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VTRC 09-CR6

EVALUATION OF TRAFFIC RESPONSIVE CONTROL ON THE RESTON PARKWAY ARTERIAL NETWORK

MONTASIR ABBAS
Assistant Professor

SHERIF ABDELAZIZ
Graduate Research Assistant

Virginia Tech Transportation Institute



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Author(s): Montasir Abbas and Sherif Abdelaziz				
Performing Organization Name and Address: Virginia Tech Transportation Institute 3500 Transportation Research Plaza (0536) Blacksburg, VA 24061				
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<p>Abstract:</p> <p>Traffic responsive plan selection (TRPS) control is considered an effective operational mode in traffic signal systems. Its efficiency stems from the fact that it can capture variations in traffic patterns and switch timing plans based on existing traffic conditions. Most of the research performed to date has focused on either small traffic networks—with up to five intersections—or theoretical networks. Past research has also focused on the threshold mechanism implemented in the National Electrical Manufacturers Association (NEMA) traffic controllers. There is very limited research on the pattern-matching mechanism implemented in the 170 controllers.</p> <p>This report documents a new approach to generating traffic scenarios for large networks, addressing issues such as the unequal traffic distribution and the large combination of traffic movements from multiple intersections. This approach is based on the selection of significant critical movements controlling the network using statistical correlation analysis of actual detector data and the use of synthetic origin-destination analysis of the entire network. The proposed approach was applied in the design of the traffic responsive control mode for the Reston Parkway arterial network, which has 14 intersections.</p> <p>Detector data were used to validate the results of the proposed approach. The validation process showed that the traffic system was correctly modeled and sufficiently represented by the proposed approach. Multi-objective optimization was used to generate the final timing plans and the TRPS pattern-matching parameters. Simulation analysis revealed that implementation of the traffic responsive control mode in the Reston Parkway network can achieve an average delay reduction of 27 percent and an average stops reduction of 14 percent on weekends and an average delay reduction of 18 percent and an average stops reduction of 21 percent on regular week days.</p> <p>The methodology documented in this report should be followed to implement TRPS control on large arterials in an optimal and stable manner. Optimal and stable operation of TRPS could significantly reduce congestion while capitalizing on existing traffic control infrastructure with a 46:1 benefit-cost ratio.</p>				

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Montasir Abbas
Assistant Professor

Sherif Abdelaziz
Graduate Research Student

Virginia Tech Transportation Institute

Project Manager
Catherine C. McGhee, P.E., Virginia Transportation Research Council

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ABSTRACT

Traffic responsive plan selection (TRPS) control is considered an effective operational mode in traffic signal systems. Its efficiency stems from the fact that it can capture variations in traffic patterns and switch timing plans based on existing traffic conditions. Most of the research performed to date has focused on either small traffic networks—with up to five intersections—or theoretical networks. Past research has also focused on the threshold mechanism implemented in the National Electrical Manufacturers Association (NEMA) traffic controllers. There is very limited research on the pattern-matching mechanism implemented in the 170 controllers.

This report documents a new approach to generating traffic scenarios for large networks, addressing issues such as the unequal traffic distribution and the large combination of traffic movements from multiple intersections. This approach is based on the selection of significant critical movements controlling the network using statistical correlation analysis of actual detector data and the use of synthetic origin-destination analysis of the entire network. The proposed approach was applied in the design of the traffic responsive control mode for the Reston Parkway arterial network, which has 14 intersections.

Detector data were used to validate the results of the proposed approach. The validation process showed that the traffic system was correctly modeled and sufficiently represented by the proposed approach. Multi-objective optimization was used to generate the final timing plans and the TRPS pattern-matching parameters. Simulation analysis revealed that implementation of the traffic responsive control mode in the Reston Parkway network can achieve an average delay reduction of 27 percent and an average stops reduction of 14 percent on weekends and an average delay reduction of 18 percent and an average stops reduction of 21 percent on regular week days.

The methodology documented in this report should be followed to implement TRPS control on large arterials in an optimal and stable manner. Optimal and stable operation of TRPS could significantly reduce congestion while capitalizing on existing traffic control infrastructure with a 46:1 benefit-cost ratio.

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Montasir Abbas
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INTRODUCTION

Traffic responsive plan selection (TRPS) control mode of operation has the potential to significantly improve the overall system performance of coordinated traffic networks. However, TRPS systems are not widely used to control traffic networks. Traffic engineers revert to the use of time-of-day (TOD) mode of operation because of its simplicity and ease of configuration.

TRPS has the advantage of switching timing plans in response to changes in traffic patterns. TOD mode lacks this ability, as it implements the same timing plan following a specified schedule regardless of what is actually happening in the network. Moreover, using traffic responsive control does not require periodic updating of timing schedules as it adjusts the timing plans break points automatically.

Although past research shows that using TRPS mode of operation improves traffic networks by reducing the total number of vehicular stops as well as delay, there is a need for more research to determine the parameters and different traffic issues that might affect traffic responsive operation. Many traffic engineers are still not familiar with traffic responsive controlling concepts.

Most of the research performed to date has focused on either small traffic networks—typically with up to five intersections—or theoretical networks. Also, past research has considered the implementation of the National Electrical Manufacturers Association (NEMA) threshold mechanism of traffic responsive control.

The work conducted in this research project evaluated the merits of implementing traffic responsive control on the Reston Parkway arterial network in Northern Virginia. The Reston Parkway is controlled by type 170 controllers, which use pattern-matching TRPS mechanism. This research, therefore, provides a framework and a systematic procedure to implement TRPS control on large arterial network. Although the parameter values and timing plans developed in

this study are pertinent to the Reston Parkway network, the framework outlined herein can be used on other arterial networks to improve system stability and optimality.

PURPOSE AND SCOPE

The objective of this research was to develop a systematic procedure and a general framework to implement TRPS control mode in order to reduