F5< F1) and (F5<F2) AND (F5<F3) AND (F5<F4) AND (F5<F6) AND (F5<F7) AND (F5<F8) AND (F5<F9)
F6_Check	(F6< F1) and (F6<F2) AND (F6<F3) AND (F6<F4) AND (F6<F5) AND (F6<F7) AND (F6<F8) AND (F6<F9)
F7_Check	(F7< F1) and (F7<F2) AND (F7<F3) AND (F7<F4) AND (F7<F5) AND (F7<F6) AND (F7<F8) AND (F7<F9)
F8_Check	(F8< F1) and (F8<F2) AND (F8<F3) AND (F8<F4) AND (F8<F5) AND (F8<F7) AND (F8<F7) AND (F8<F9)
F9_Check	(F9< F1) and (F9<F2) AND (F9<F3) AND (F9<F4) AND (F9<F5) AND (F9<F7) AND (F9<F7) AND (F9<F8)
F10_Check	(F10< F1) and (F10<F2) AND (F10<F3) AND (F10<F4) AND (F10<F5) AND (F10<F7) AND (F10<F7) AND (F10<F8) AND (F10<F9) AND (F10<F11)
F11_Check	(F11 < F1) and (F11<F2) AND (F11<F3) AND (F11<F4) AND (F11<F5) AND (F11<F6) AND (F11<F7) AND (F11<F8) AND (F11<F9) AND (F11<F10)
F12_Check	(F12 < F1) and (F12<F2) AND (F12<F3) AND (F12<F4) AND (F12<F5) AND (F12<F6) AND (F12<F7) AND (F12<F8) AND (F12<F9) AND (F12<F10)
F13_Check	(F13 < F1) and (F13<F2) AND (F13<F3) AND (F13<F4) AND (F13<F5) AND (F13<F6) AND (F13<F7) AND (F13<F8) AND (F13<F9) AND (F13<F10)
F14_Check	(F14 < F1) and (F14<F2) AND (F14<F3) AND (F14<F4) AND (F14<F5) AND (F14<F6) AND (F14<F7) AND (F14<F8) AND (F14<F9) AND (F14<F10)
F15_Check	(F15 < F1) and (F15<F2) AND (F15<F3) AND (F15<F4) AND (F15<F5) AND (F15<F6) AND (F15<F7) AND (F15<F8) AND (F15<F9) AND (F15<F10)
F16_Check	(F16 < F1) and (F16<F2) AND (F16<F3) AND (F16<F4) AND (F16<F5) AND (F16<F6) AND (F16<F7) AND (F16<F8) AND (F16<F9) AND (F16<F10)
Time_check1	sh_all_timer <= TOD[1,1]
Time_check2	(sh_all_timer<=TOD[2,1]) AND (sh_all_timer > TOD[1,1])
Time_check3	(sh_all_timer<=TOD[3,1]) AND (sh_all_timer > TOD[2,1])
Time_check4	(sh_all_timer<=TOD[4,1]) AND (sh_all_timer > TOD[3,1])
Time_check5	(sh_all_timer<=TOD[5,1]) AND (sh_all_timer > TOD[4,1])
Time_check6	sh_all_timer > TOD[5,1]

Figure A.17 Expressions Window for Main Code Part 2



SUBROUTINES	Filename
Plan1	Plan_C33.vv
S2007_07_31	S2007_07_31_C33.vv
PL_Timers	PL_Timers_C33.vv
Plan_A	Plan_A_C33.vv
SWITCH_B	SWITCH_B_C33.vv
SWITCH_ADD_C	SWITCH_ADD_C_C33.vv
Plan_D	Plan_D_C33.vv
SWITCH_ADD1_F	SWITCH_ADD1_F_C33.vv
SWITCH1_E	SWITCH1_E_C33.vv
SWITCH2_E	SWITCH2_E_C33.vv
SWITCH_ADD2_F	SWITCH_ADD2_F_C33.vv
Positive_Fj	Positive_Fj.vv
Free	Free.vv

Figure A.18 Subroutines Window for Main Code

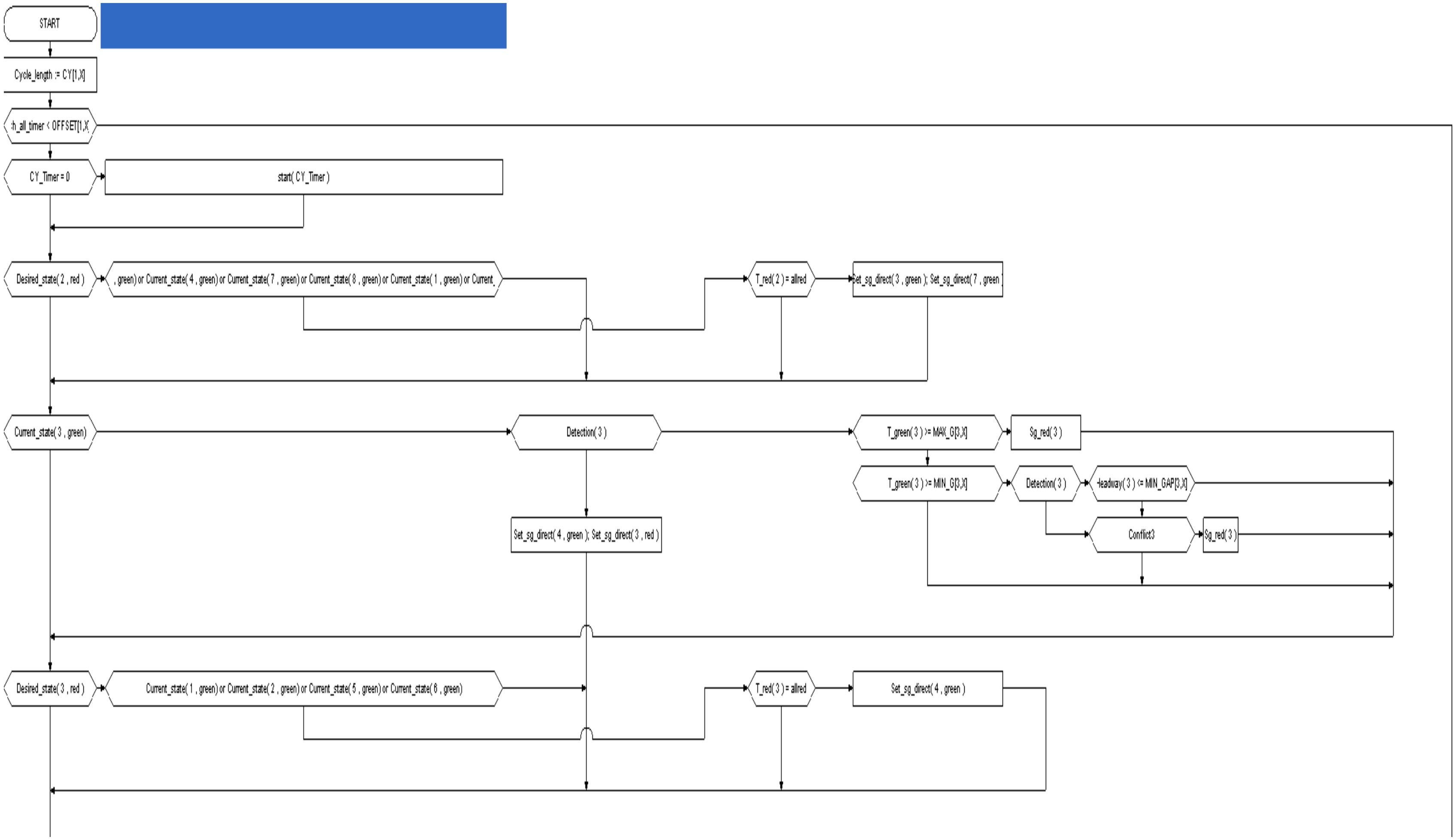


Figure A.19 Plan1 Subroutine Part 1

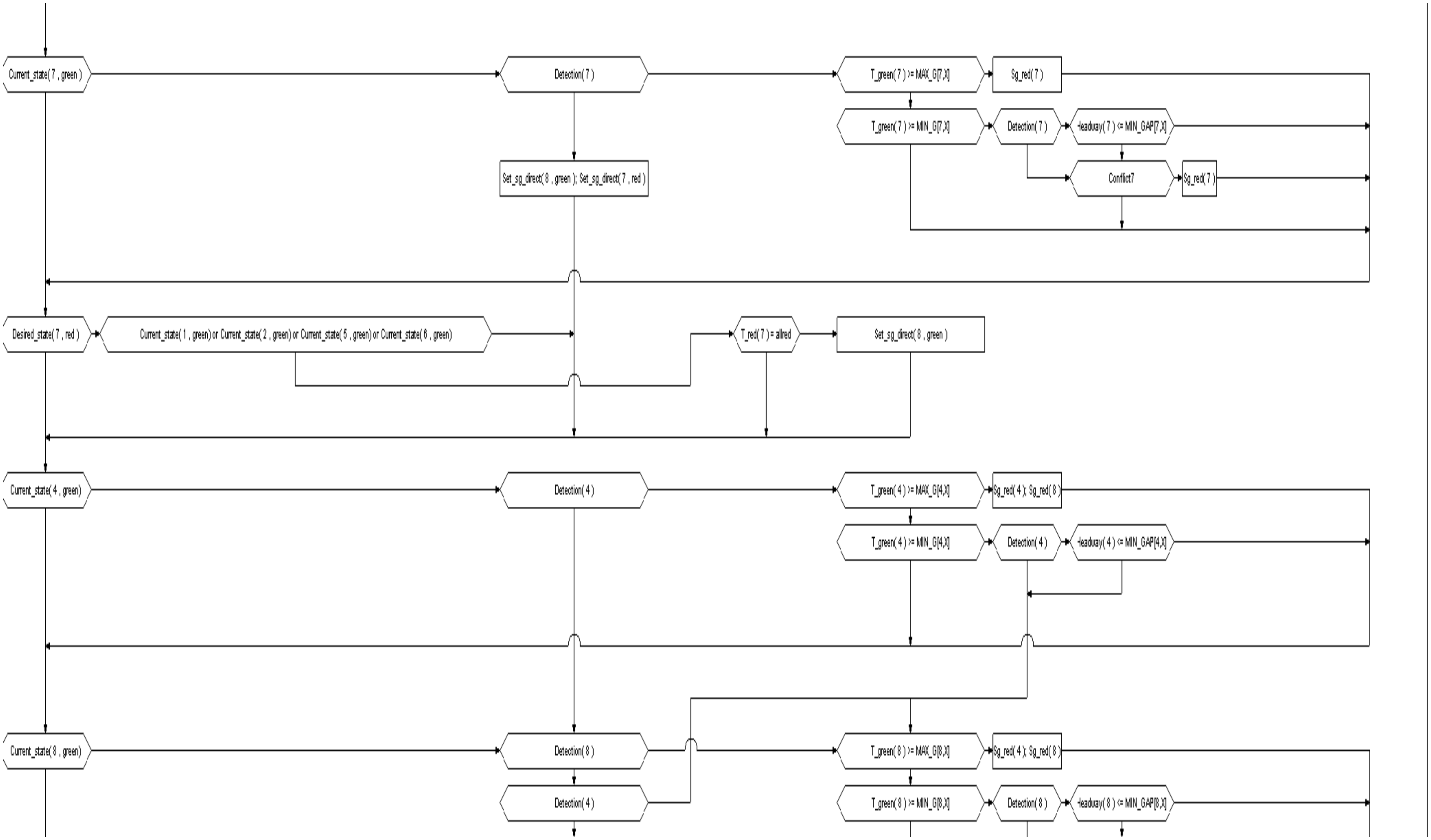


Figure A.20 Plan1 Subroutine Part 2

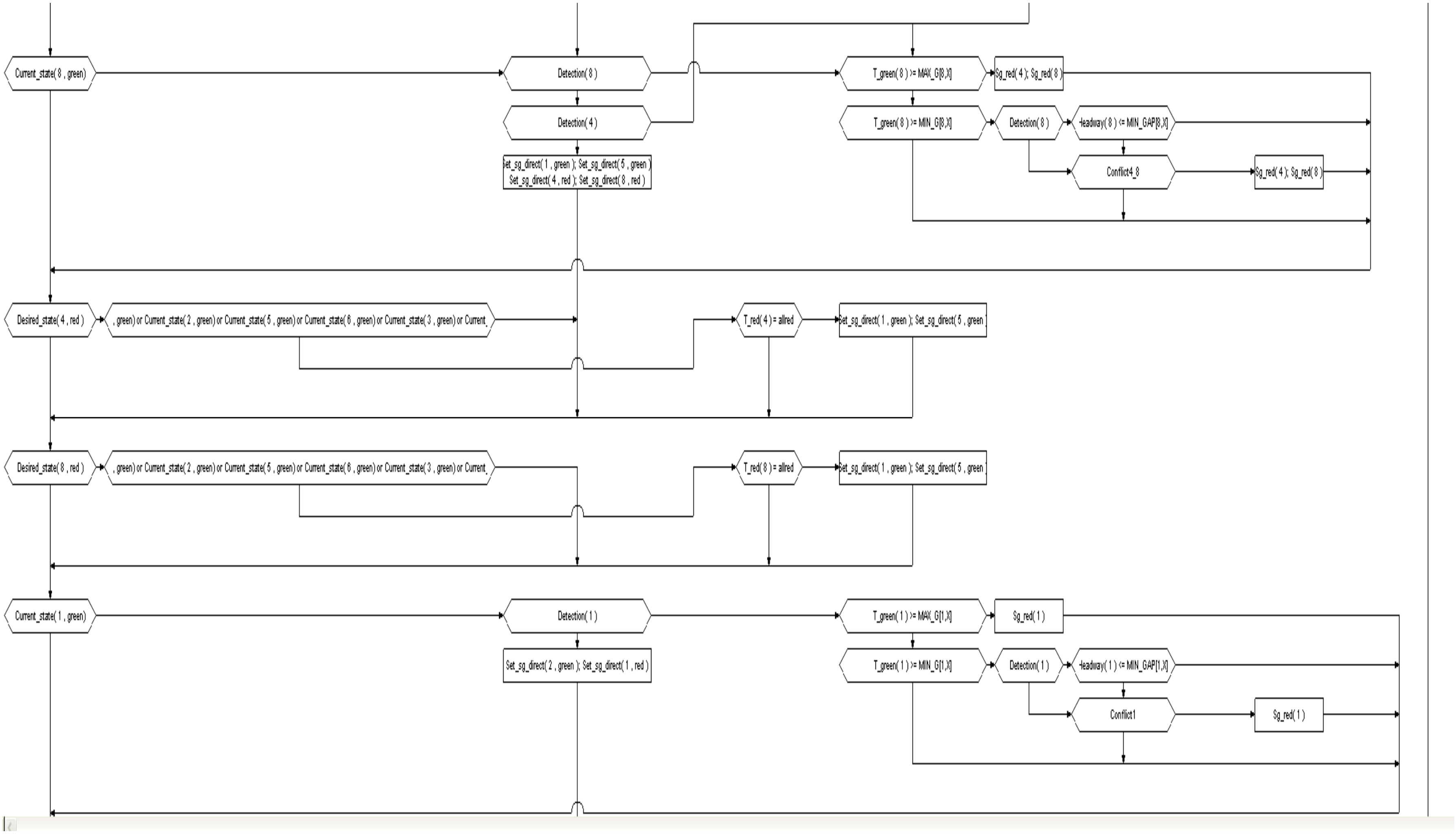


Figure A.21 Plan1 Subroutine Part 3

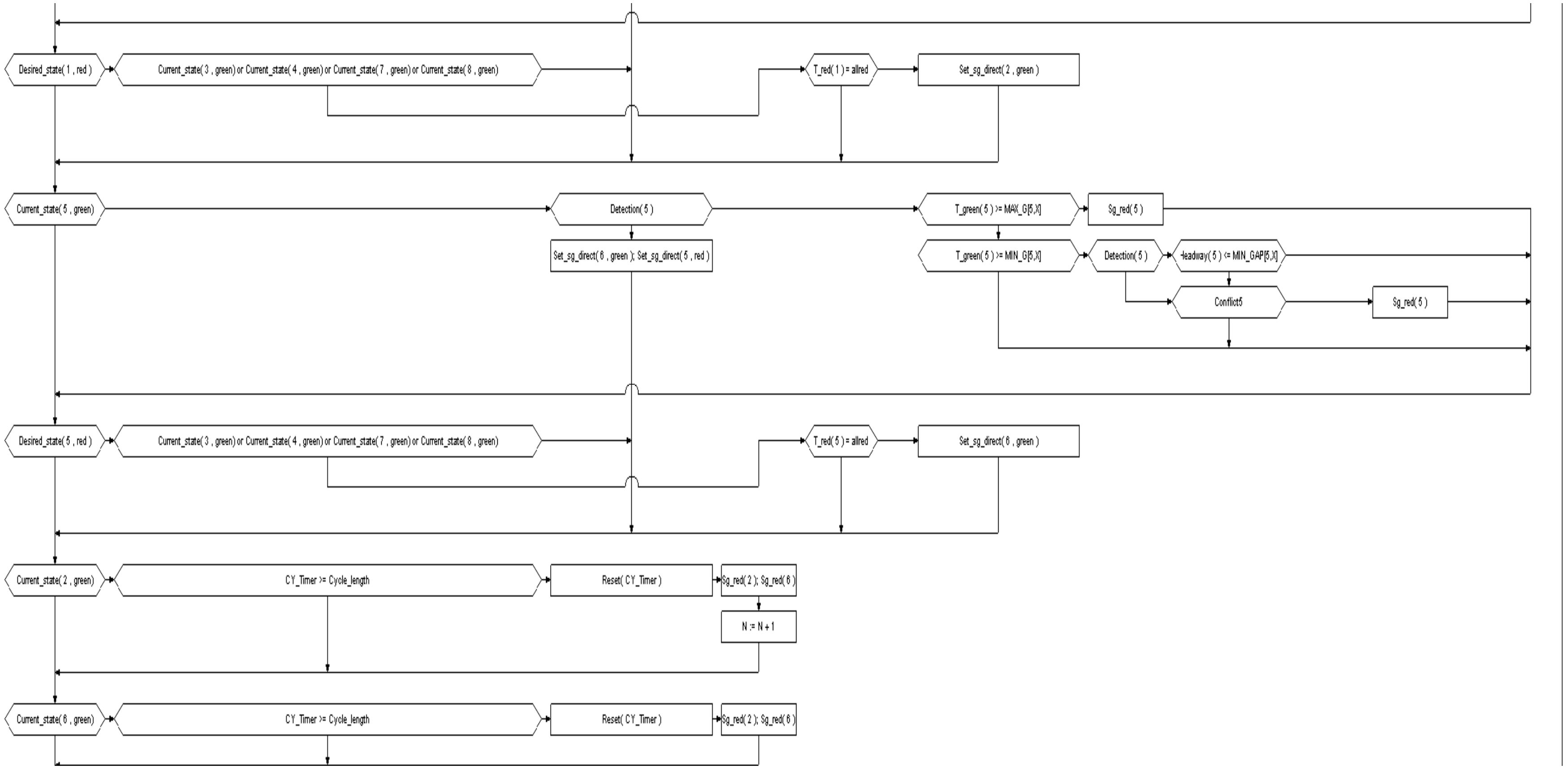


Figure A.22 Plan1 Subroutine Part 4

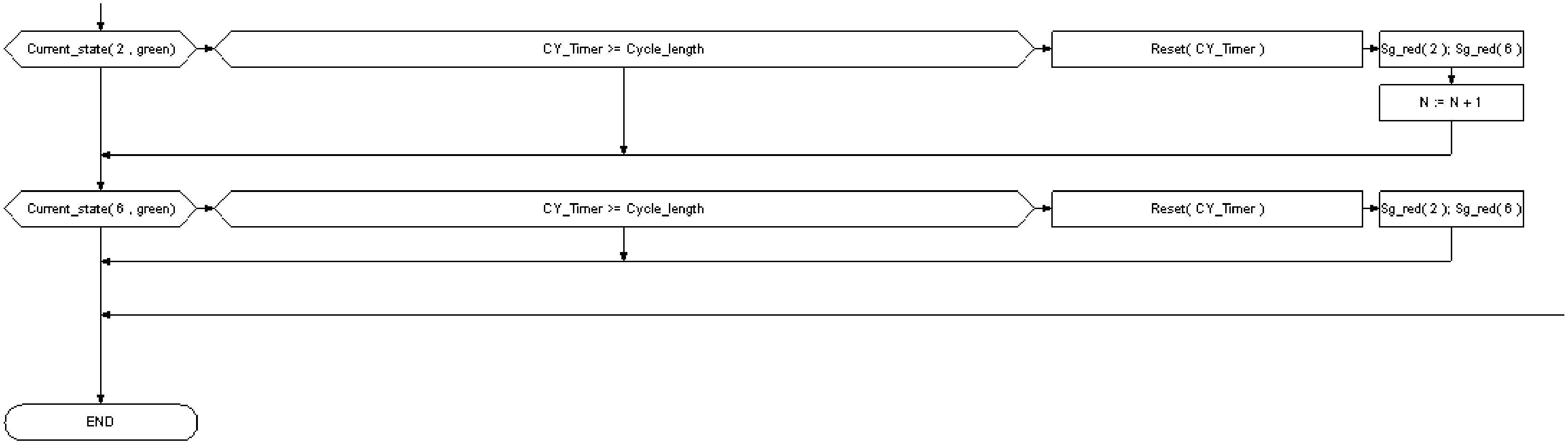


Figure A.23 Plan1 Subroutine Part 5

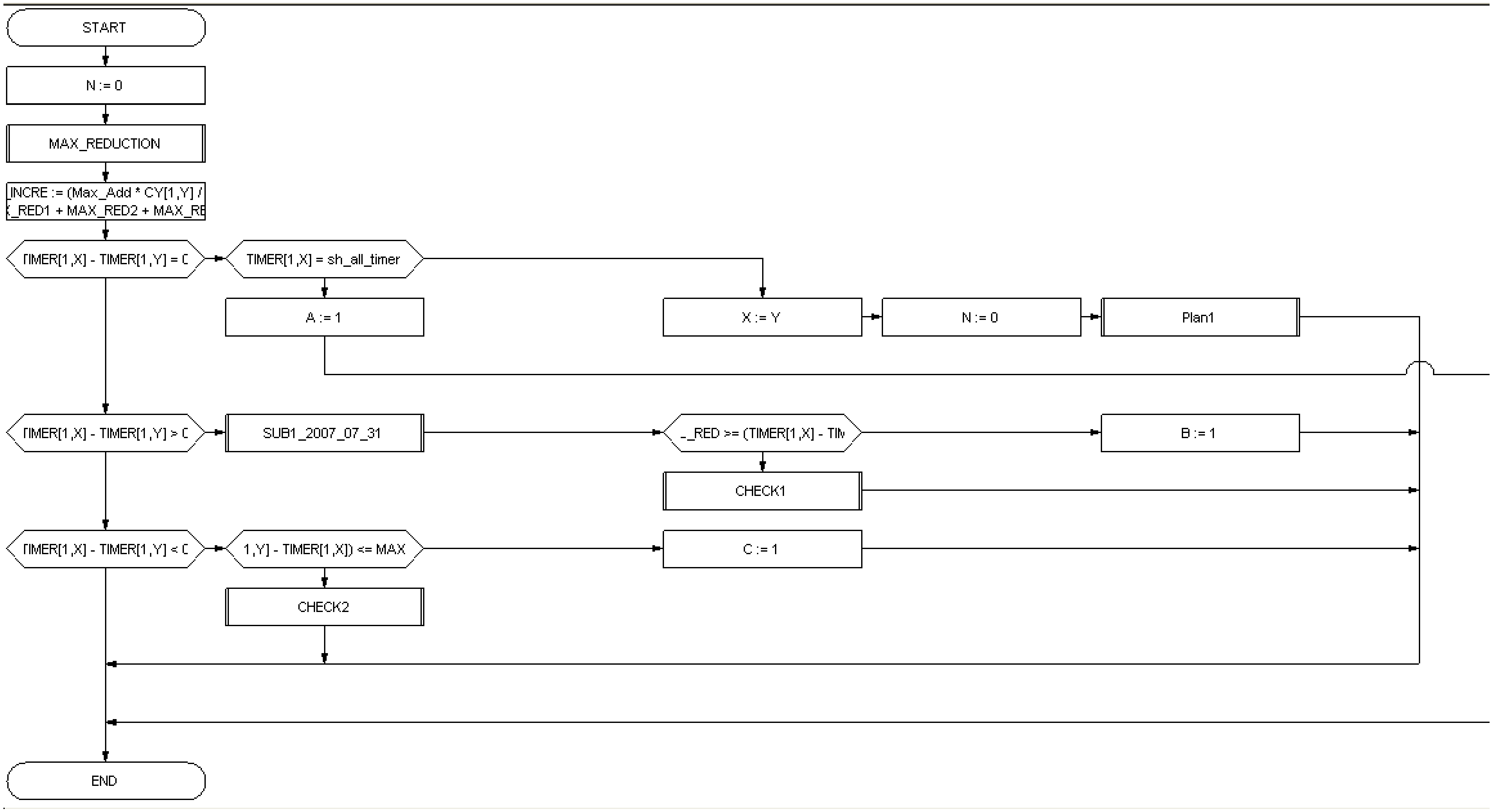


Figure A.24 S2007_07_31 Subroutine

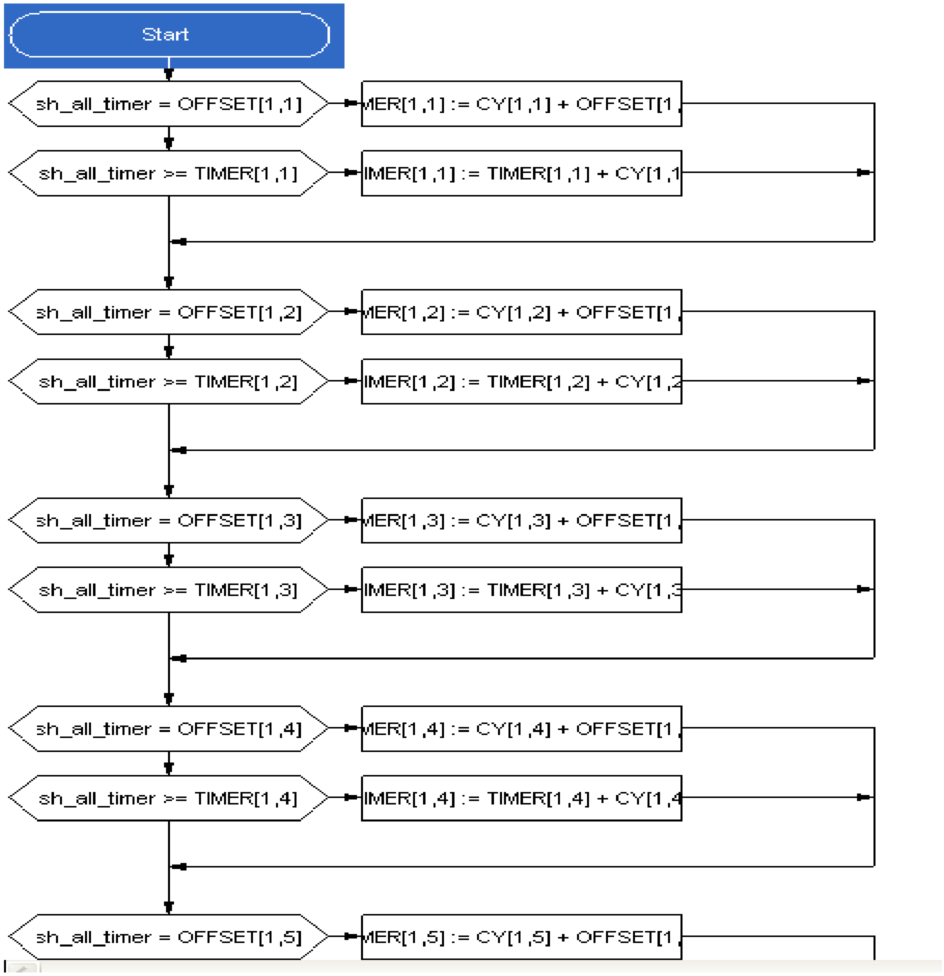


Figure A.25 PL_Timers Subroutine Part 1

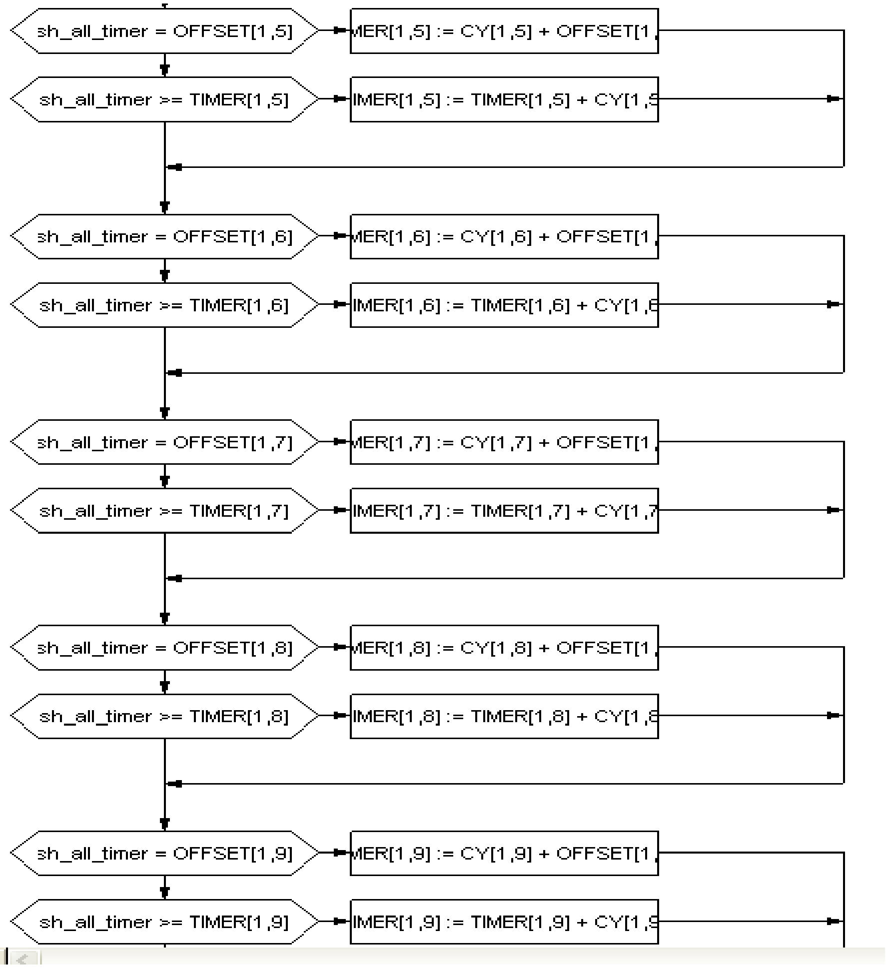


Figure A.26 PL_Timers Subroutine Part 2

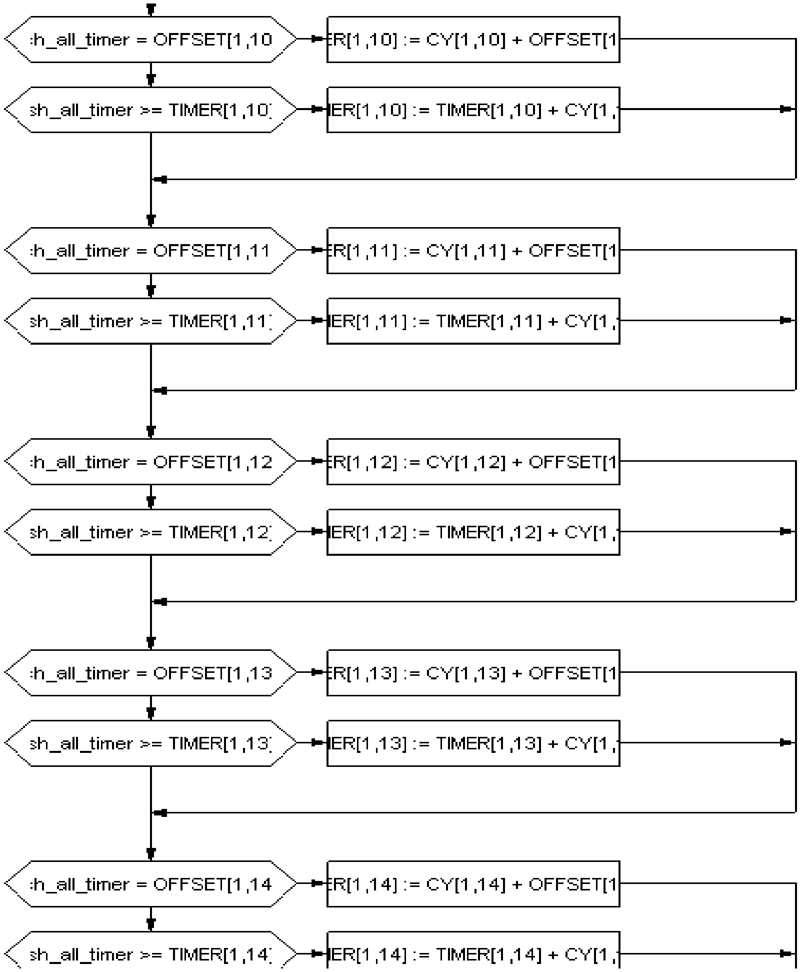


Figure A.27 PL_Timers Subroutine Part 3

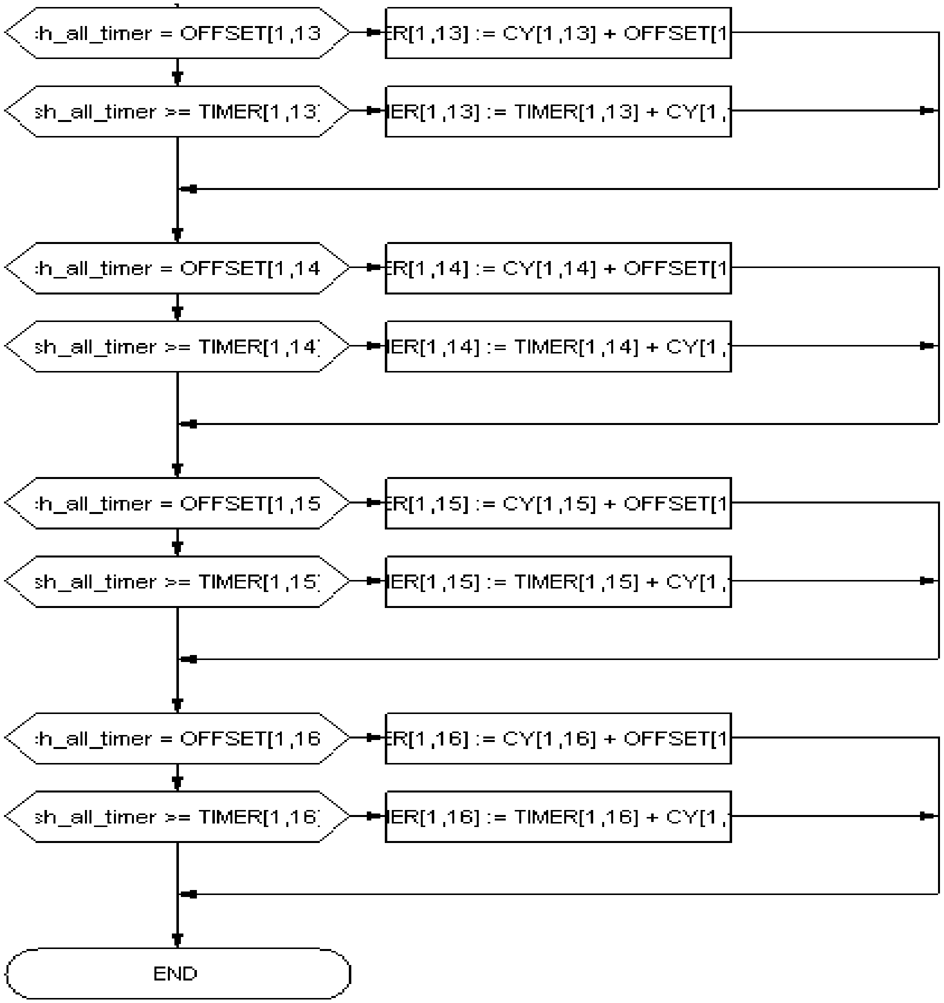


Figure A.28 PL_Timers Subroutine Part 4

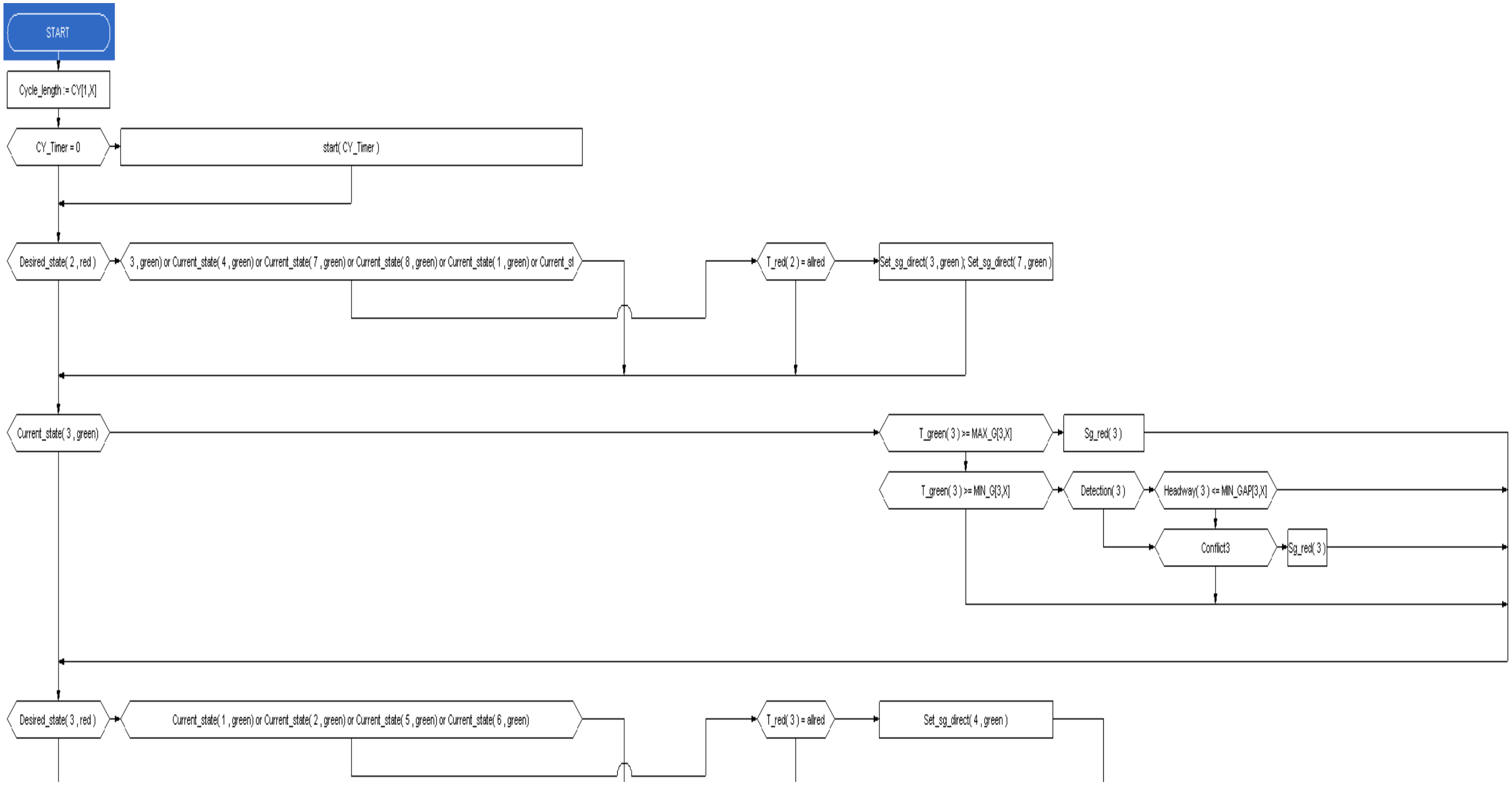


Figure A.29 Plan_A Subroutine Part 1

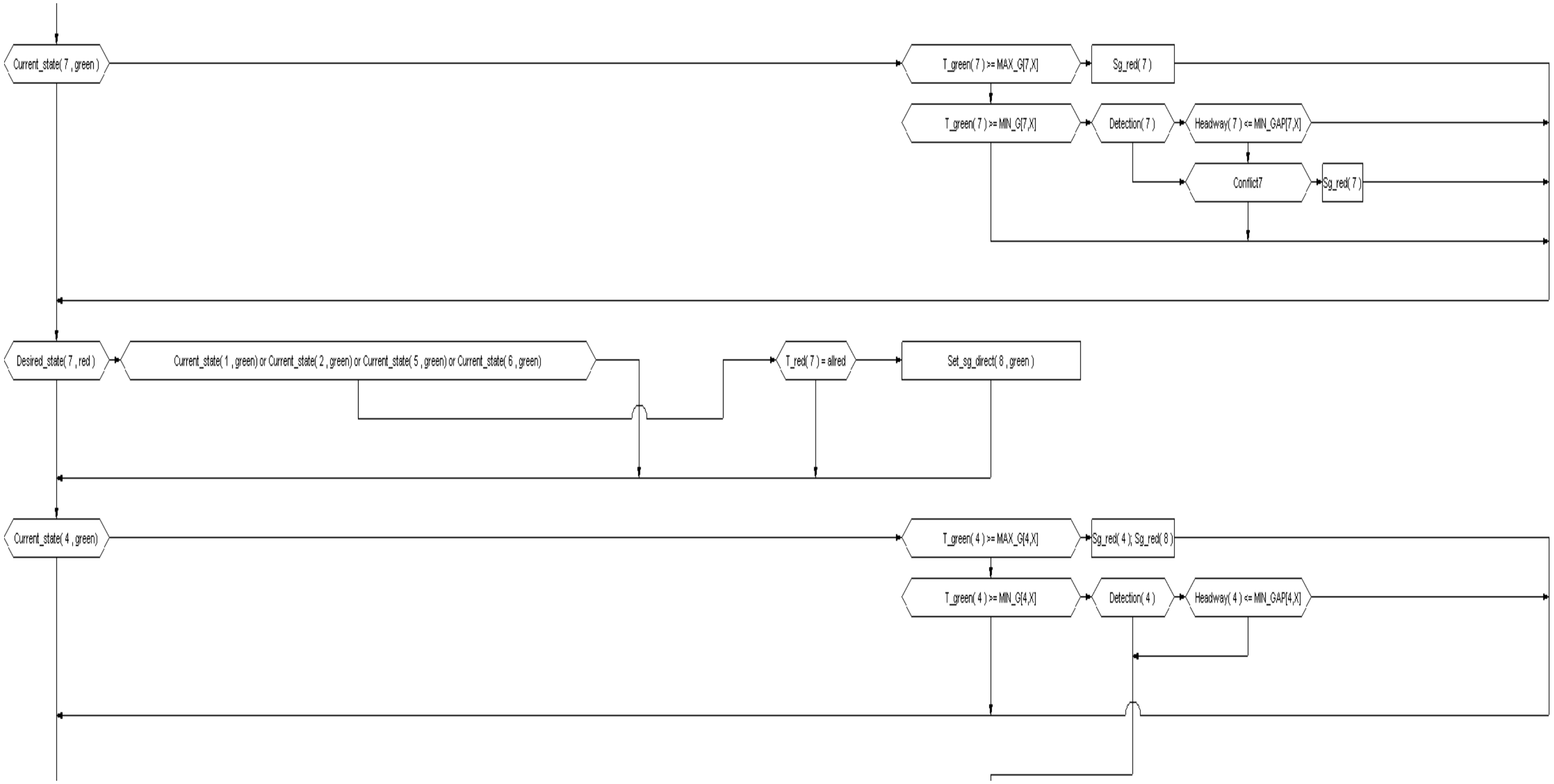


Figure A.30 Plan_A Subroutine Part 2

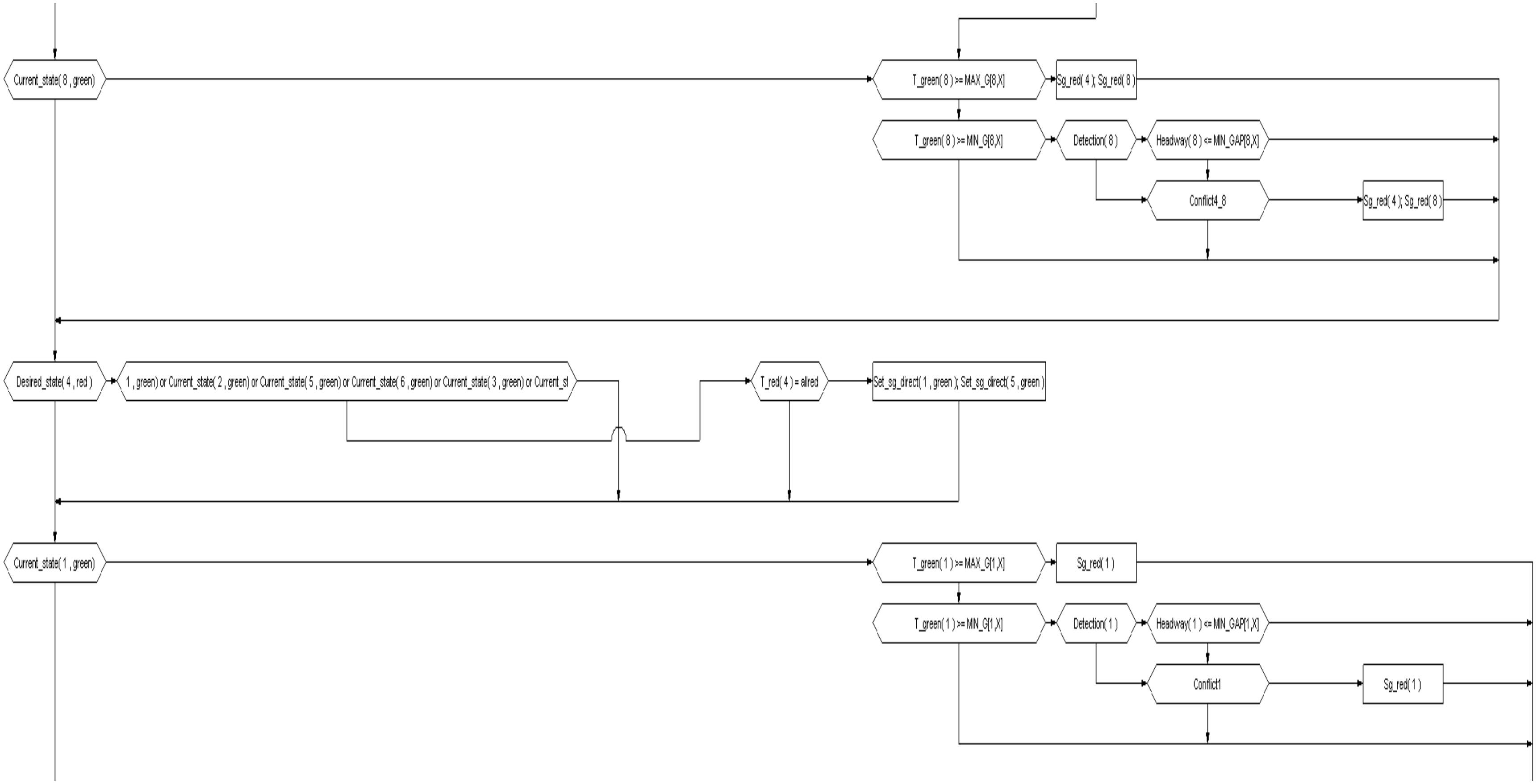


Figure A.31 Plan_A Subroutine Part 3

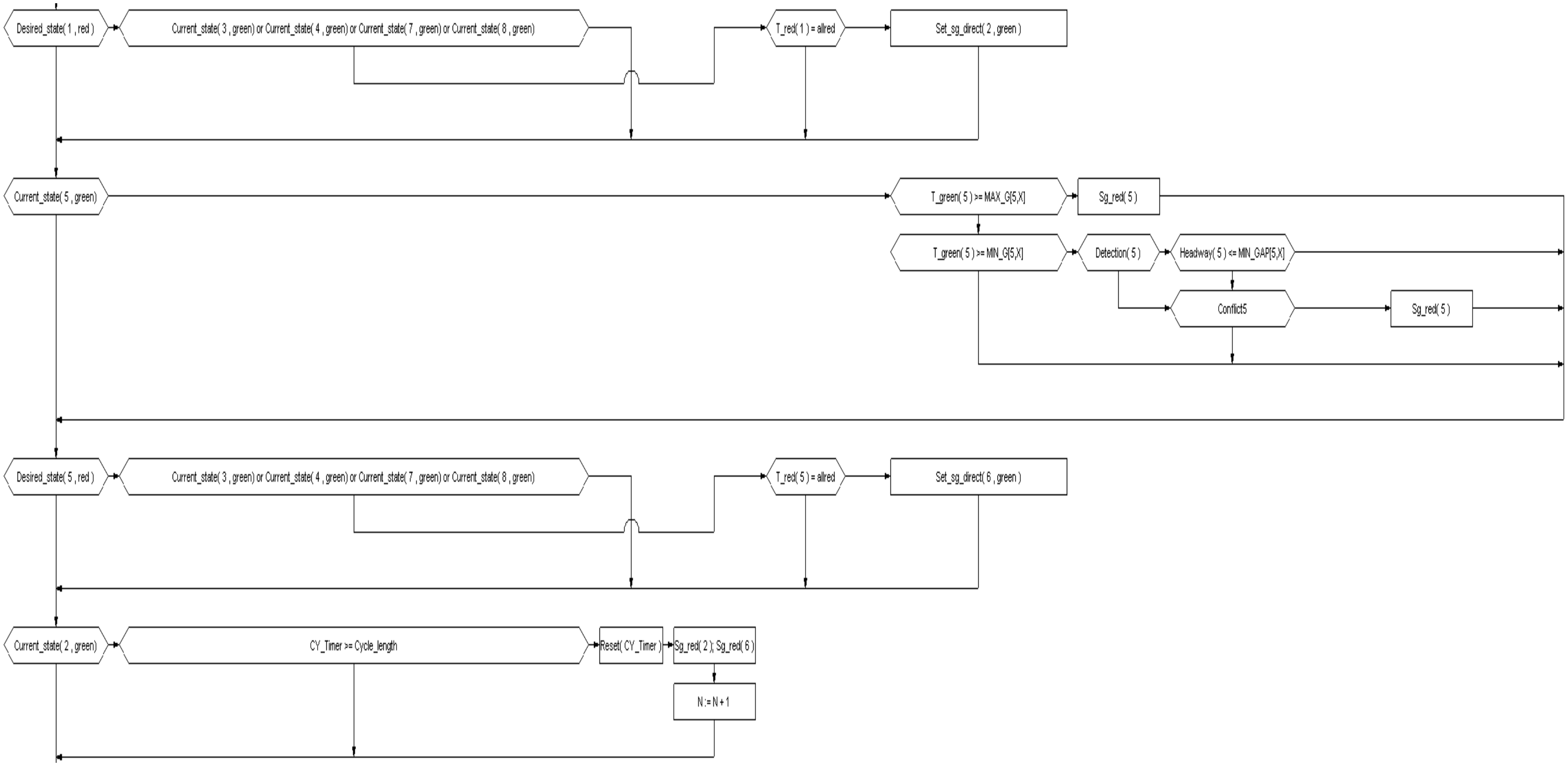


Figure A.32 Plan_A Subroutine Part 4

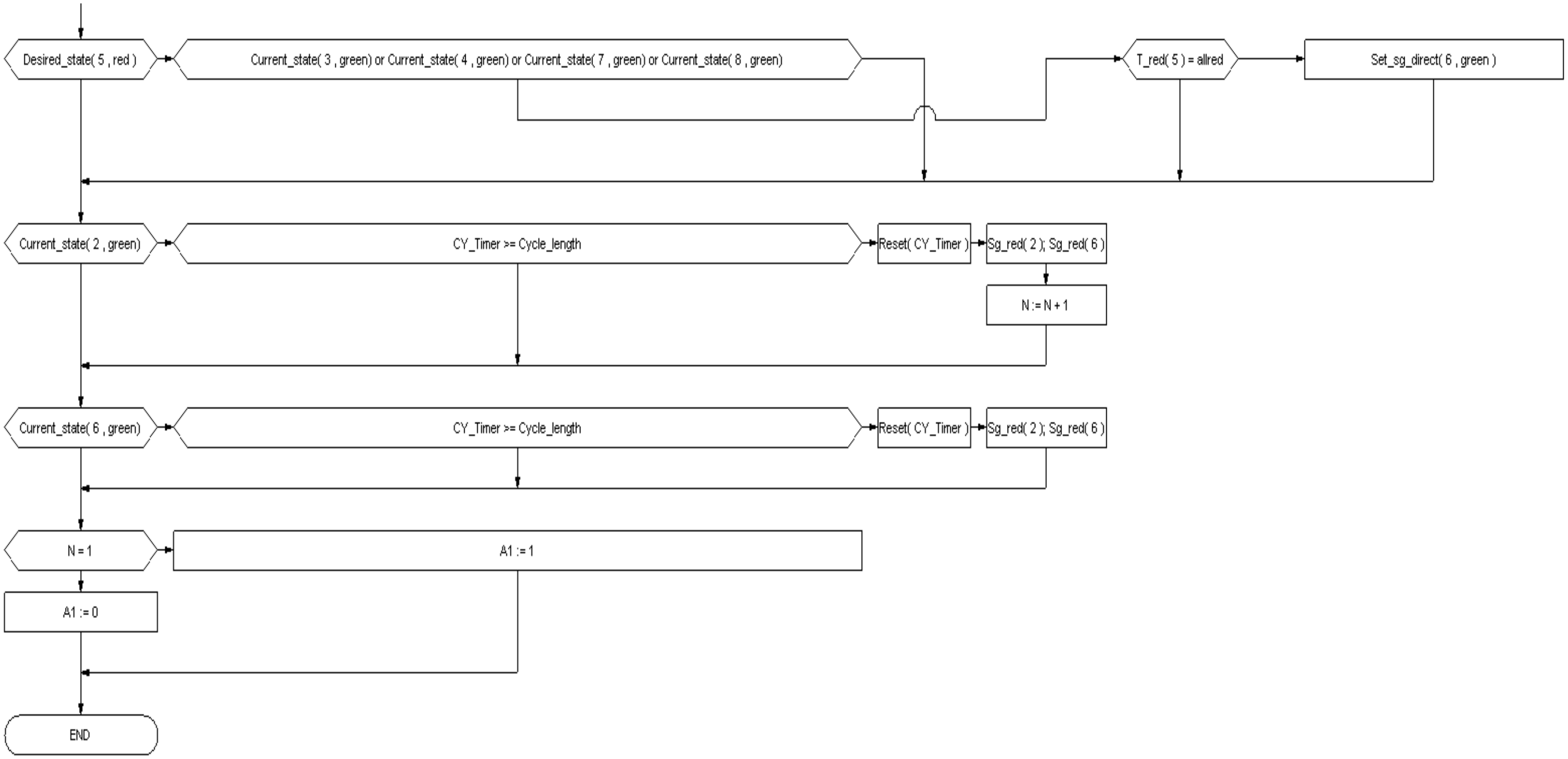


Figure A.33 Plan_A Subroutine Part 5

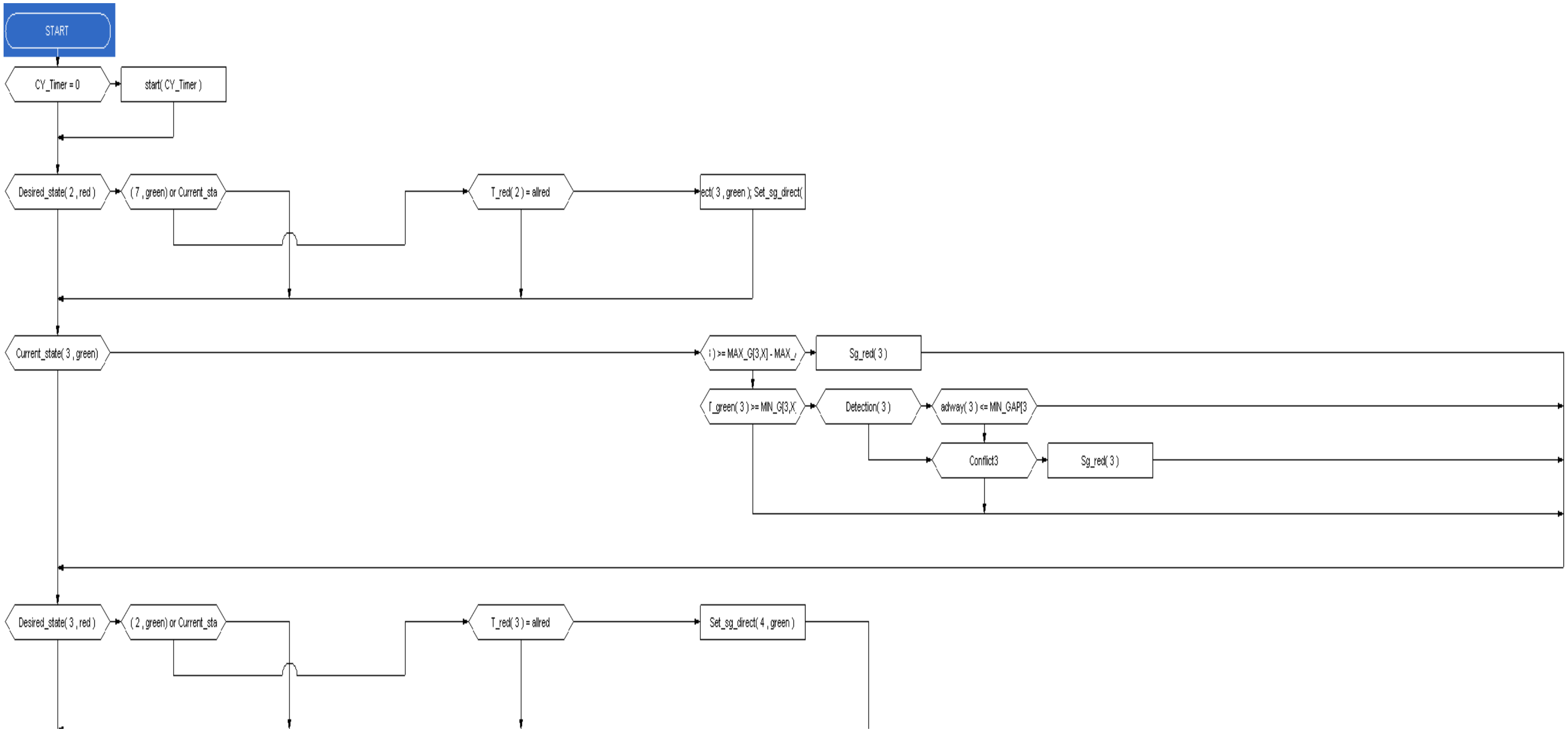


Figure A.34 SWITCH_B Subroutine Part 1

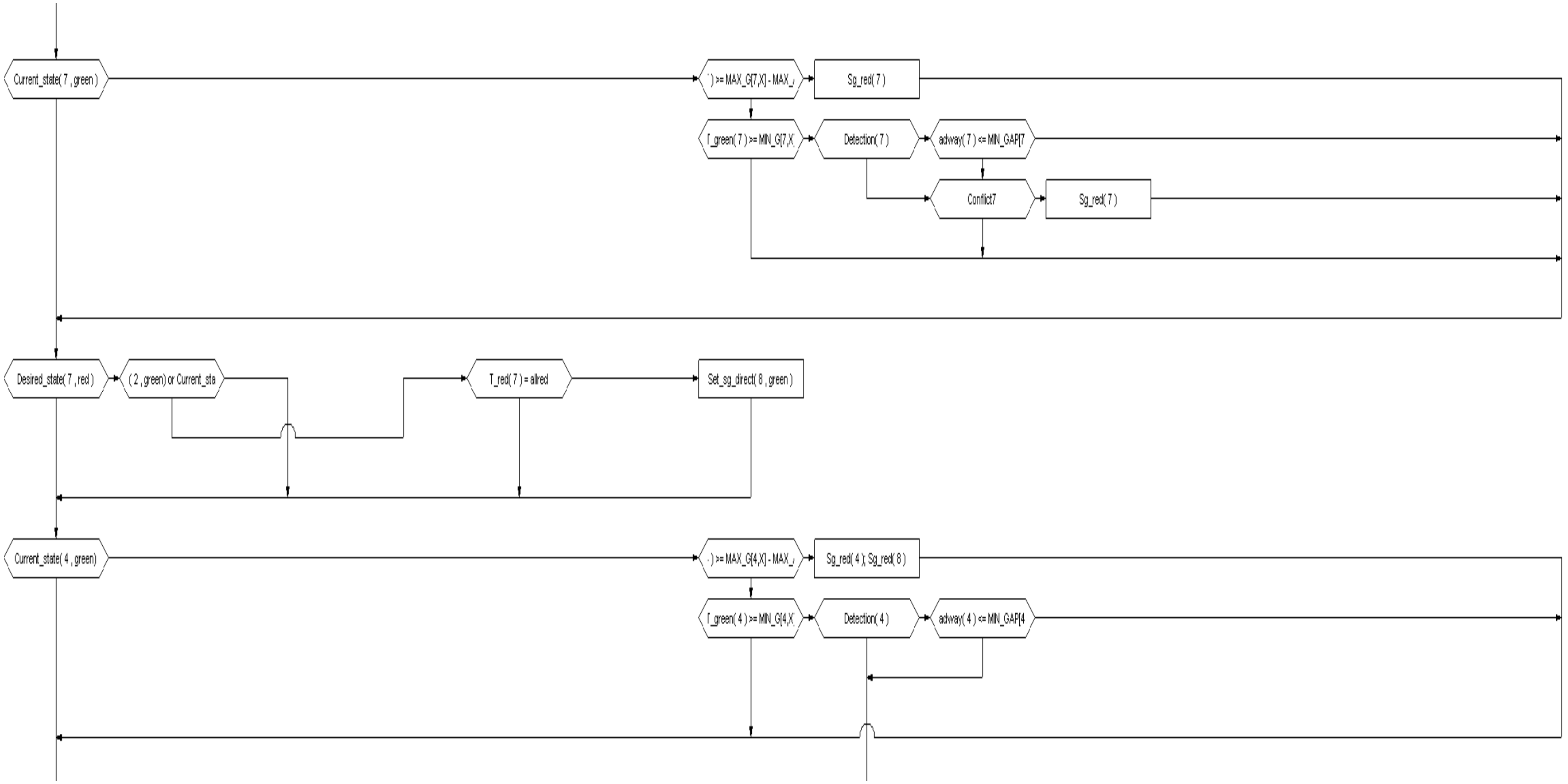


Figure A.35 SWITCH_B Subroutine Part 2

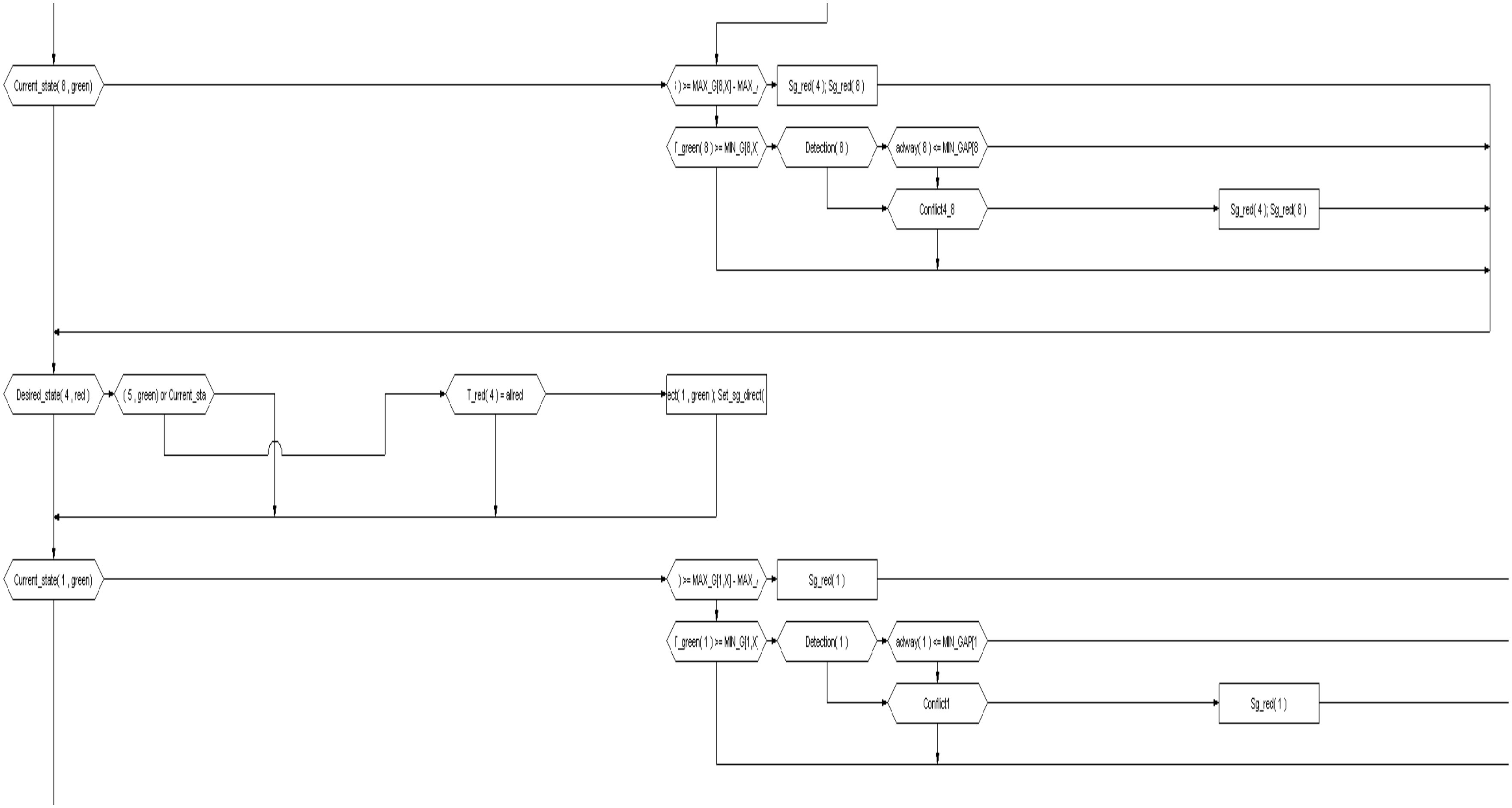


Figure A.36 SWITCH_B Subroutine Part 3

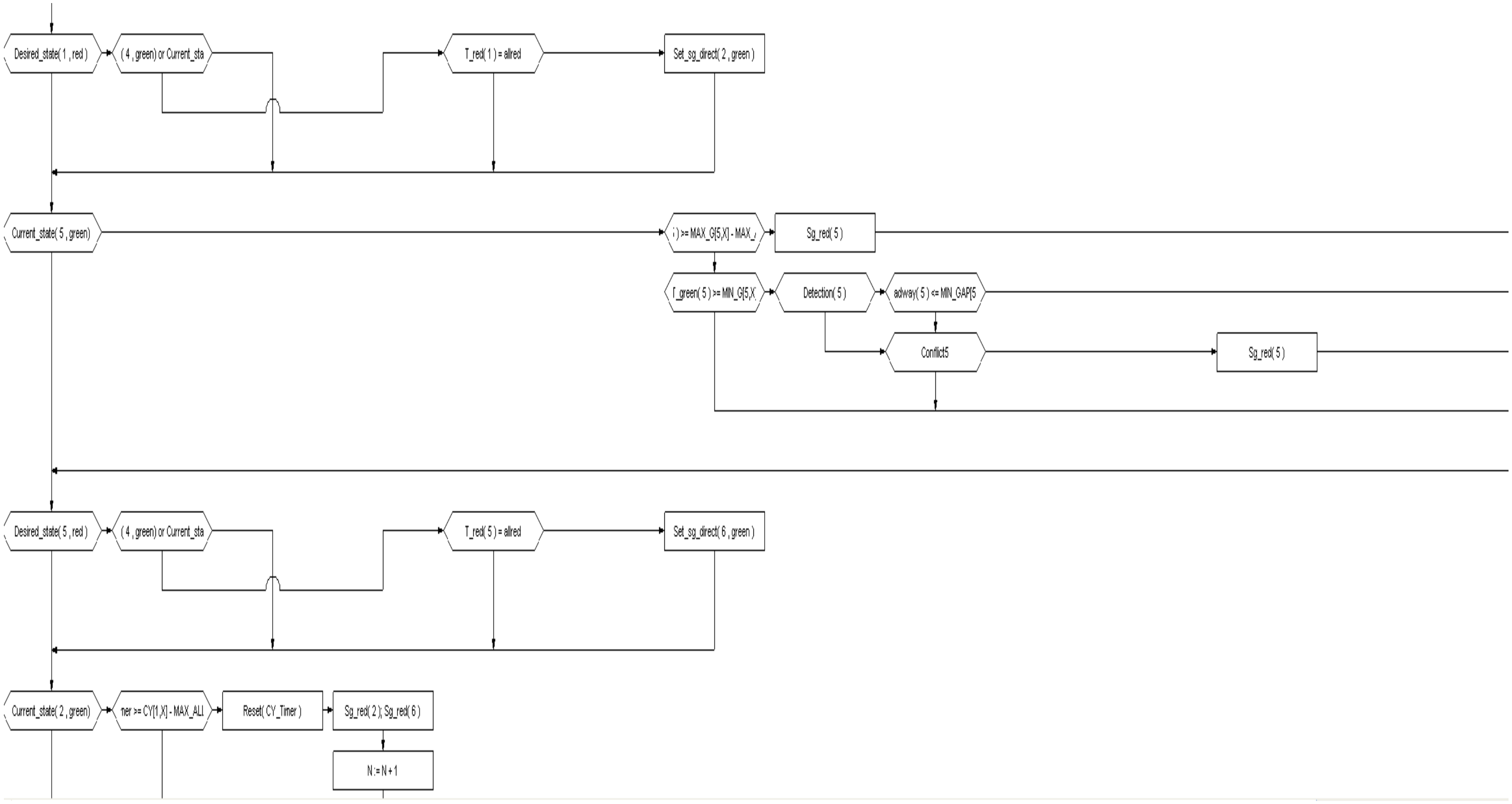


Figure A.37 SWITCH_B Subroutine Part 4

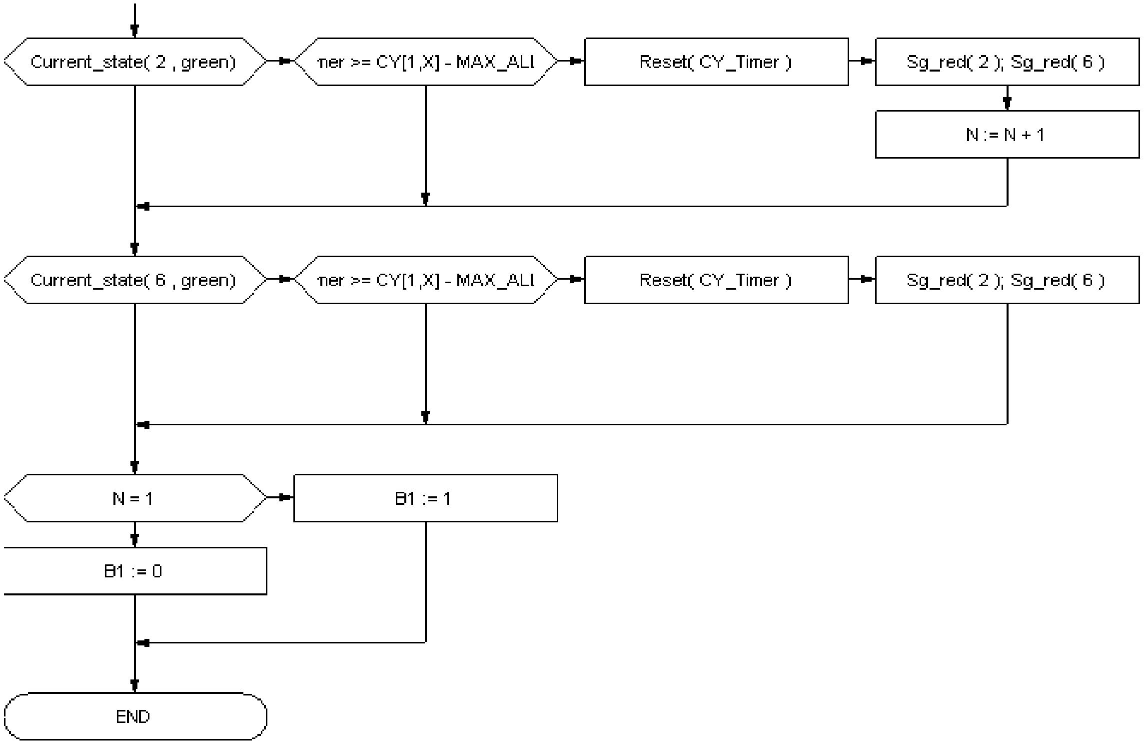


Figure A.38 SWITCH_B Subroutine Part 5

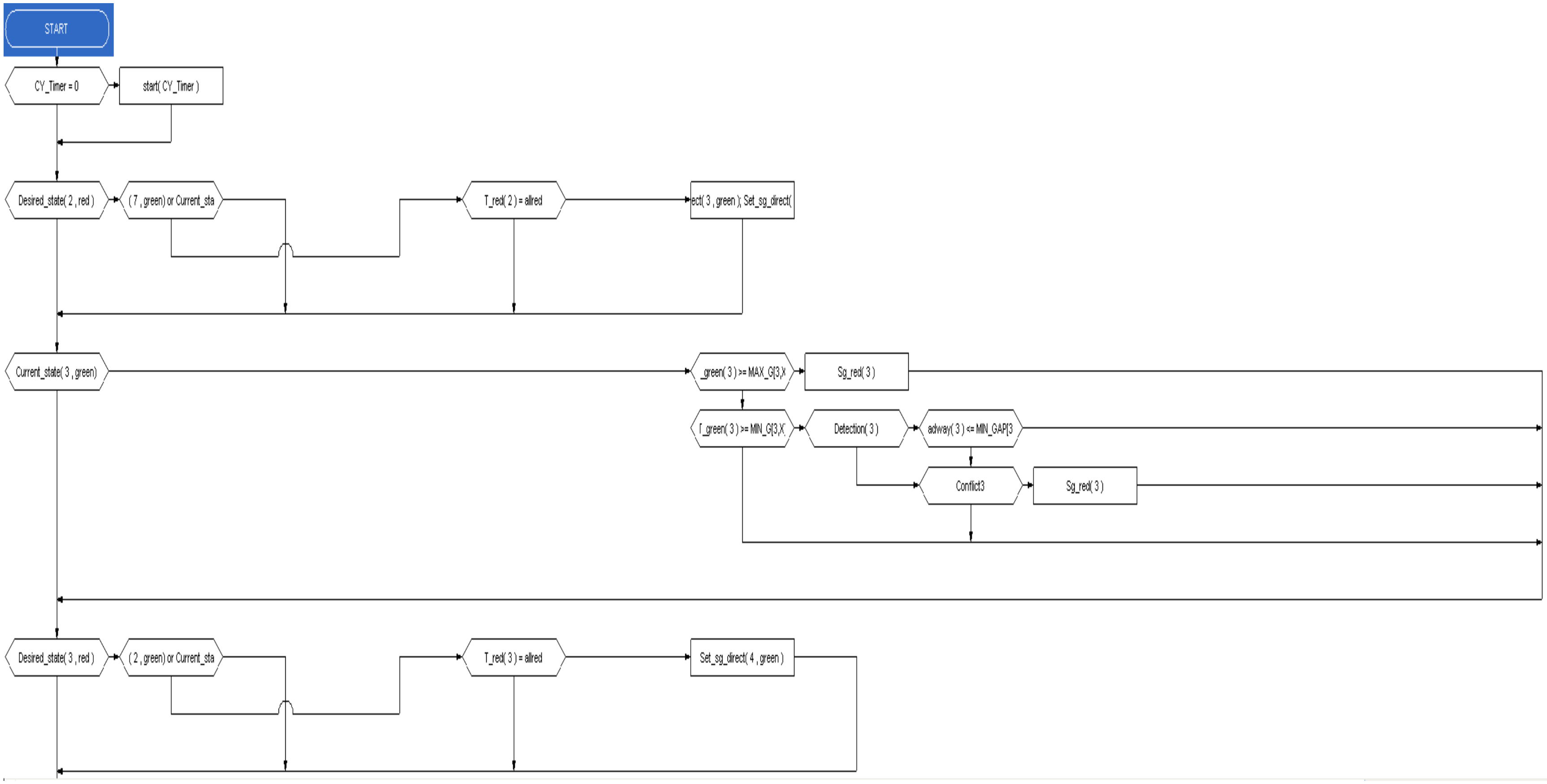


Figure A.39 SWITCH_ADD_C Subroutine Part 1

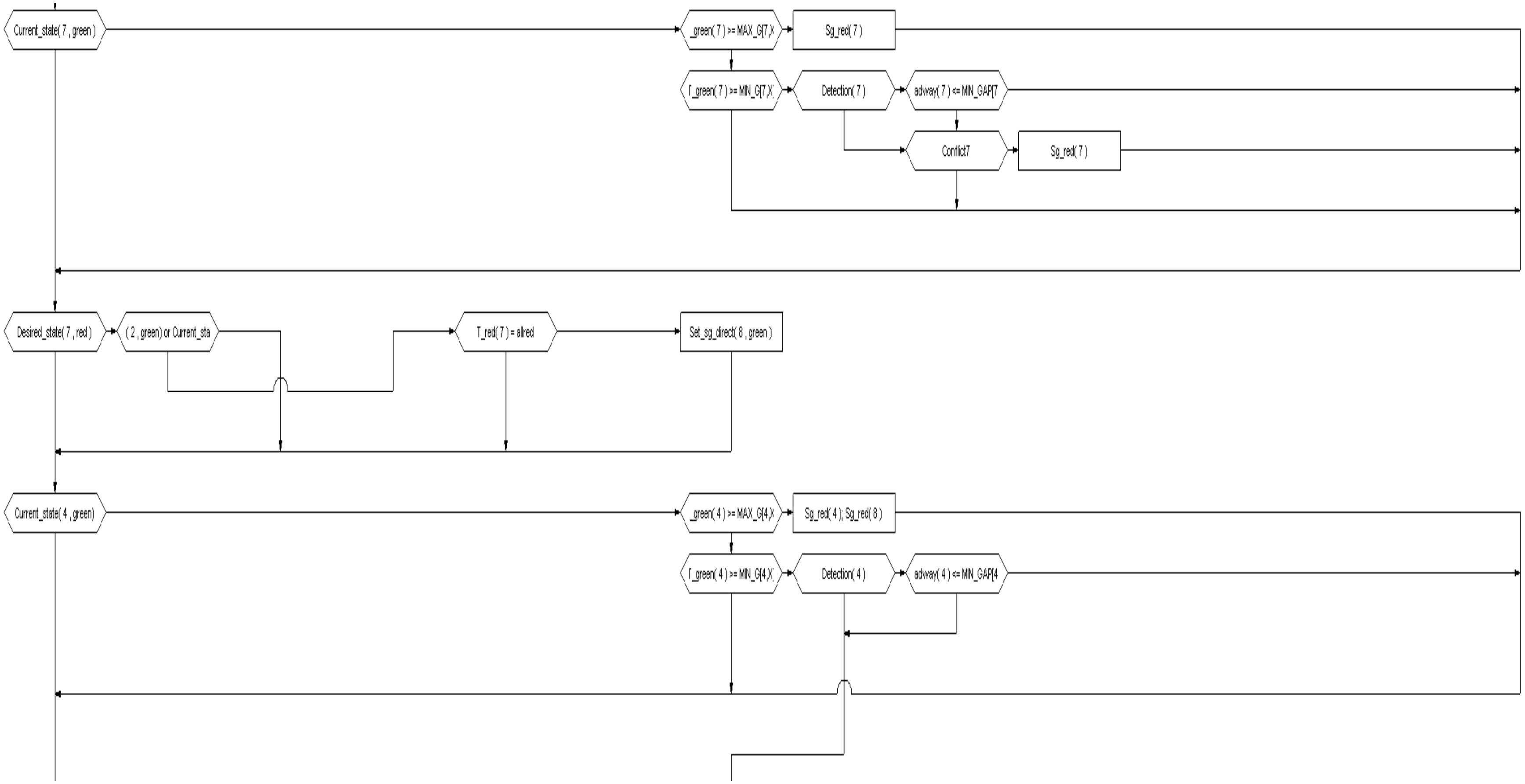


Figure A.40 SWITCH_ADD_C Subroutine Part 2

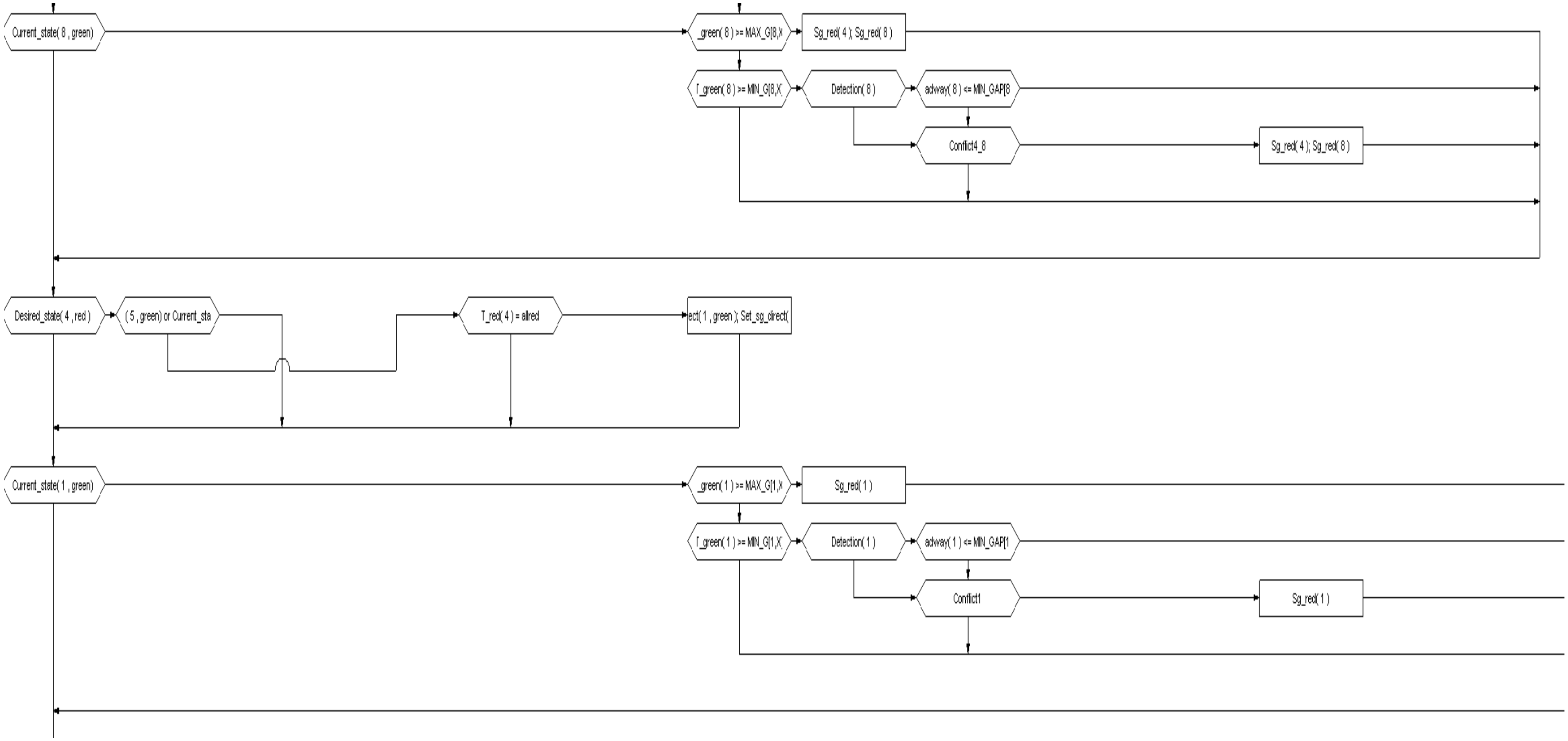


Figure A.41 SWITCH_ADD_C Subroutine Part 3

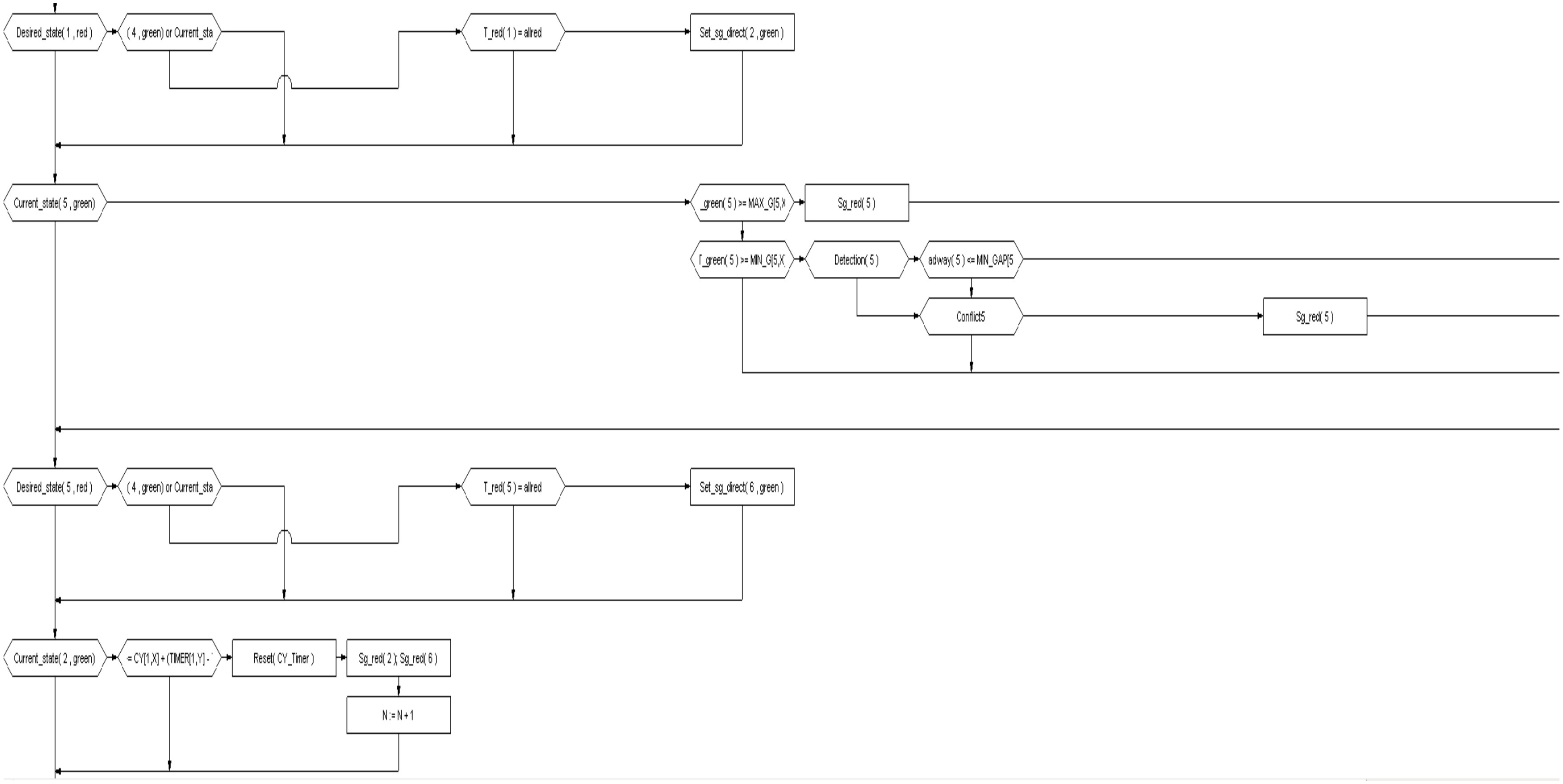


Figure A.42 SWITCH_ADD_C Subroutine Part 4

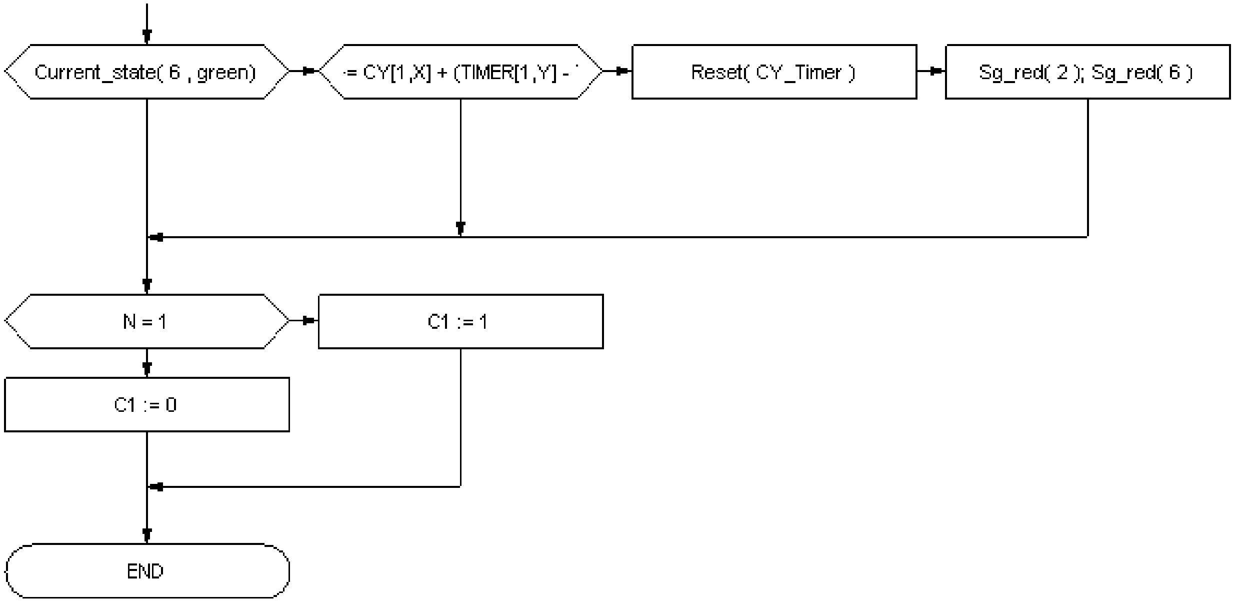


Figure A.43 SWITCH_ADD_C Subroutine Part 5

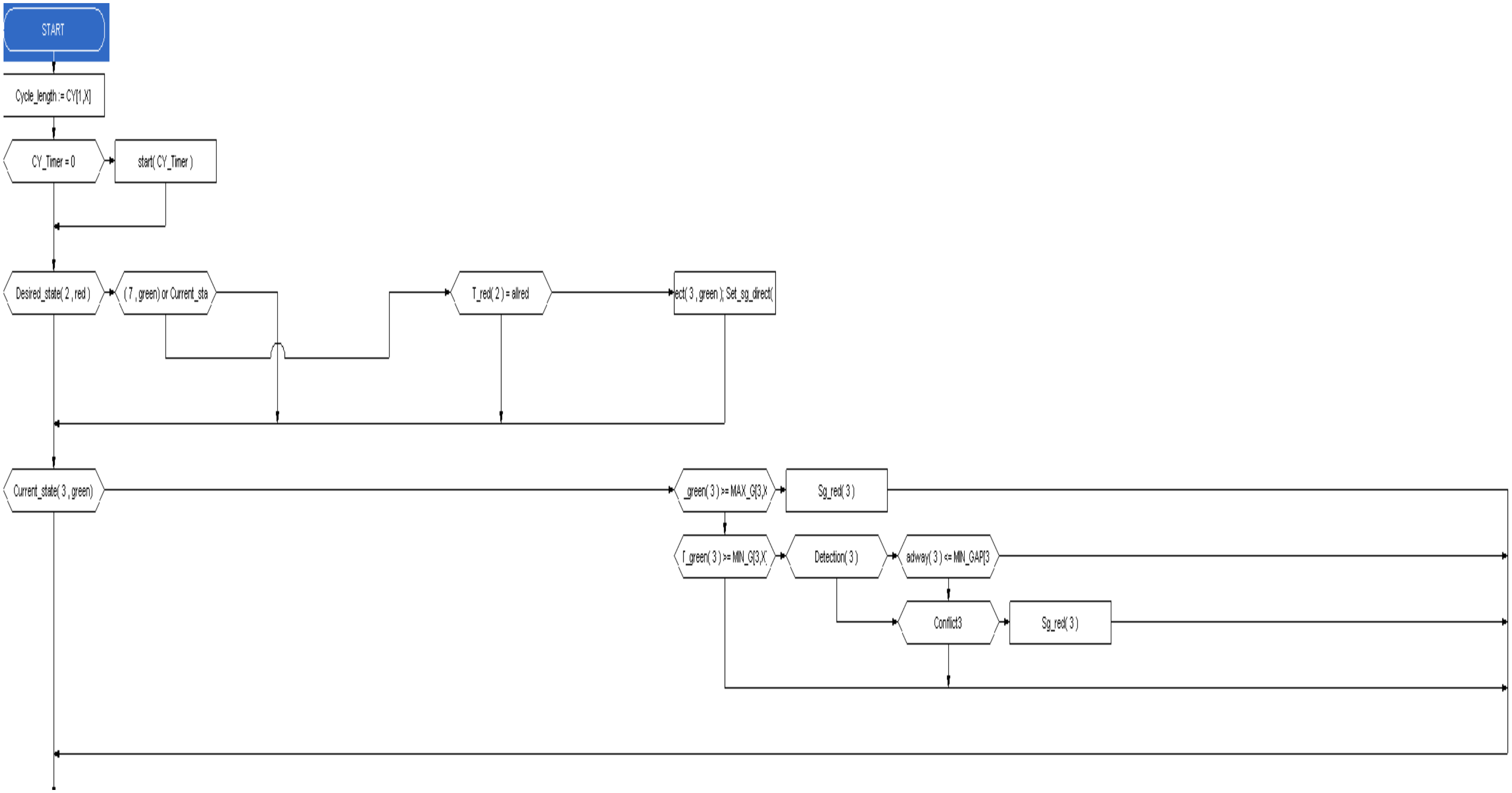


Figure A.44 Plan_D Subroutine Part 1

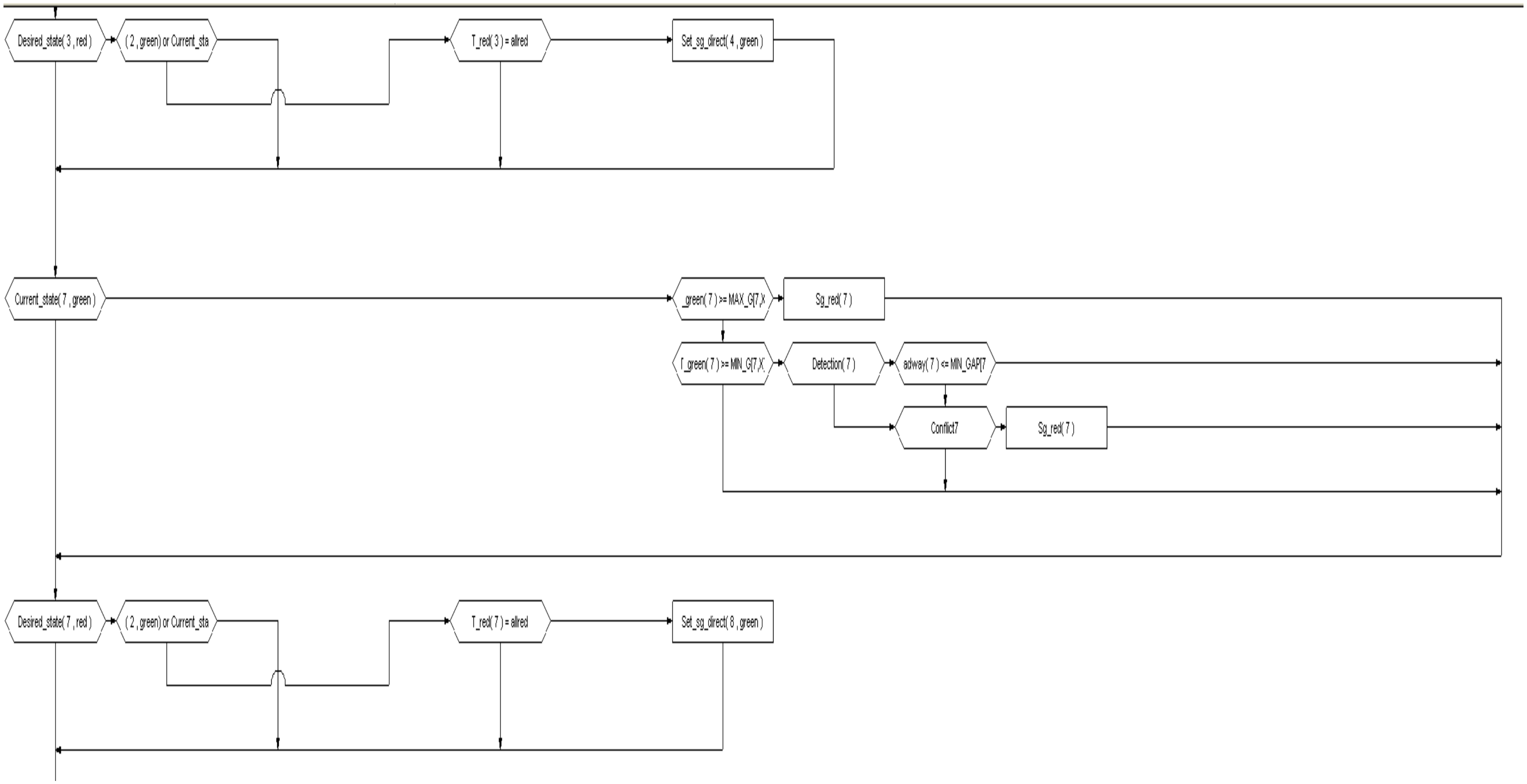


Figure A.45 Plan_D Subroutine Part 2

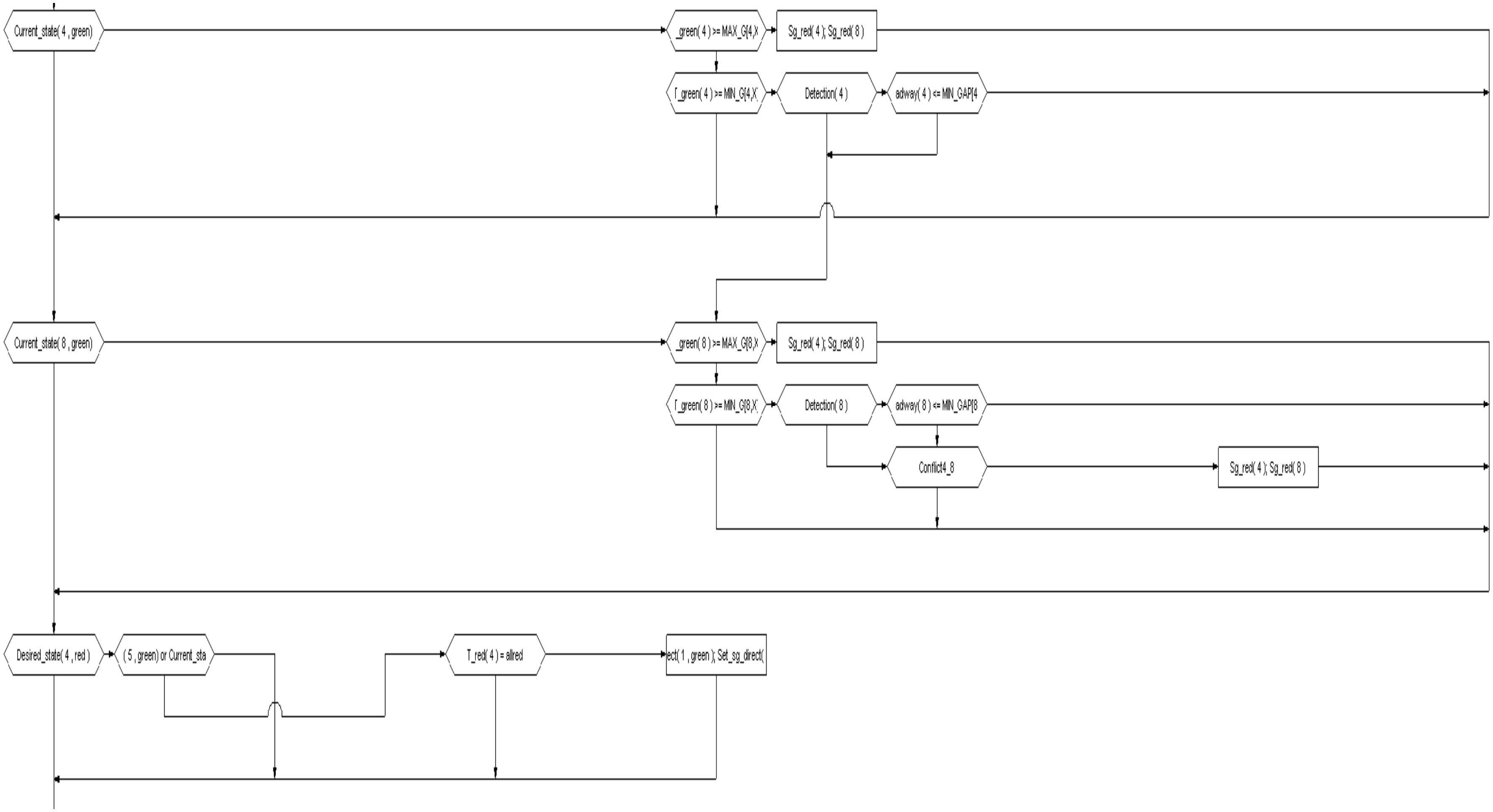


Figure A.46 Plan_D Subroutine Part 3

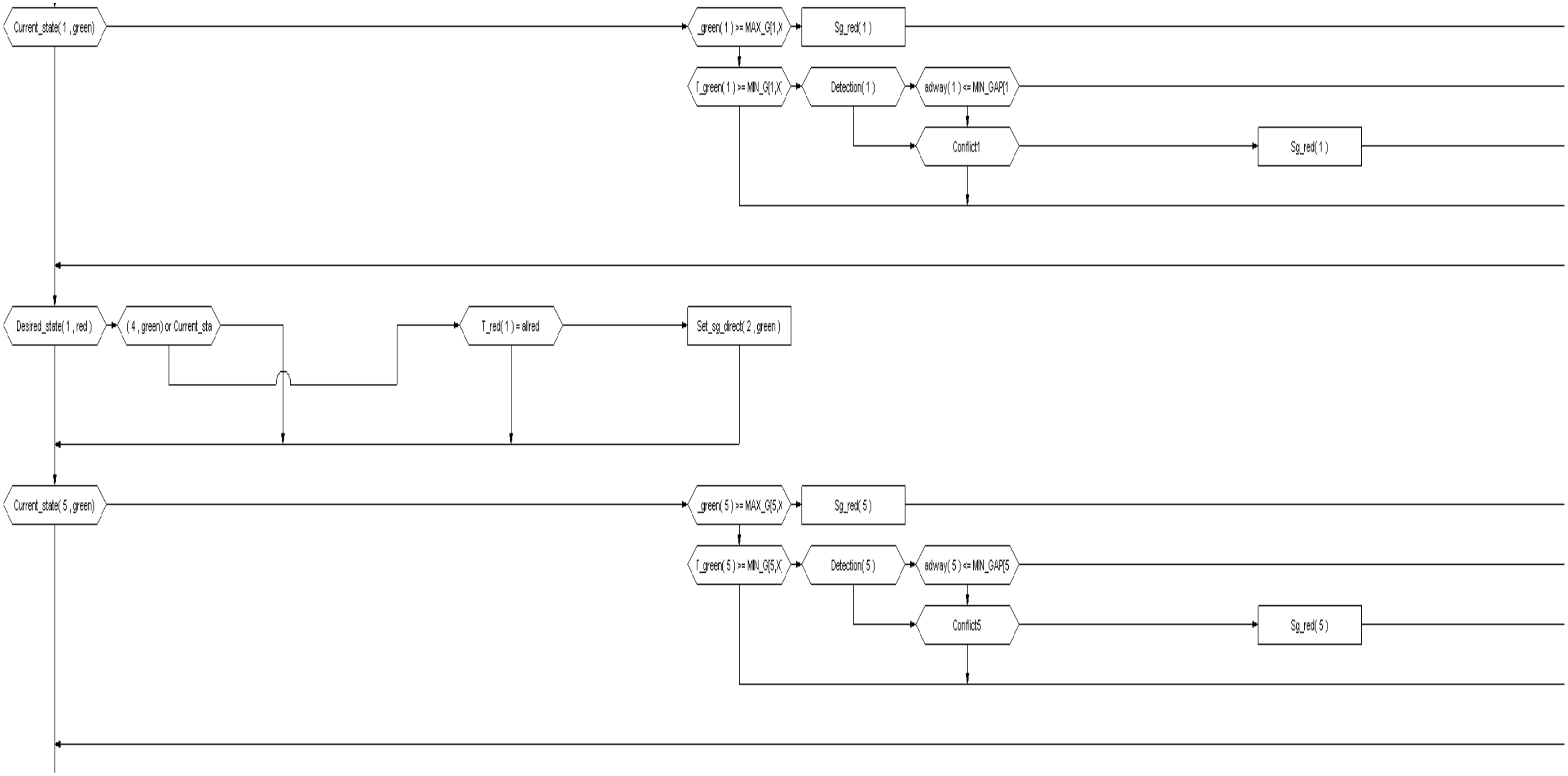


Figure A.47 Plan_D Subroutine Part 4

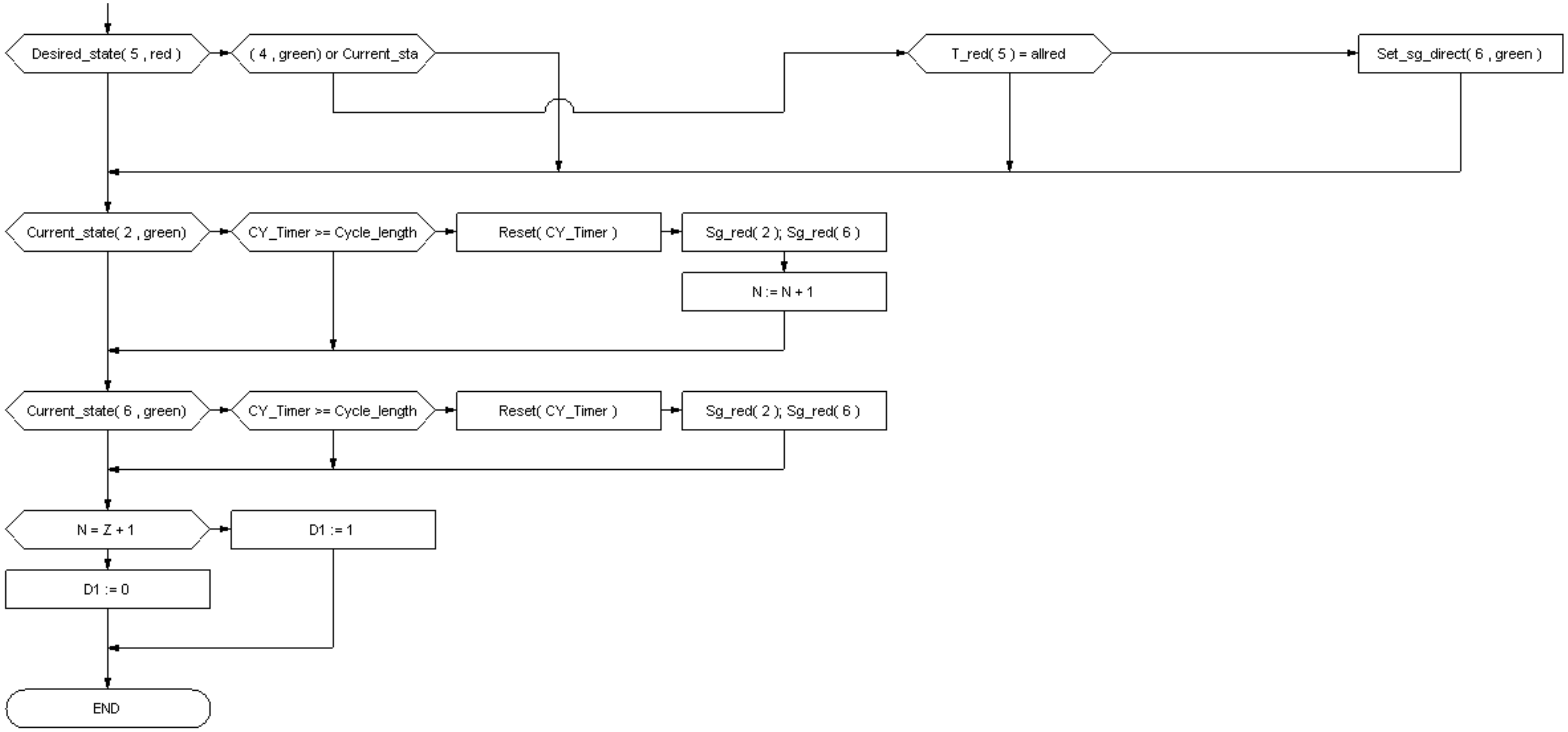


Figure A.48 Plan_D Subroutine Part 5

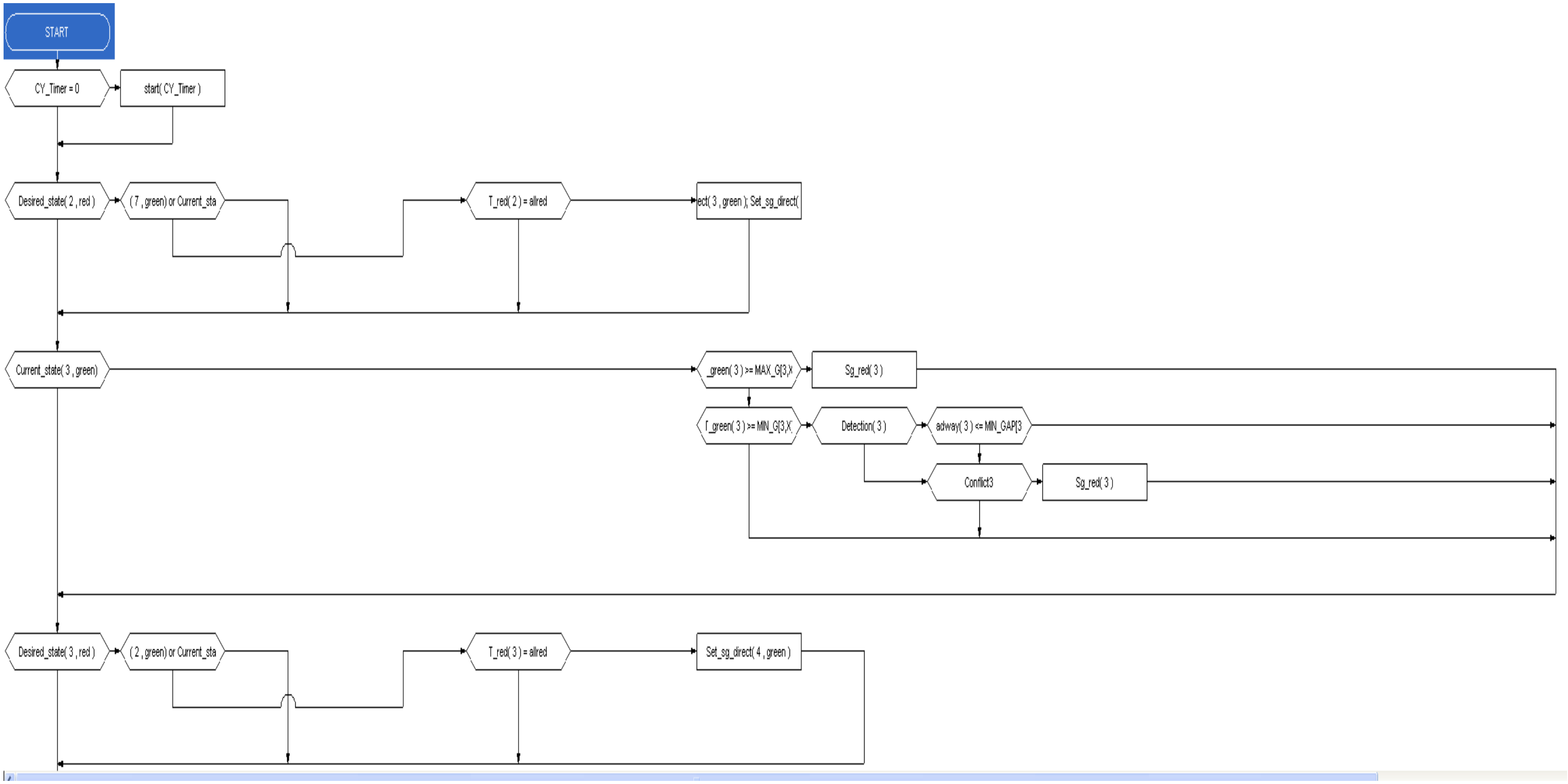


Figure A.49 SWITCH_ADD1_F Subroutine Part 1

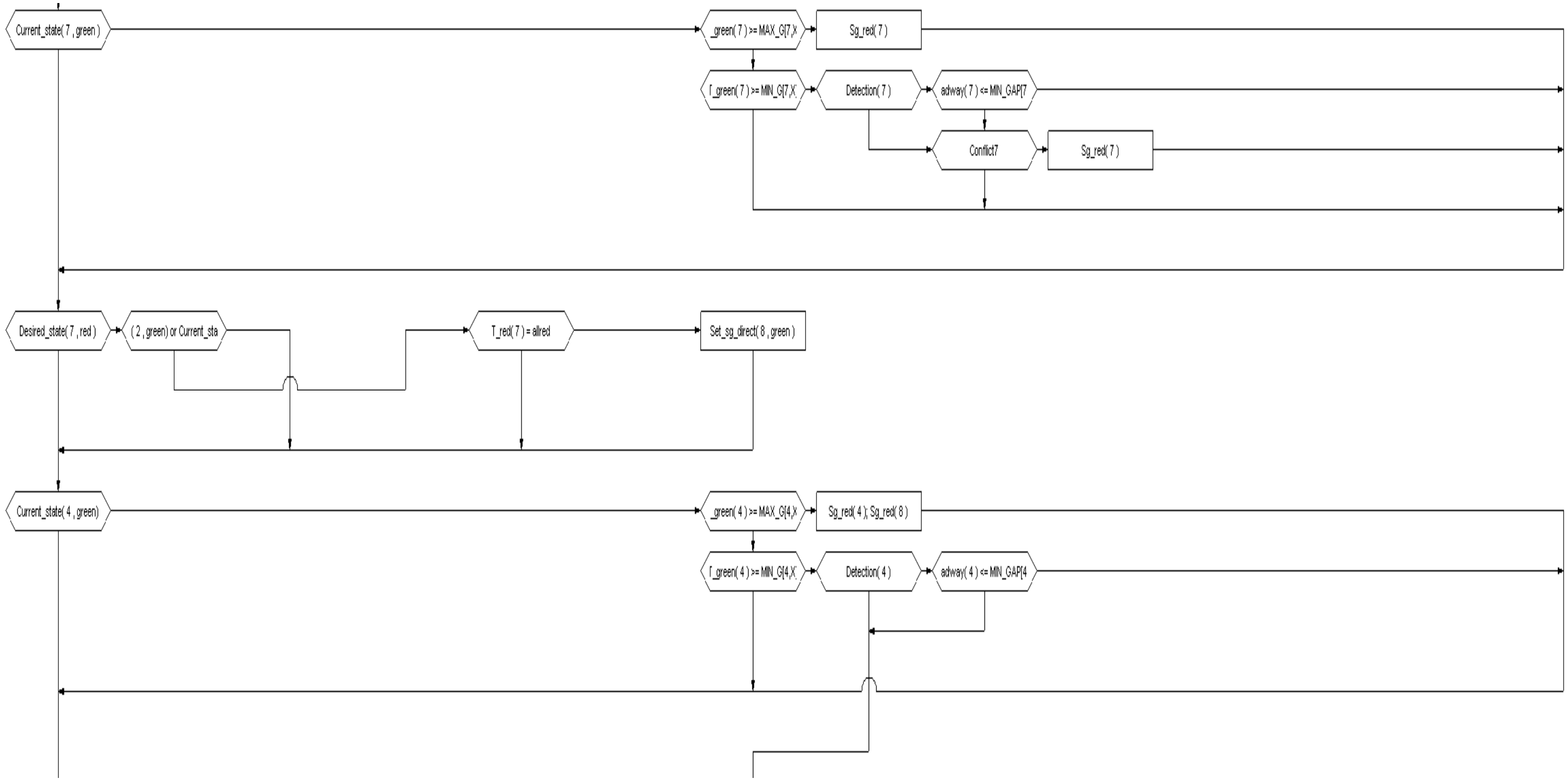


Figure A.50 SWITCH_ADD1_F Subroutine Part 2

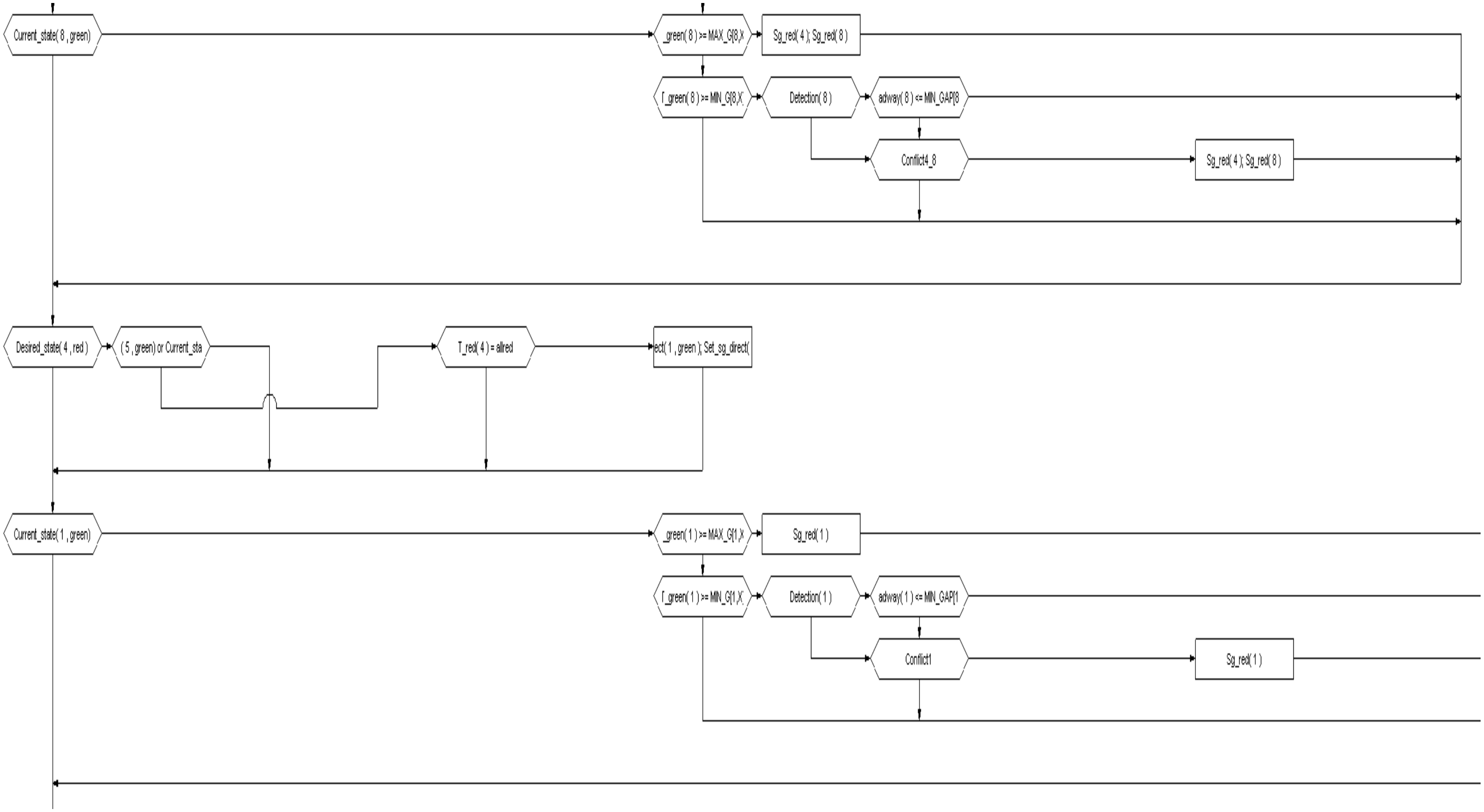


Figure A.51 SWITCH_ADD1_F Subroutine Part 3

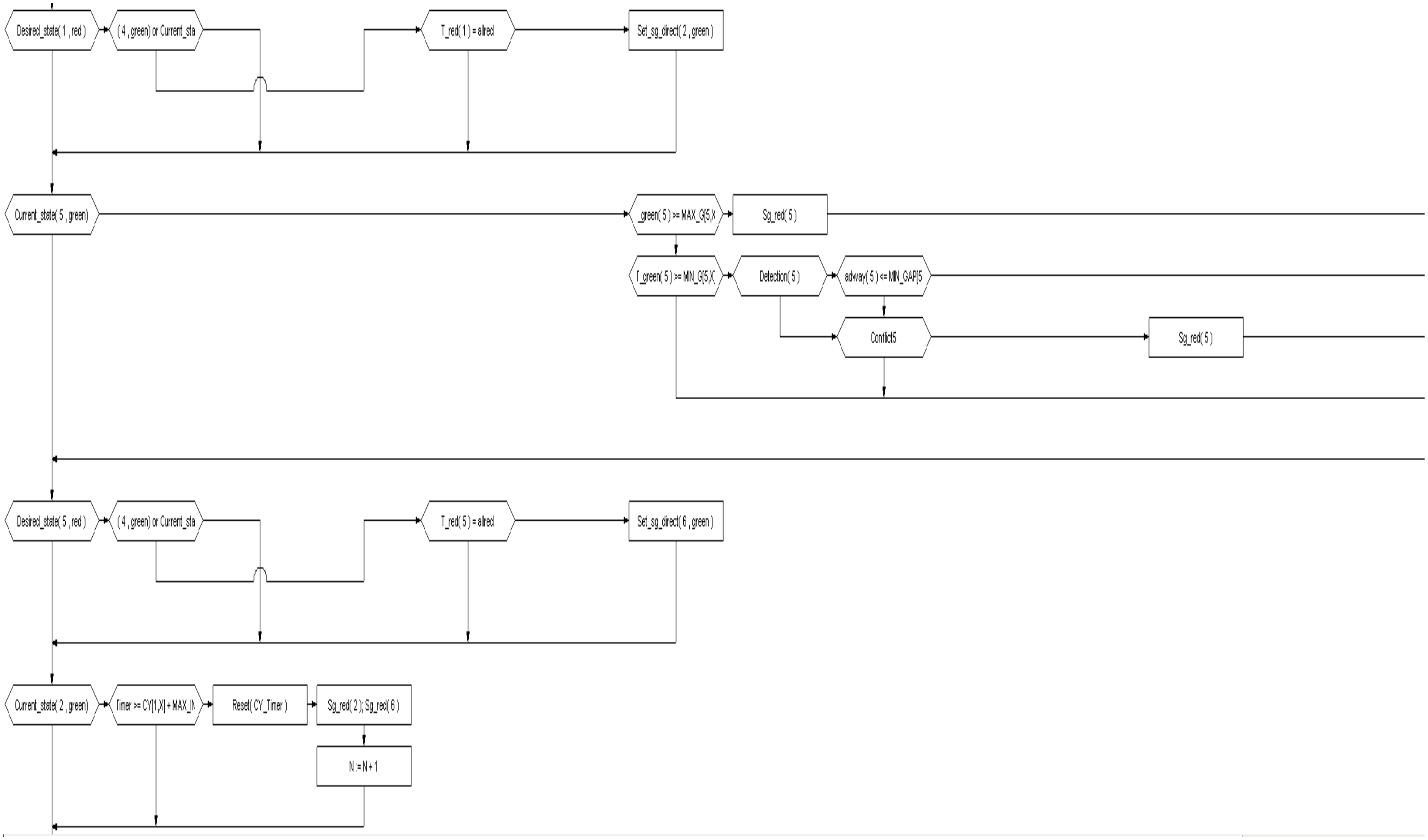


Figure A.52 SWITCH_ADD1_F Subroutine Part 4

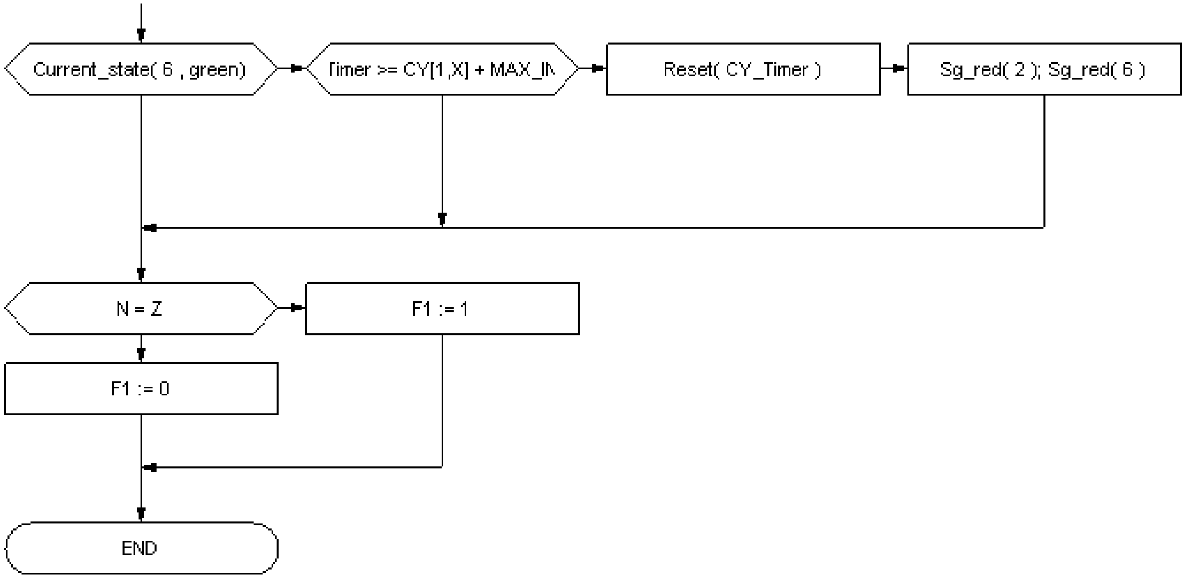


Figure A.53 SWITCH_ADD1_F Subroutine Part 5

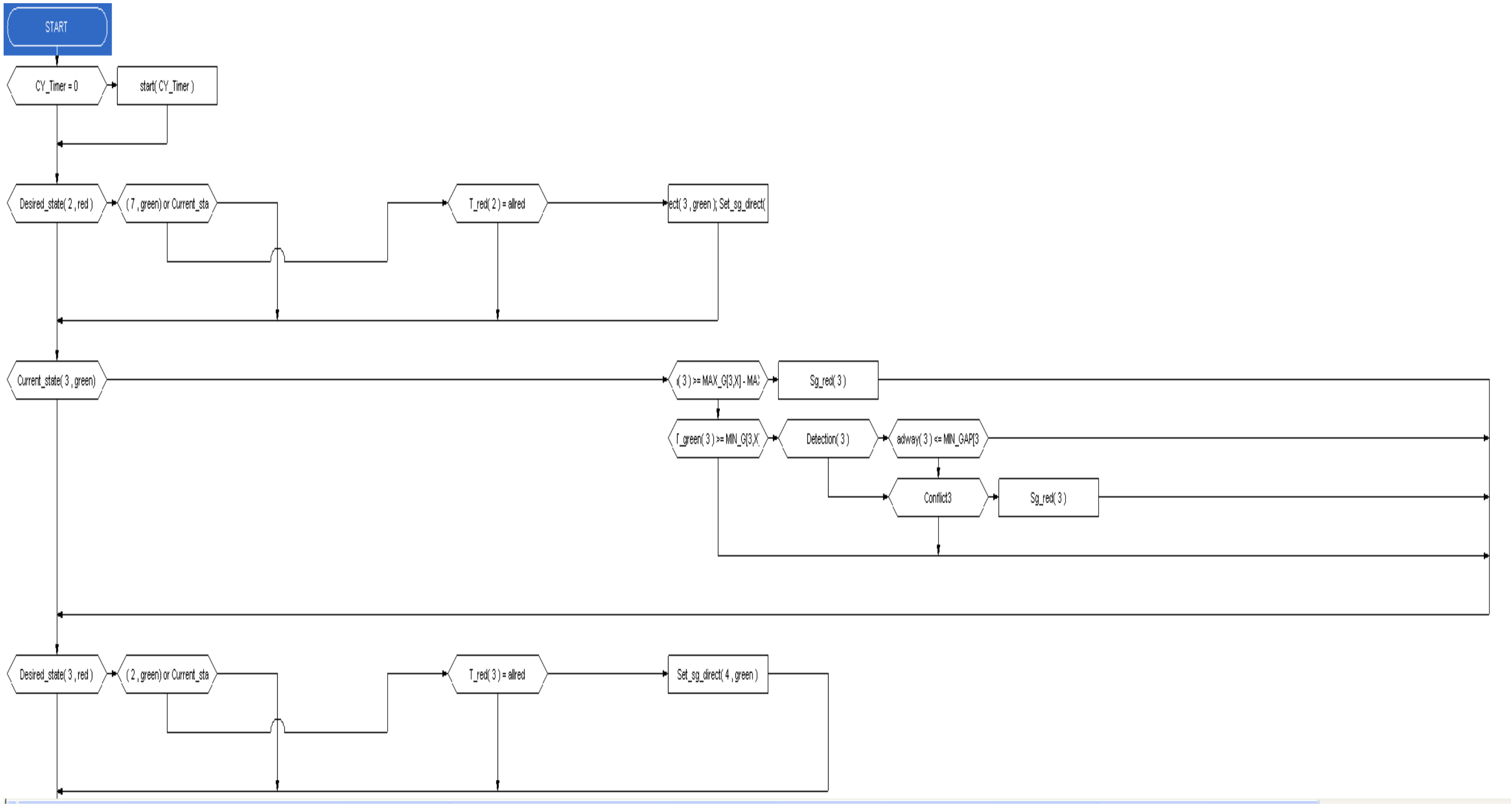


Figure A.54 SWITCH1_E Subroutine Part 1

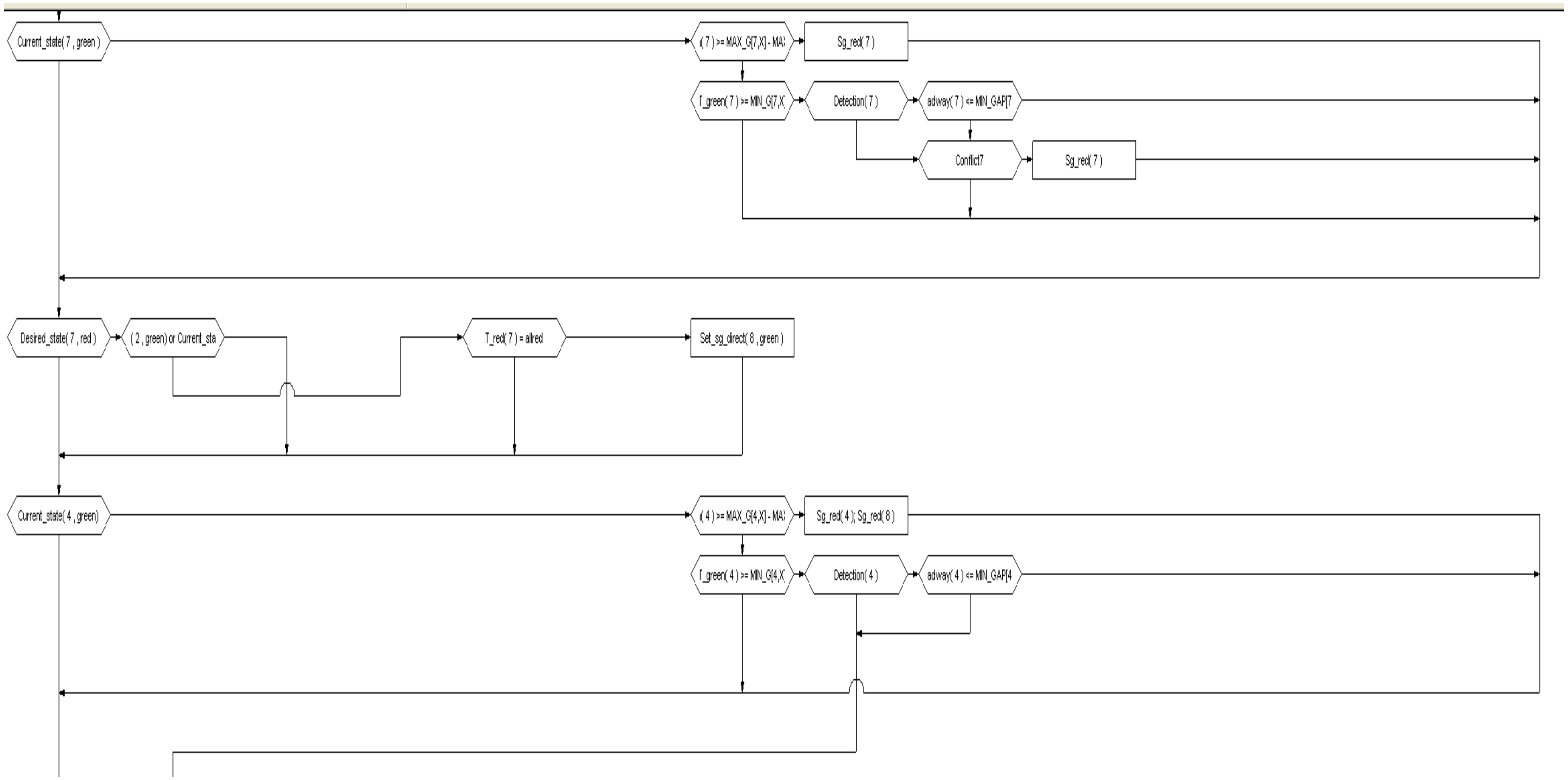


Figure A.55 SWITCH1_E Subroutine Part 2

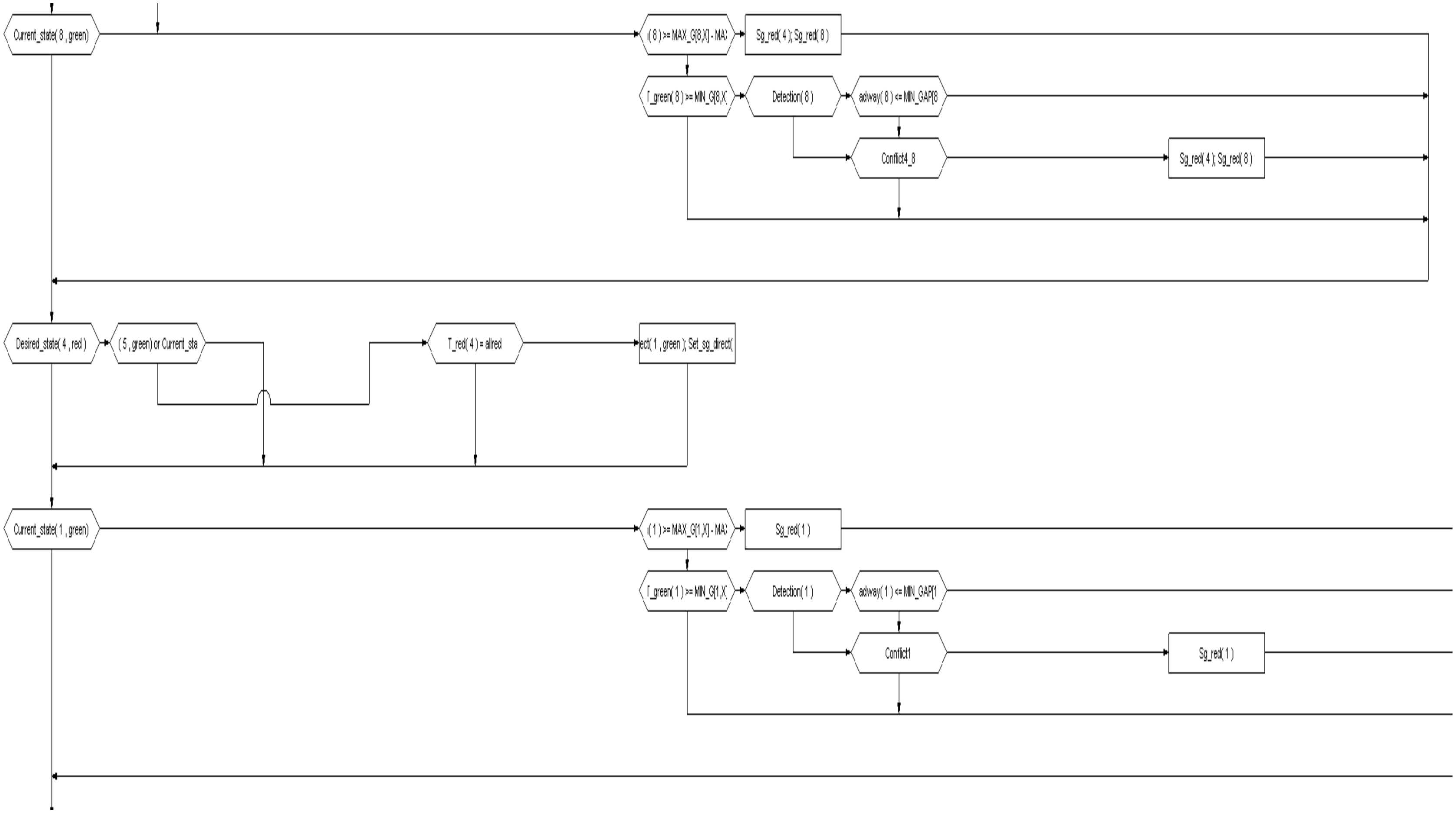


Figure A.56 SWITCH1_E Subroutine Part 3

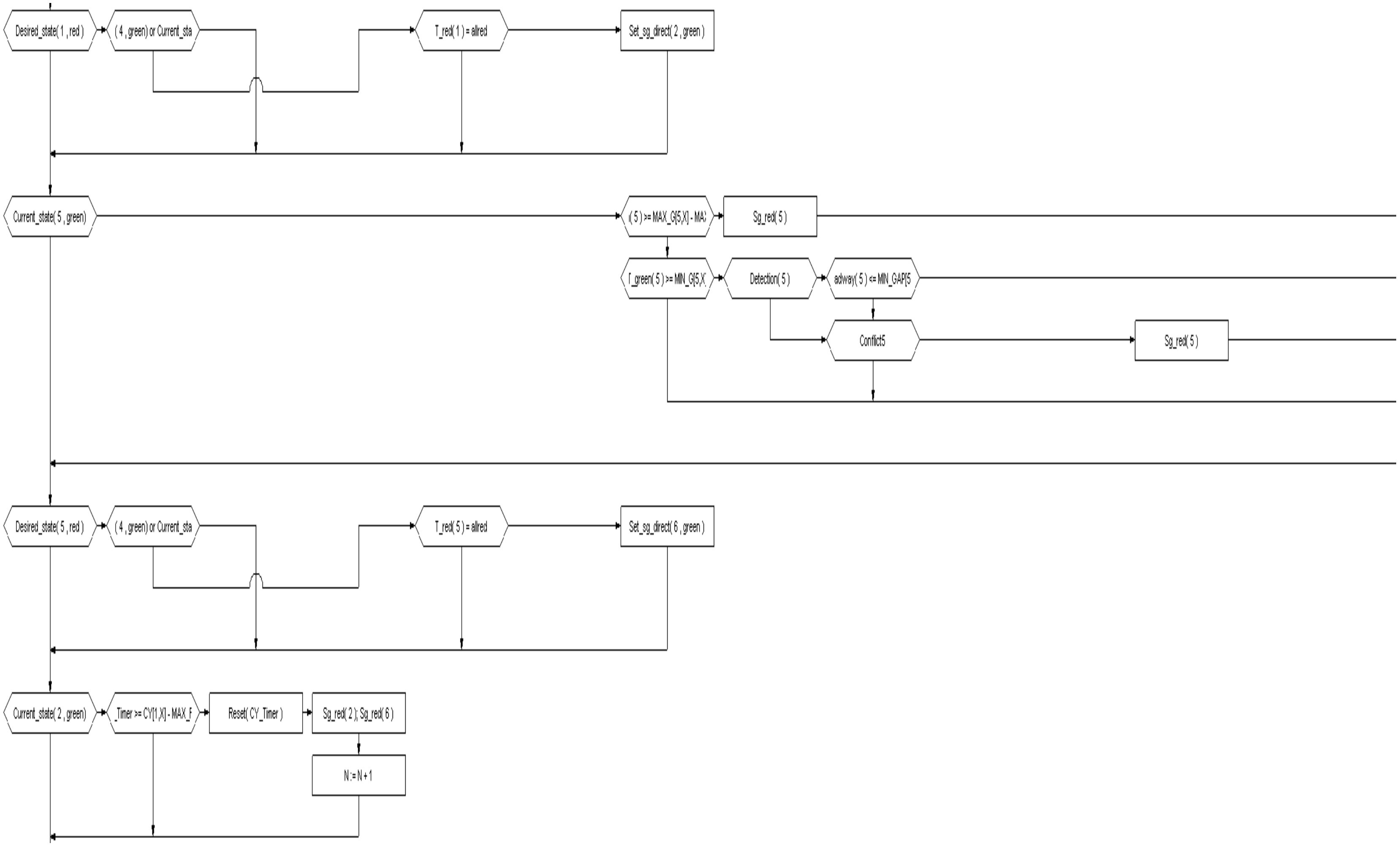


Figure A.57 SWITCH1_E Subroutine Part 4

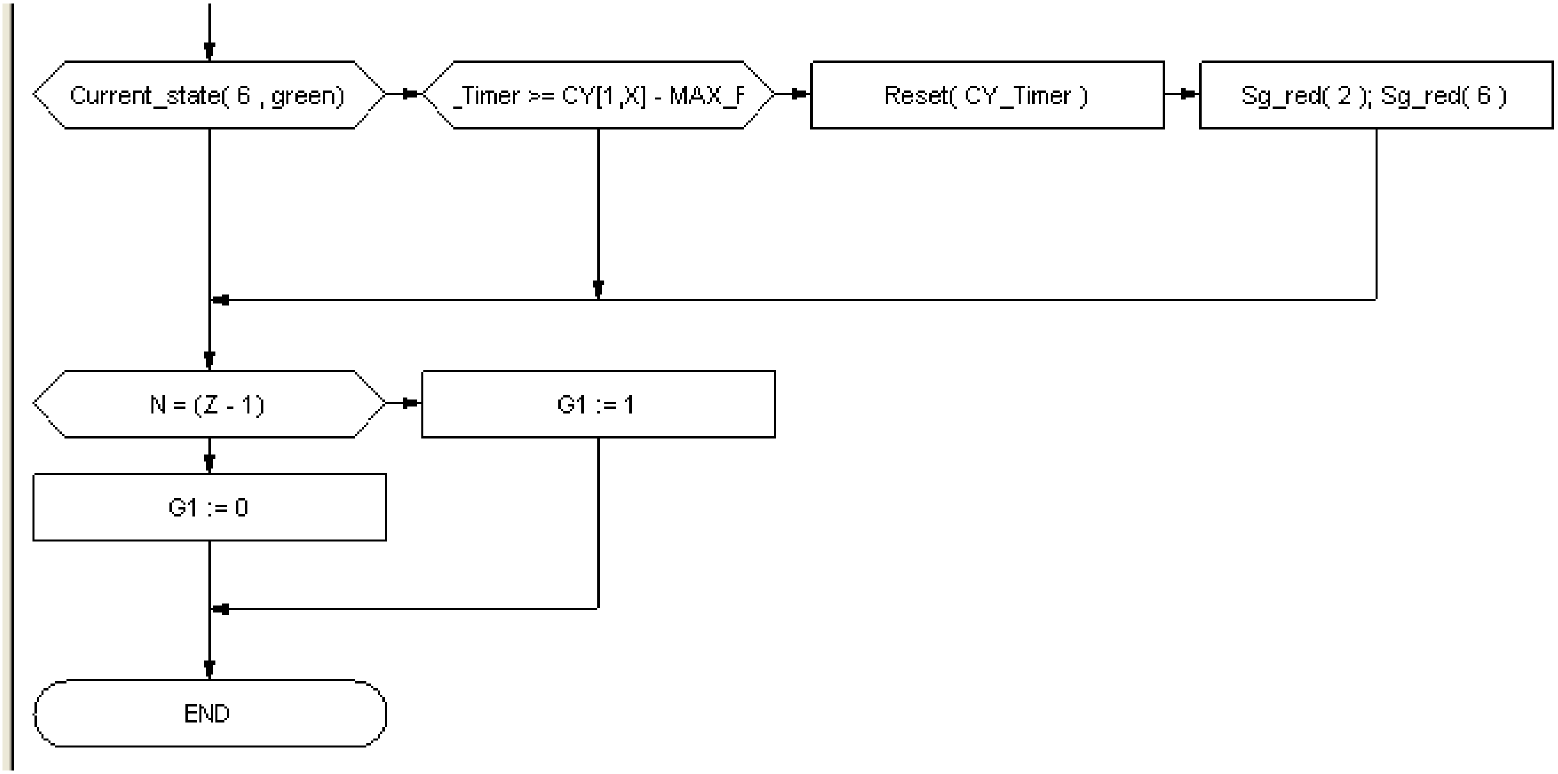


Figure A.58 SWITCH1_E Subroutine Part 5

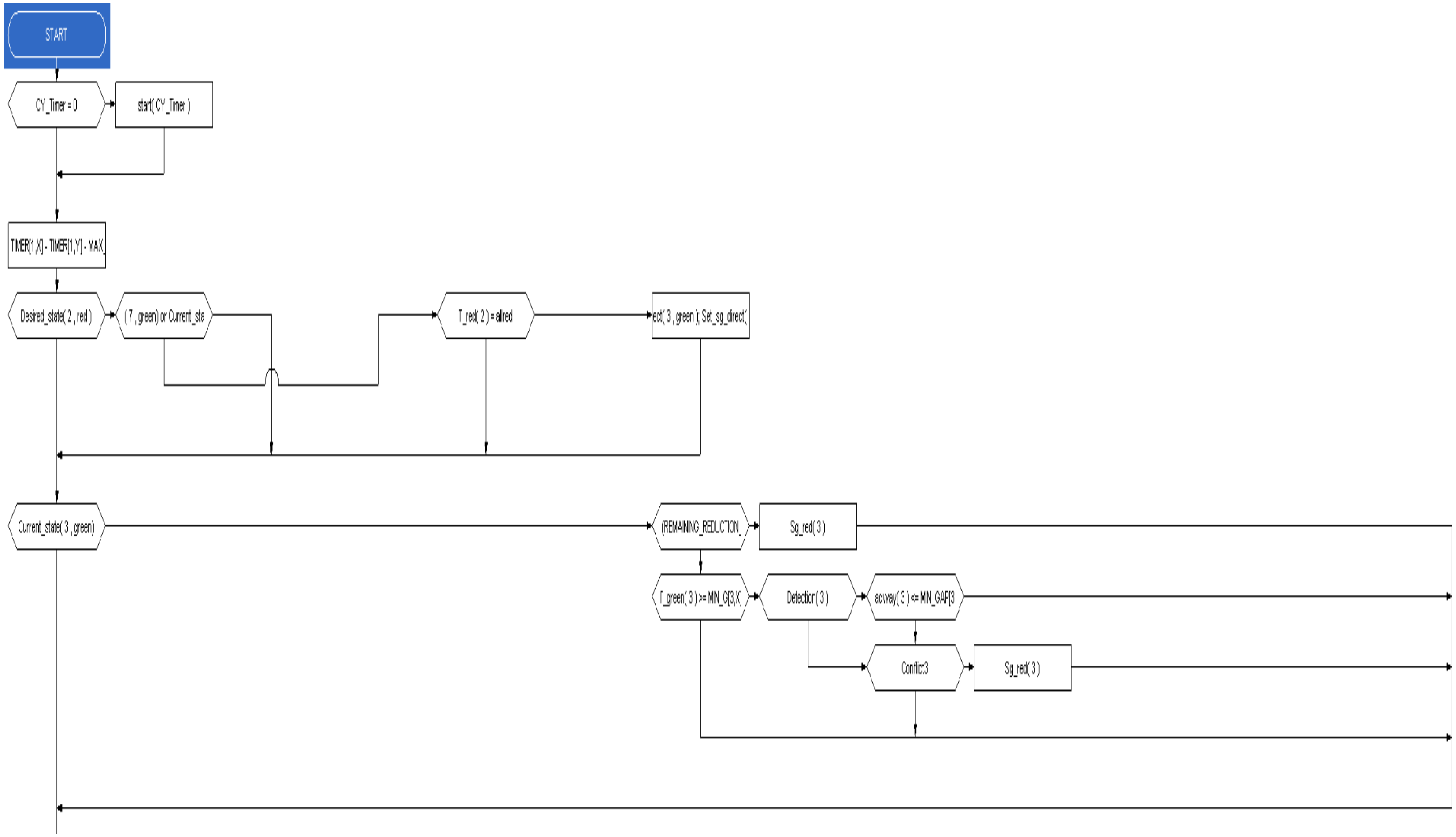


Figure A.59 SWITCH2_E Subroutine Part 1

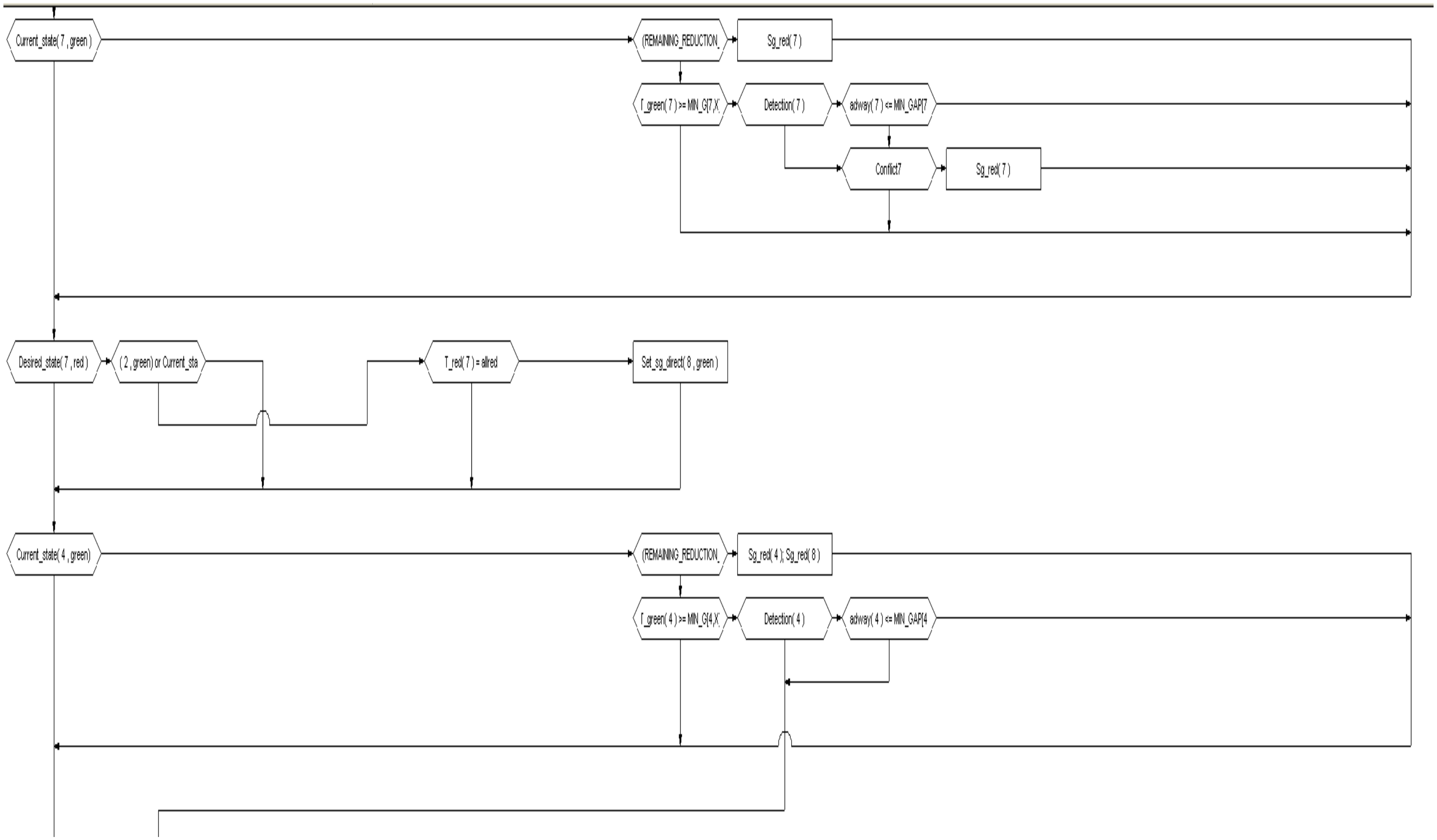


Figure A.60 SWITCH2_E Subroutine Part 2

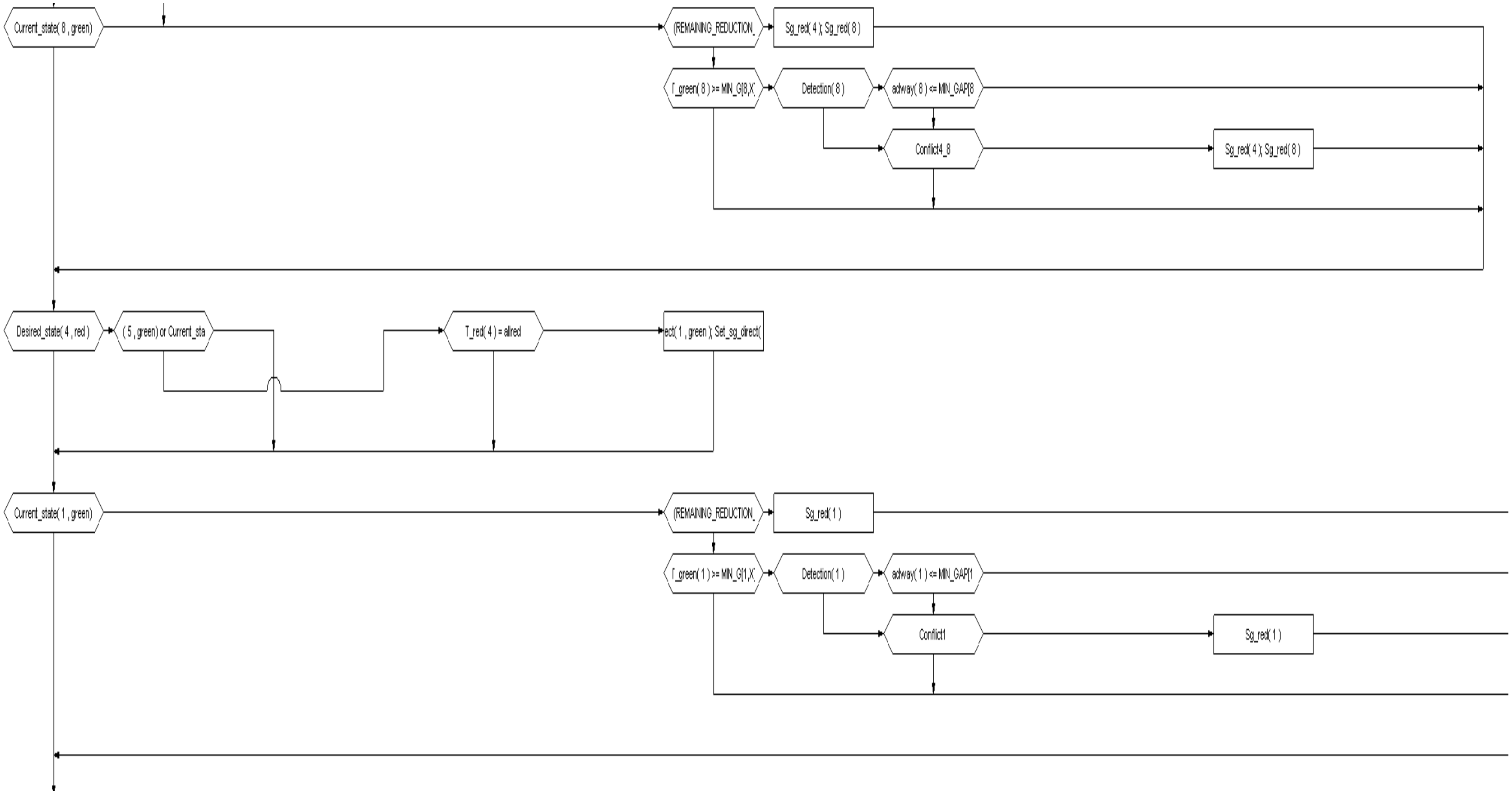


Figure A.61 SWITCH2_E Subroutine Part 3

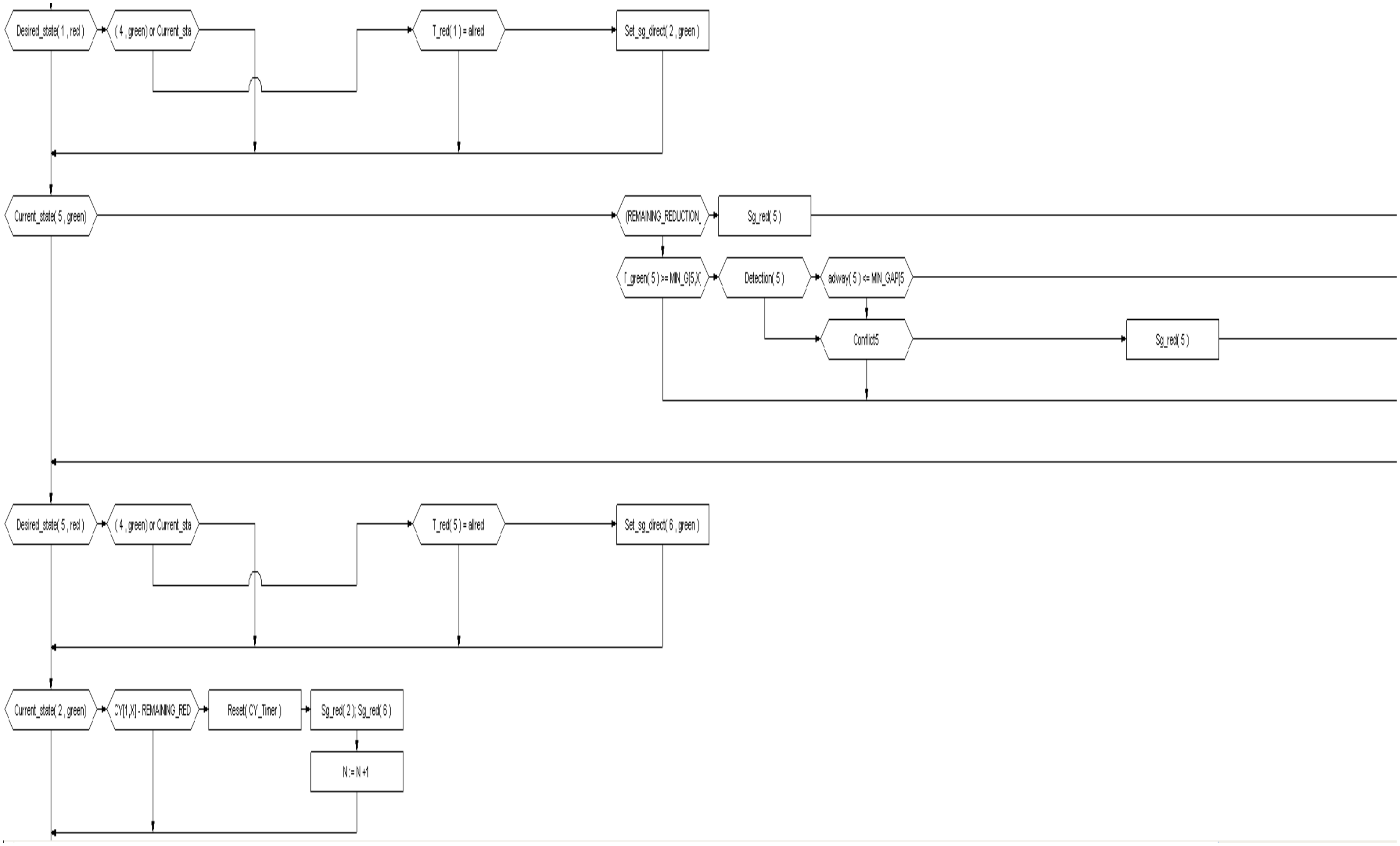


Figure A.62 SWITCH2_E Subroutine Part 4

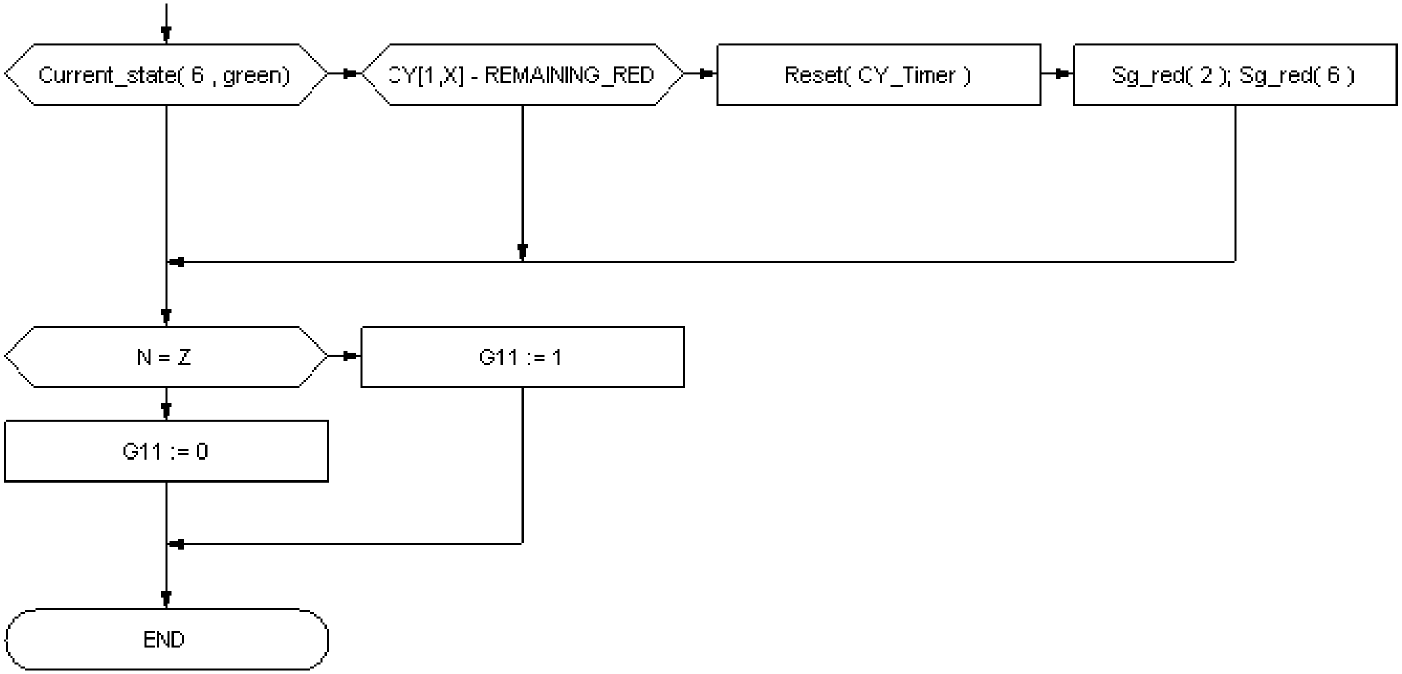


Figure A.63 SWITCH2_E Subroutine Part 5

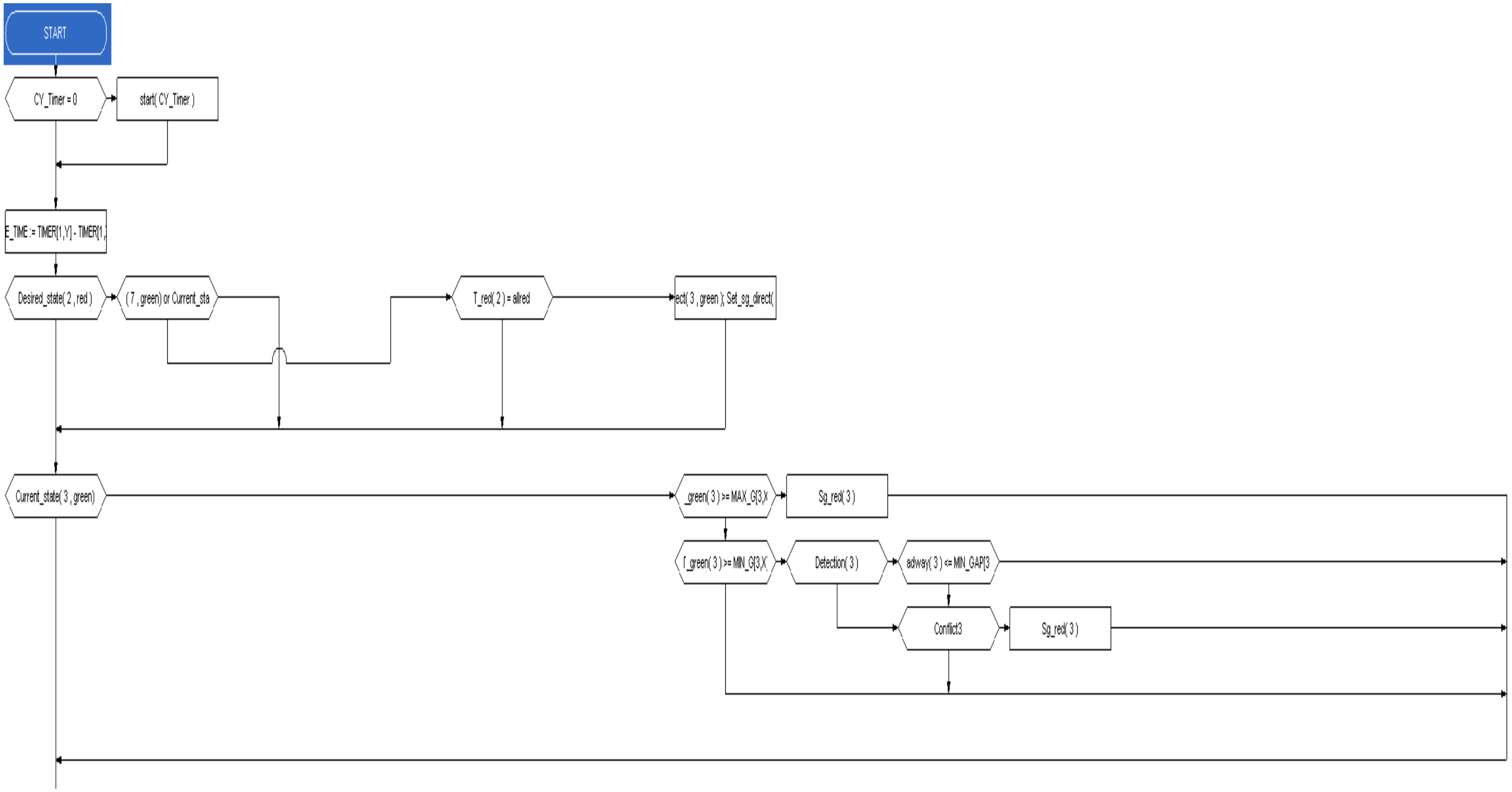


Figure A.64 SWITCH_ADD2_F Subroutine Part 1

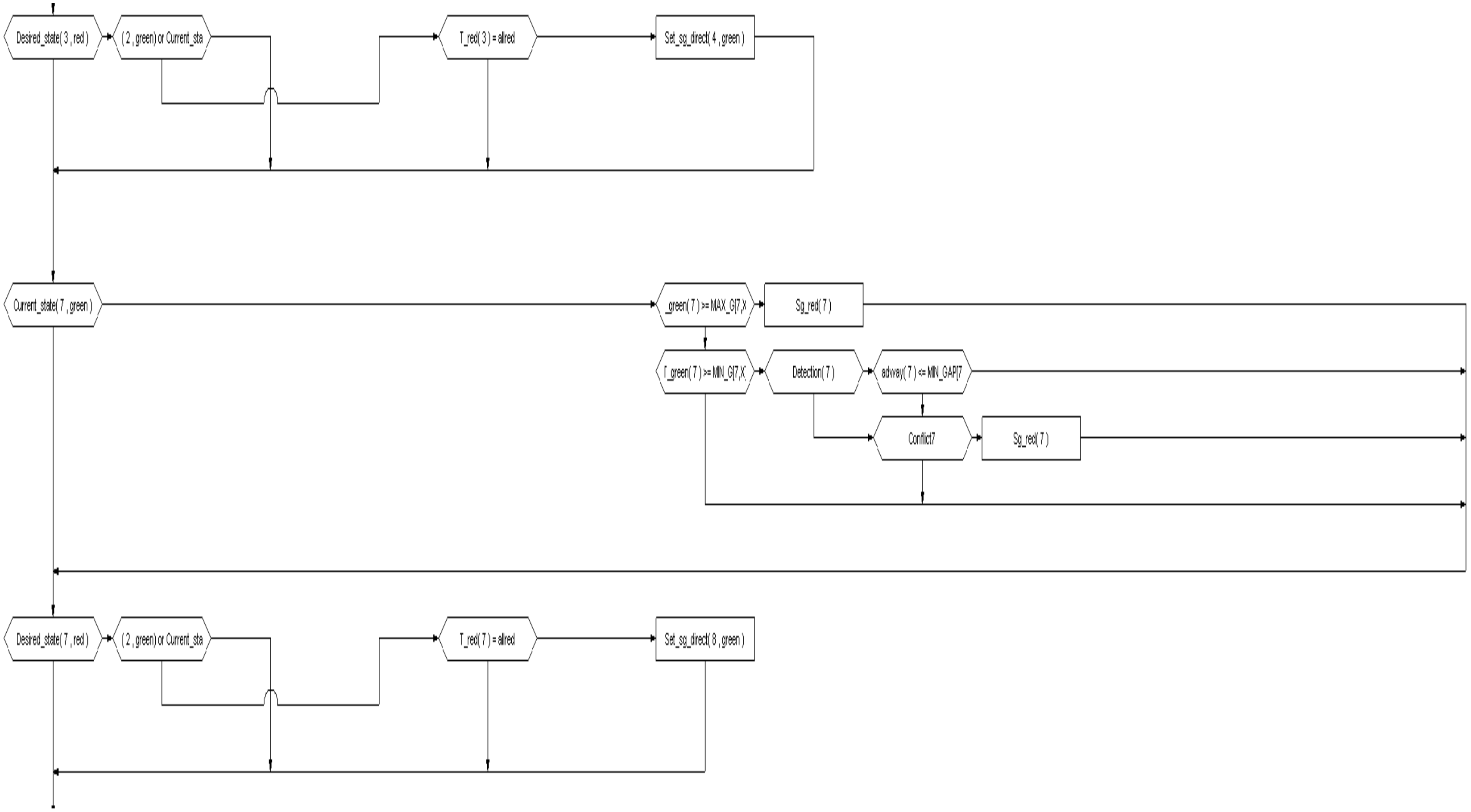


Figure A.65 SWITCH_ADD2_F Subroutine Part 2

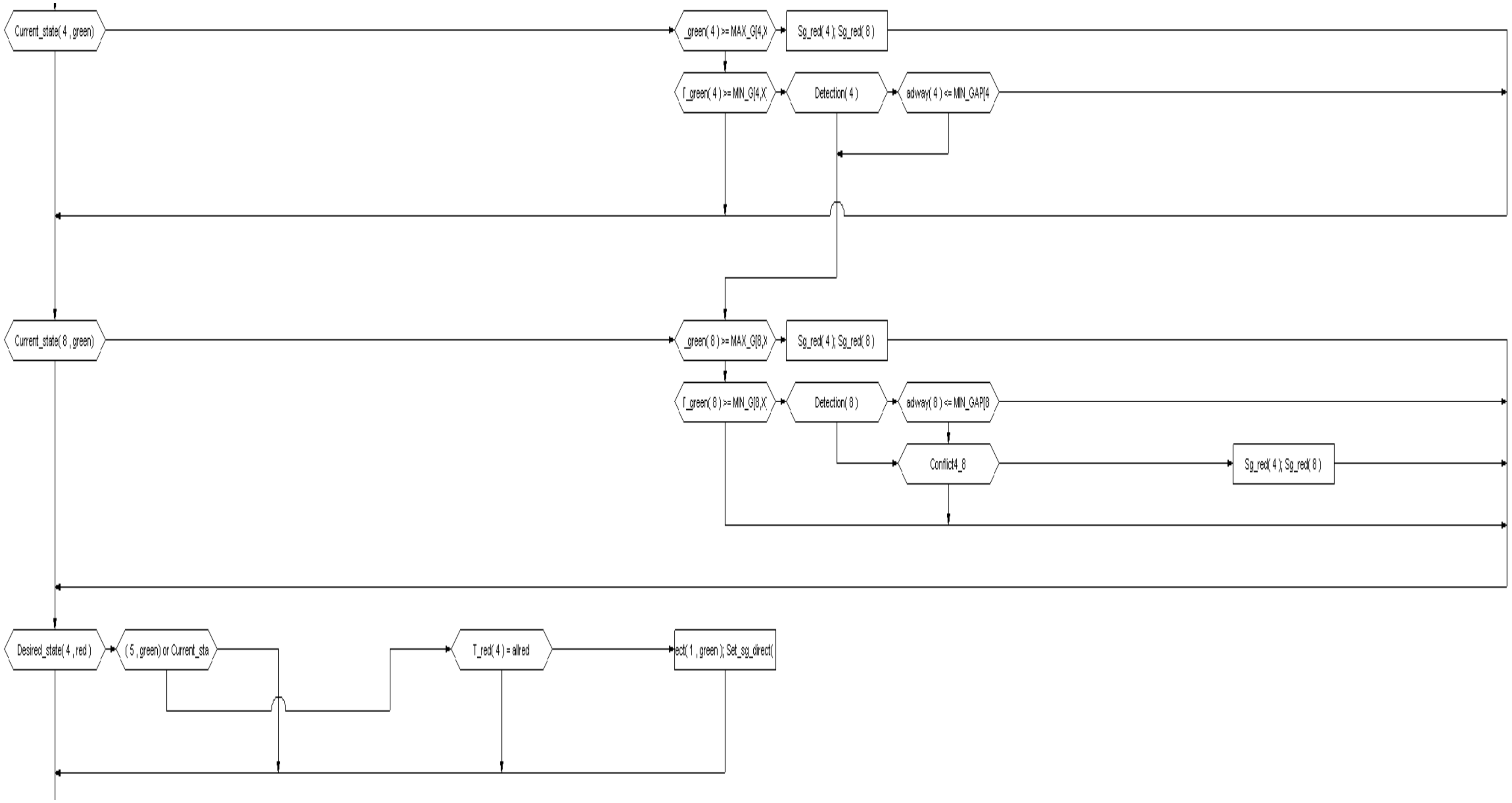


Figure A.66 SWITCH_ADD2_F Subroutine Part 3

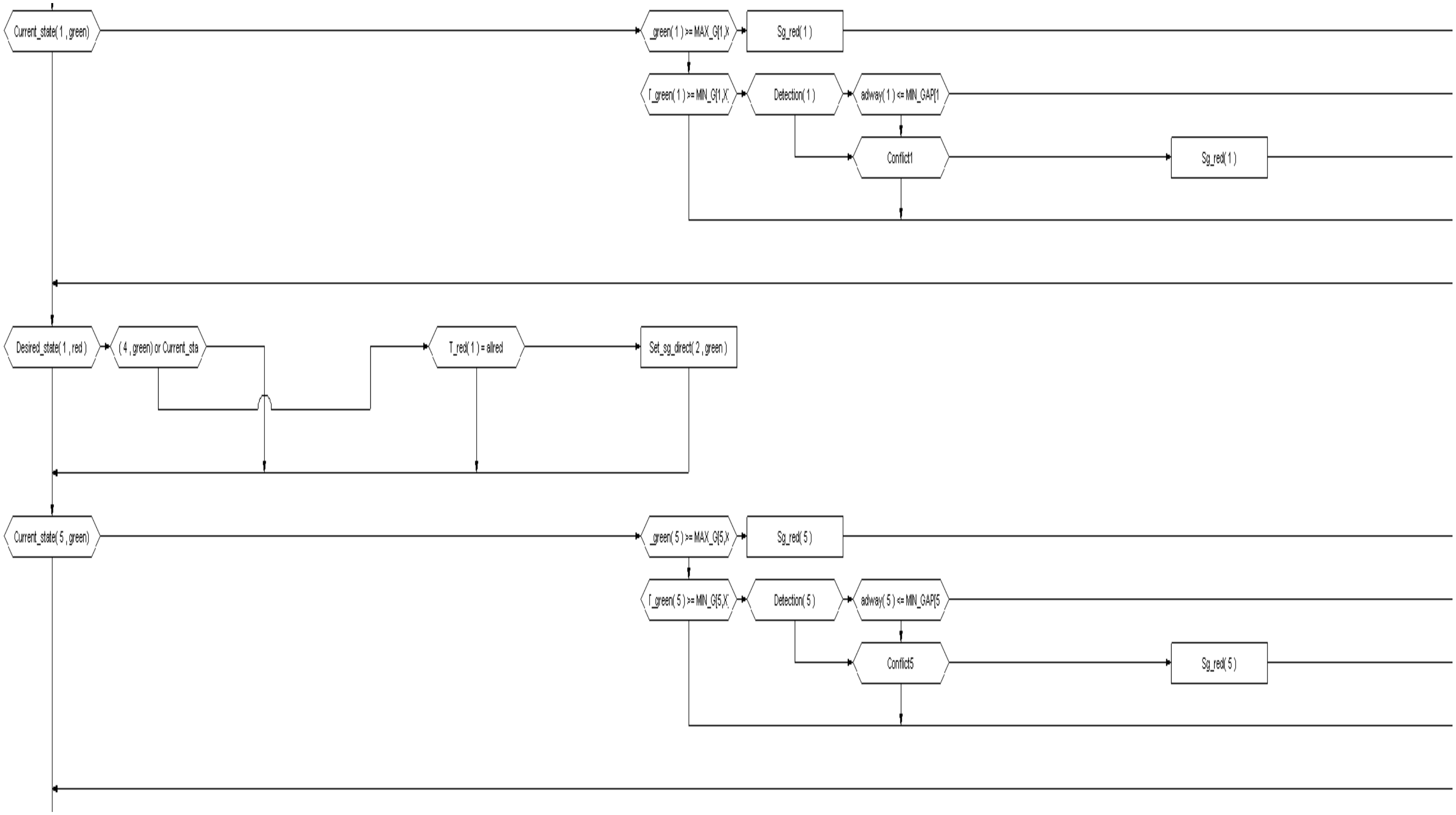


Figure A.67 SWITCH_ADD2_F Subroutine Part 4

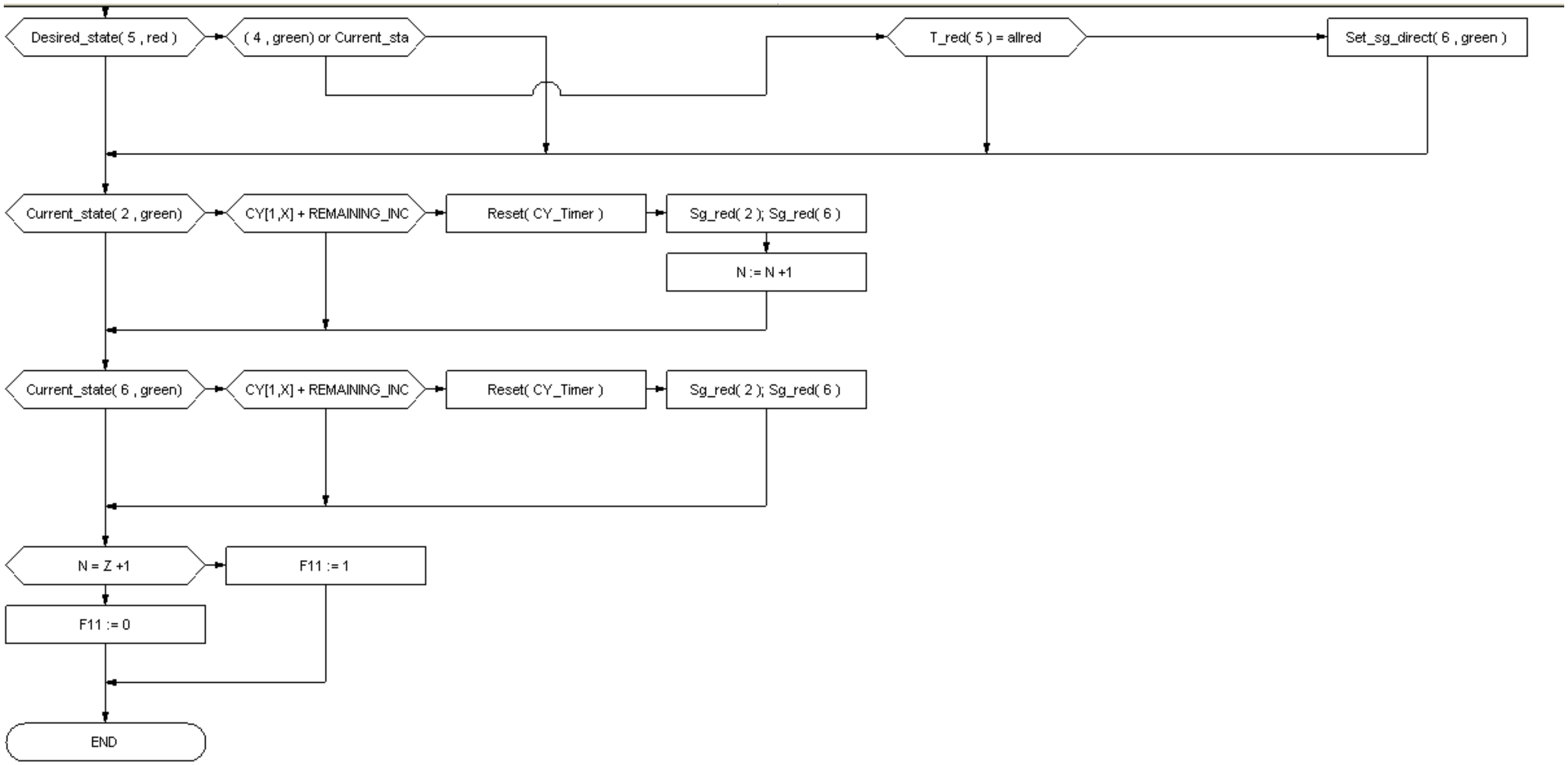


Figure A.68 SWITCH_ADD2_F Subroutine Part 5

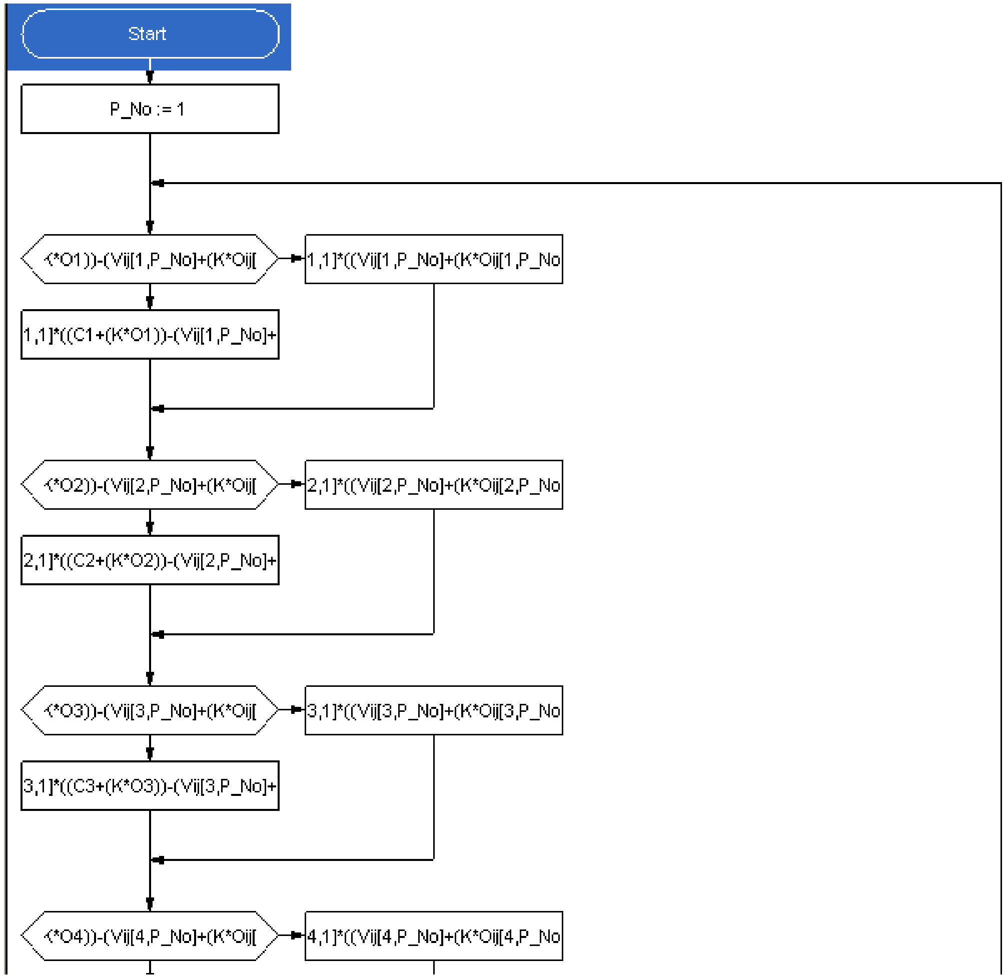


Figure A.69 Positive_Fj Subroutine Part 1

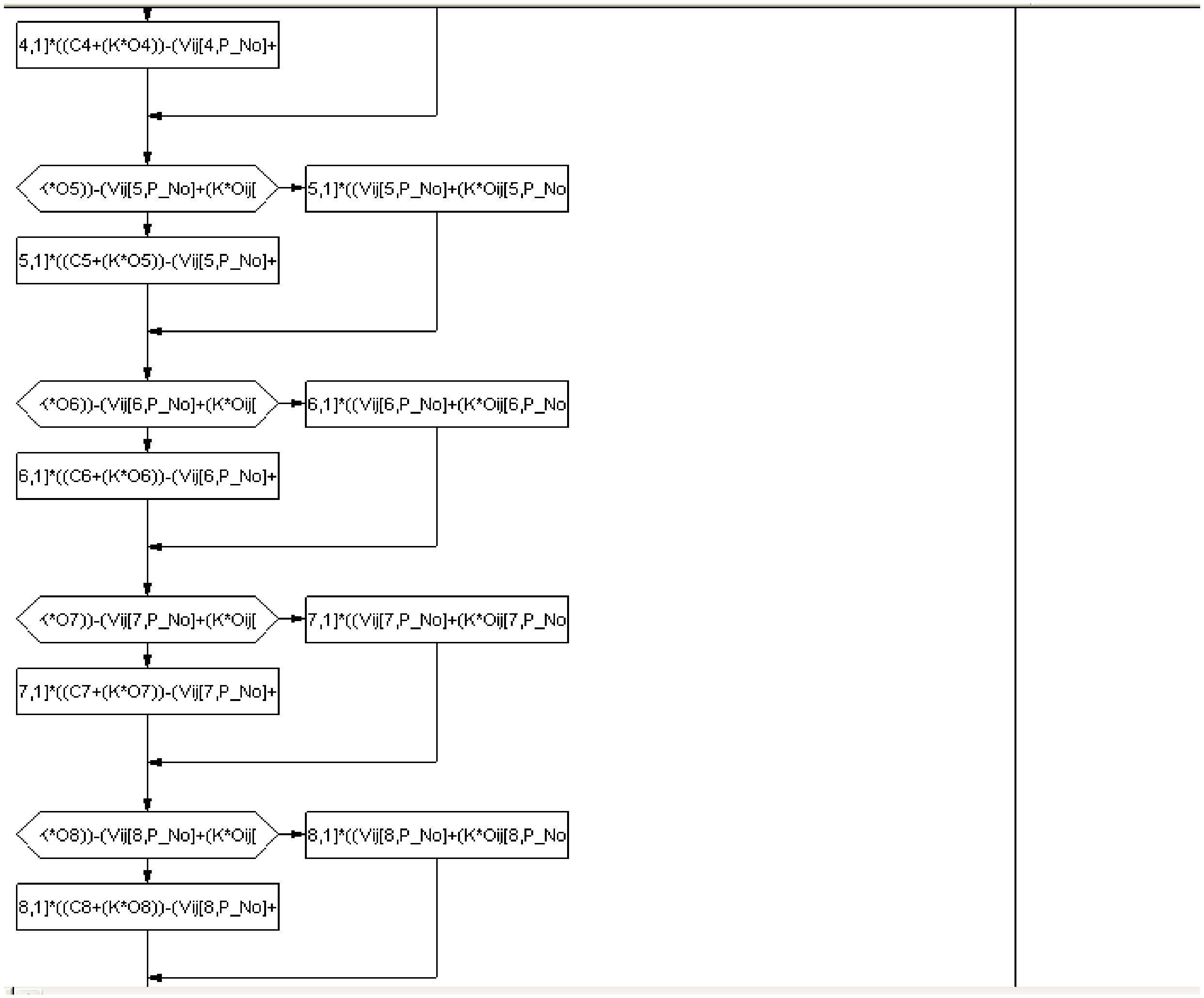


Figure A.70 Positive_Fj Subroutine Part 2

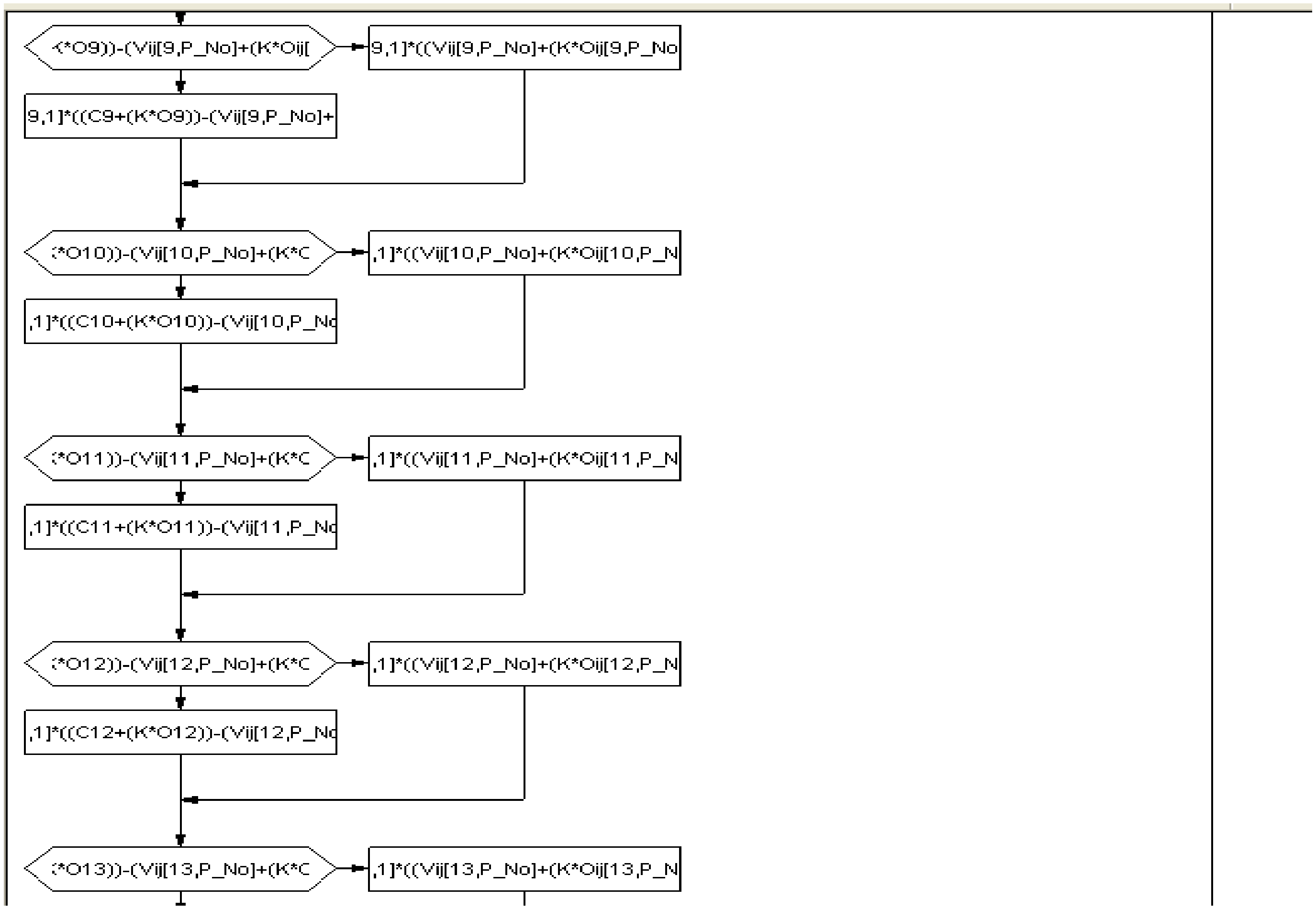


Figure A.71 Positive_Fj Subroutine Part 3

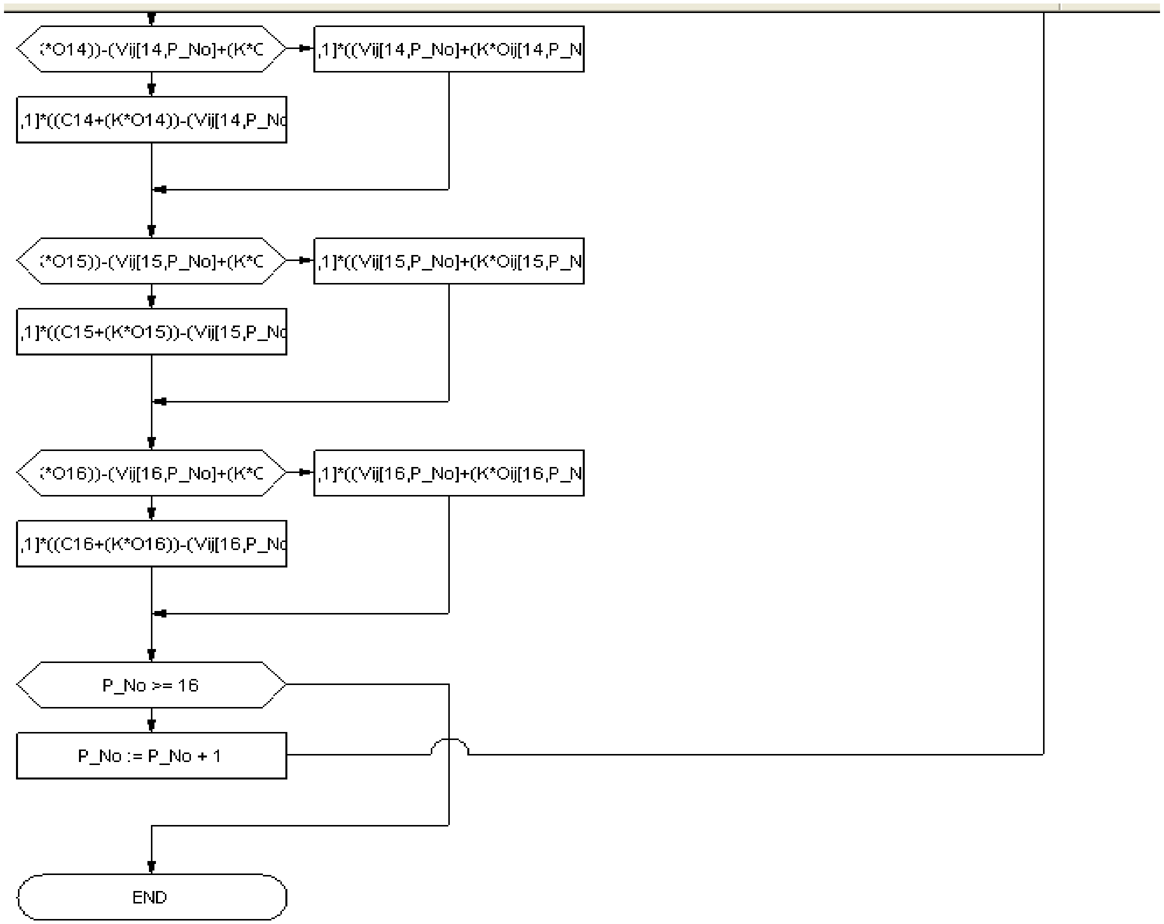


Figure A.72 Positive_Fj Subroutine Part 4

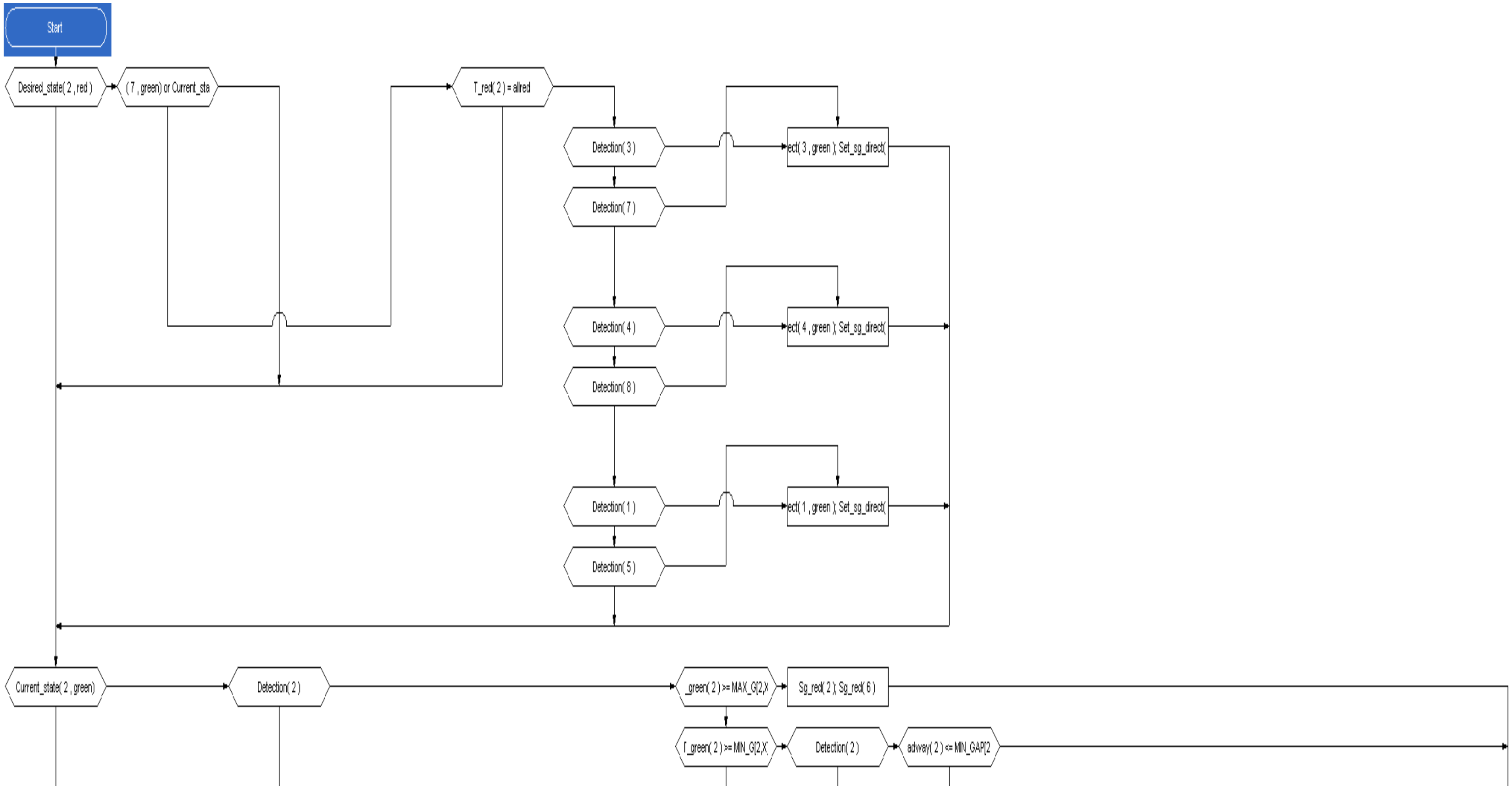


Figure A.73 Free Subroutine Part 1

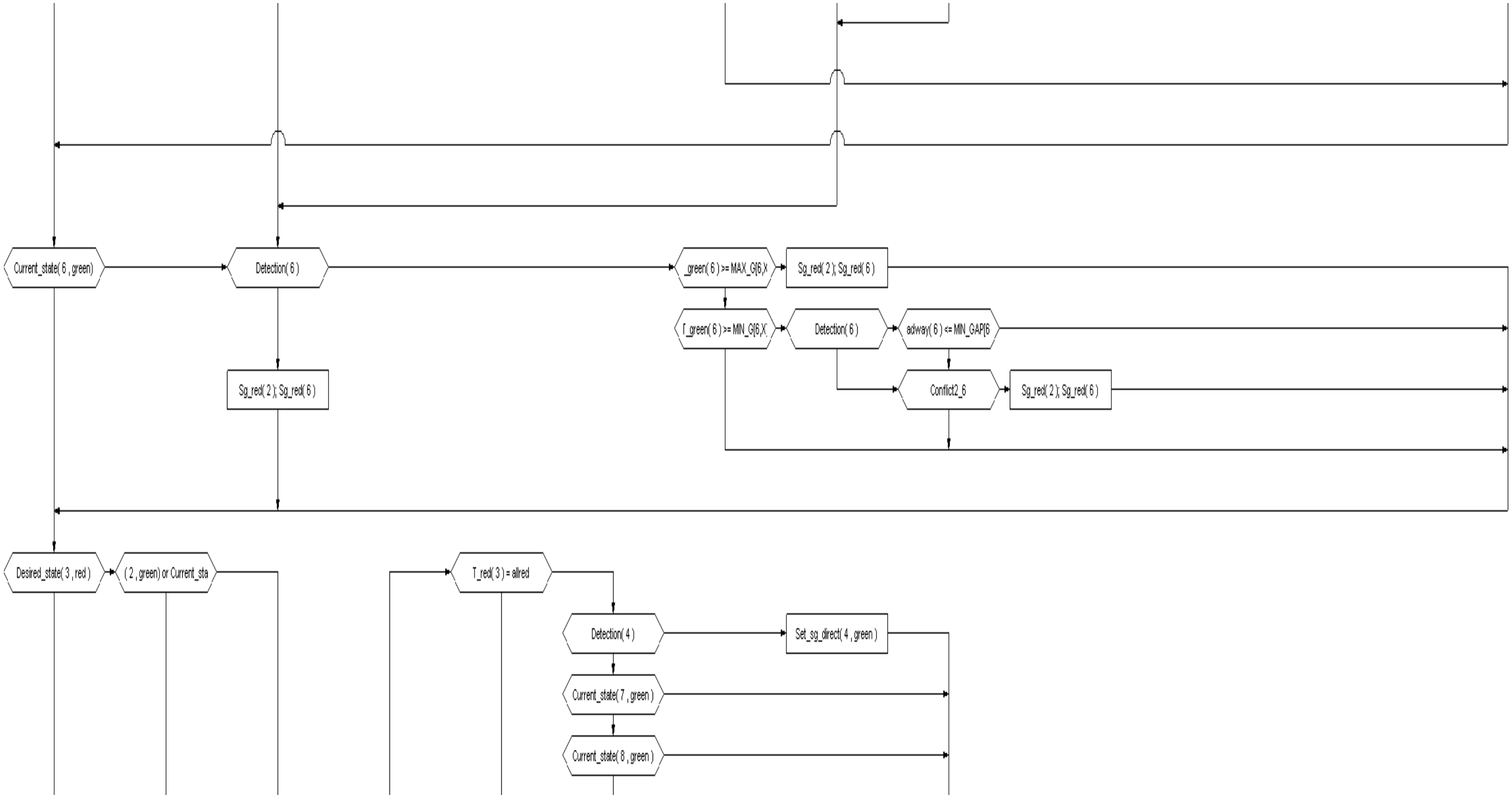


Figure A.74 Free Subroutine Part 2

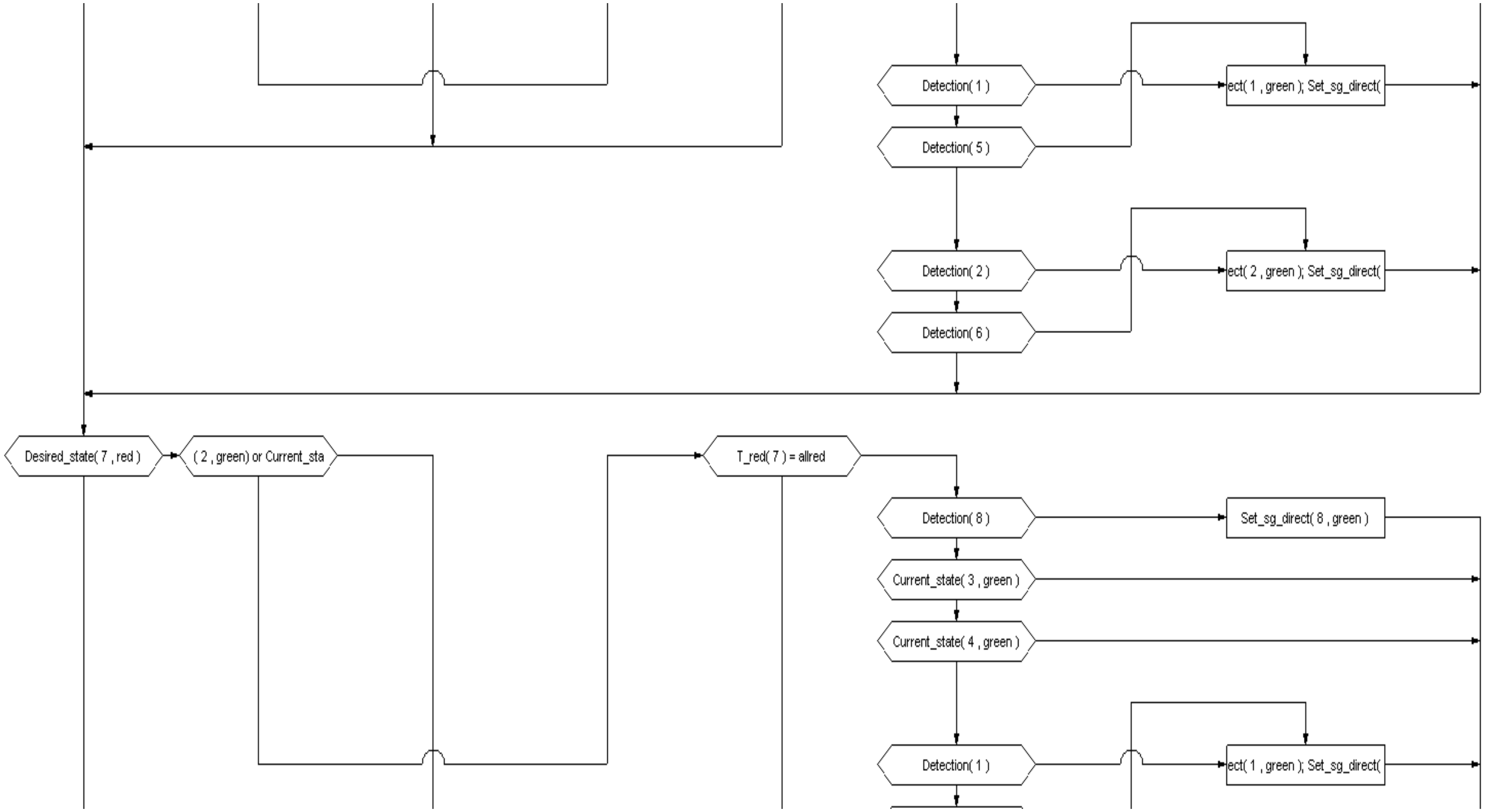


Figure A.75 Free Subroutine Part 3

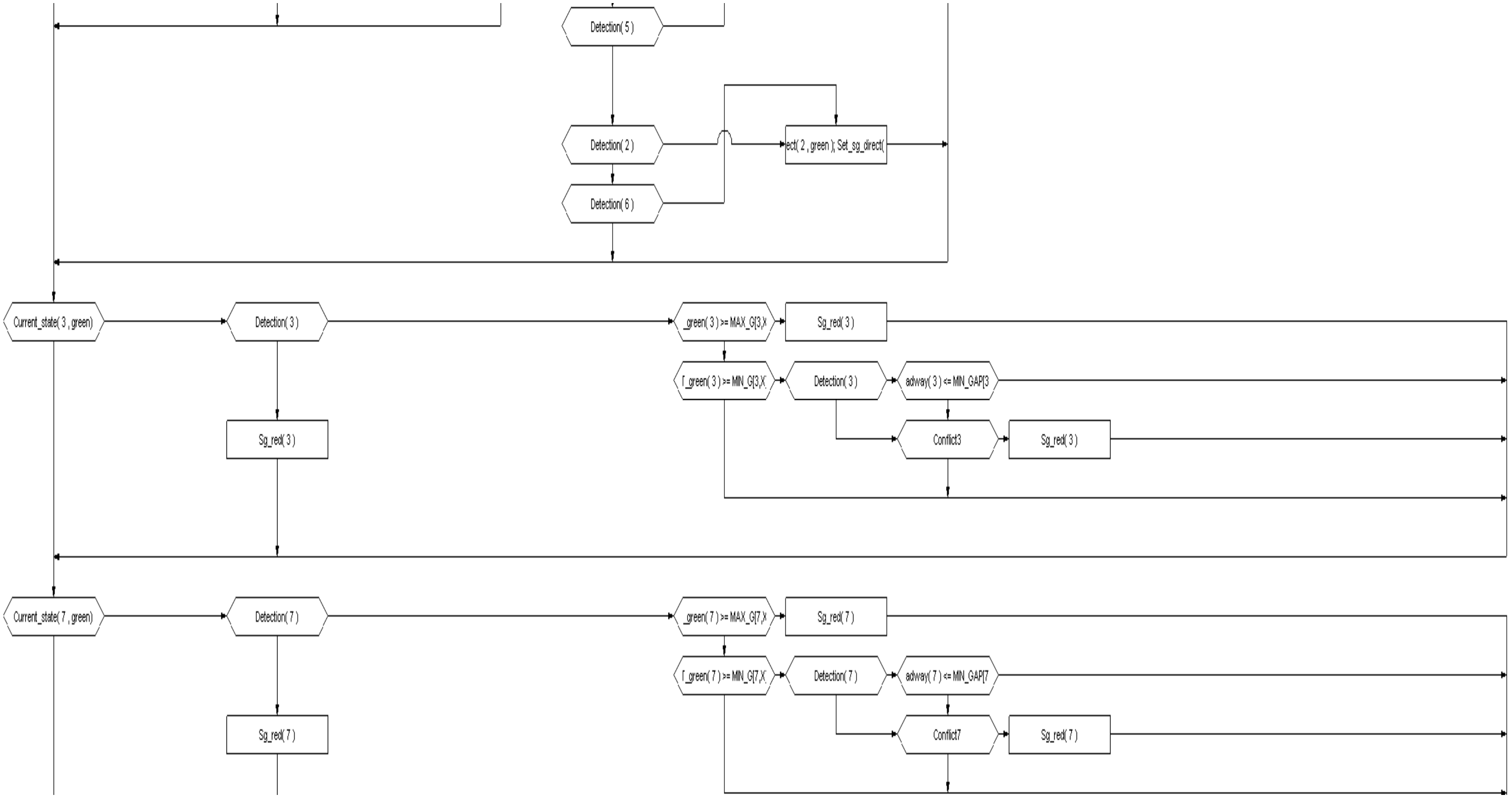


Figure A.76 Free Subroutine Part 4

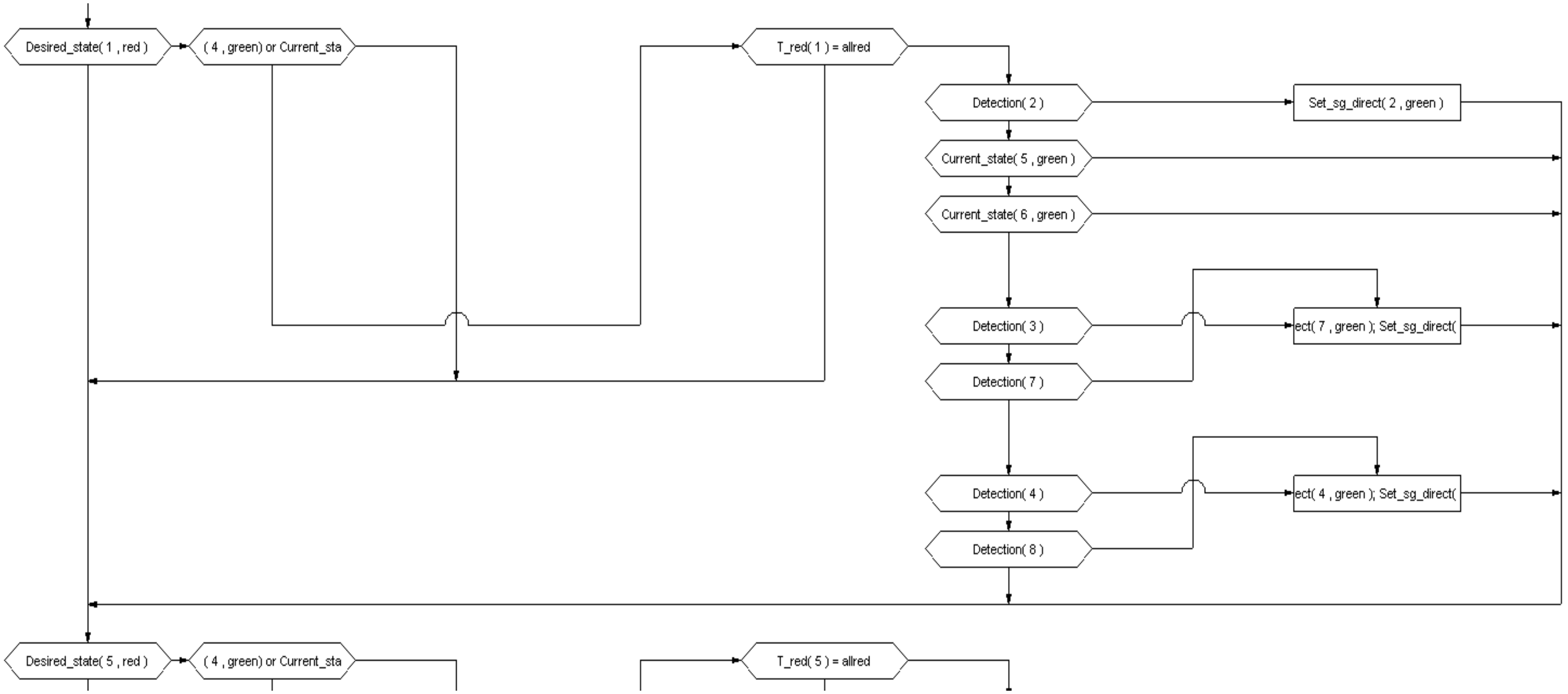


Figure A.77 Free Subroutine Part 5

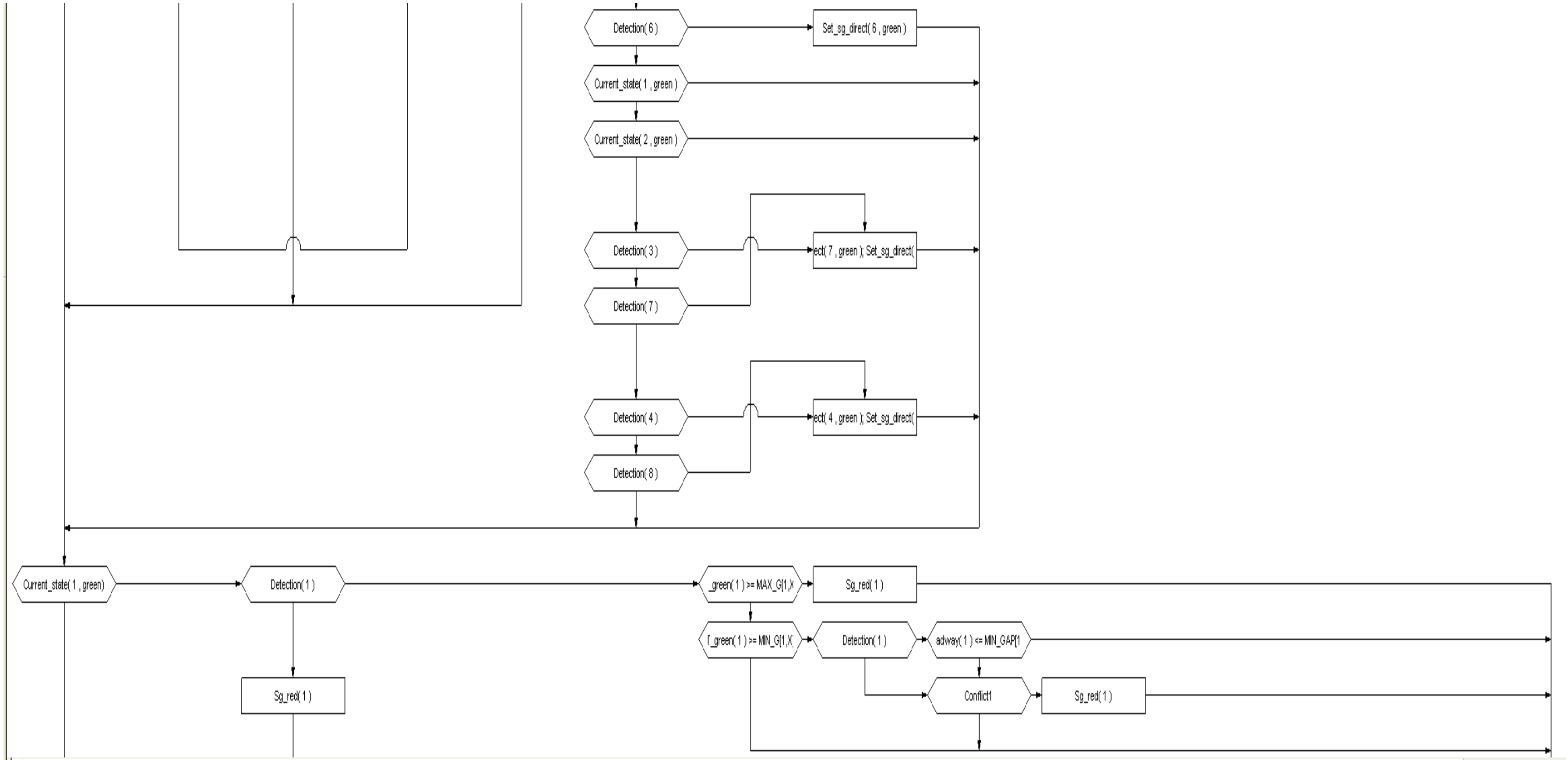


Figure A.78 Free Subroutine Part 6

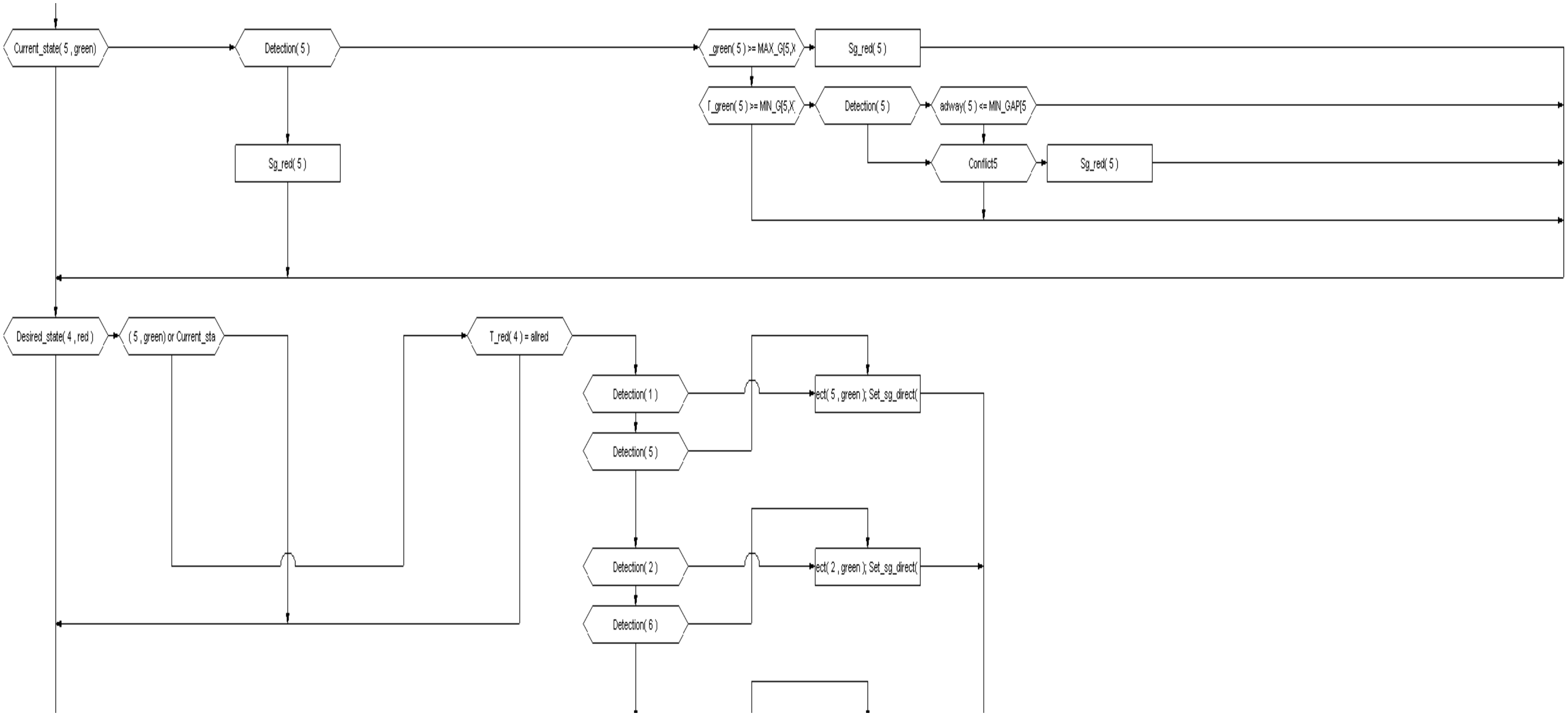


Figure A.79 Free Subroutine Part 7

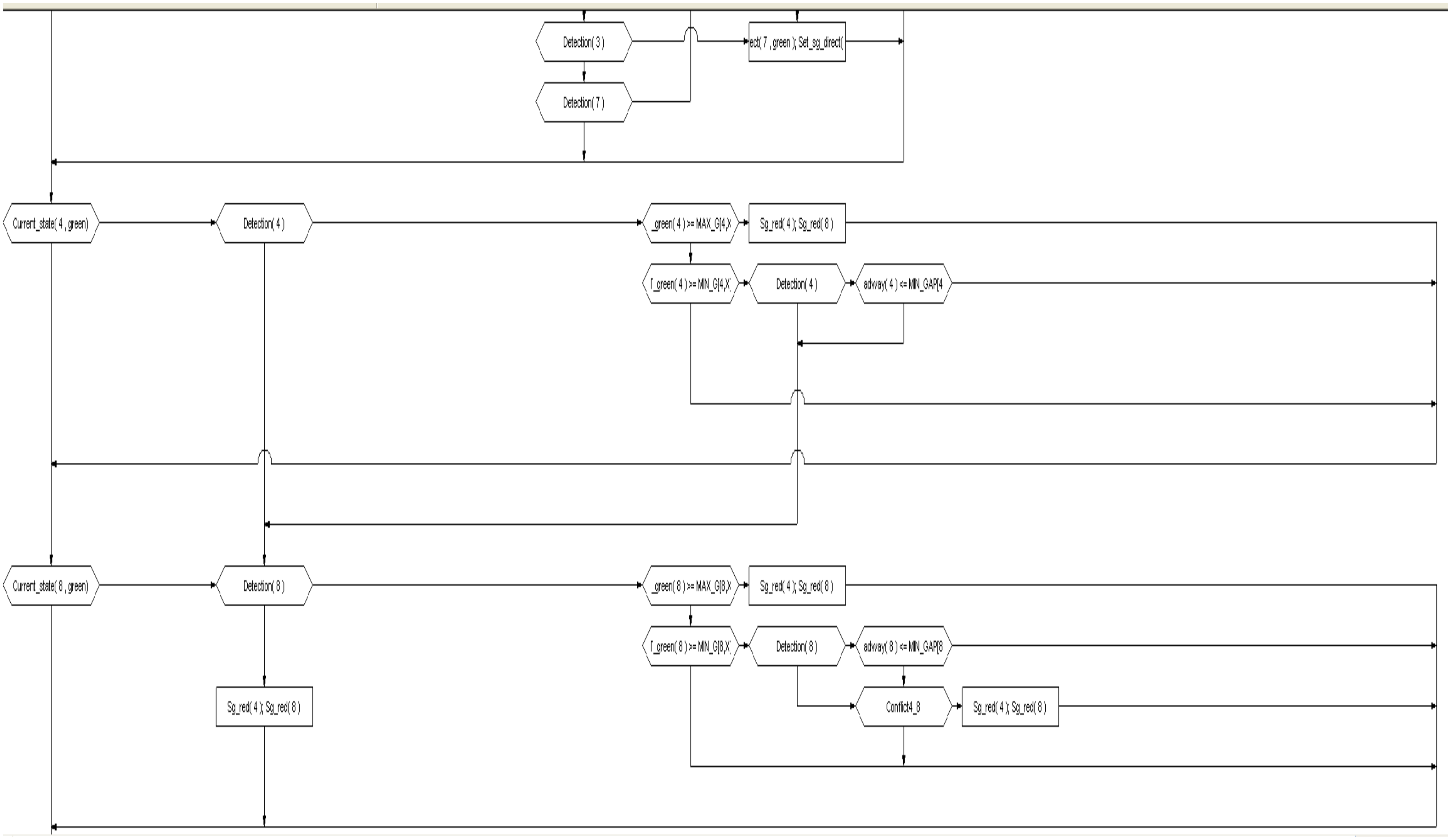


Figure A.80 Free Subroutine Part 8

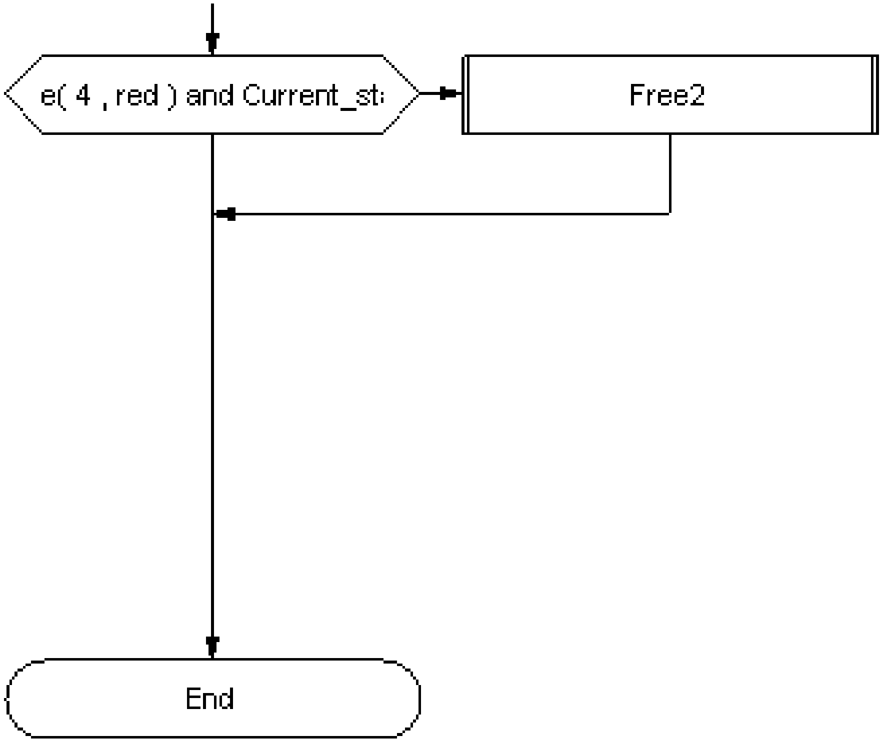


Figure A.81 Free Subroutine Part 9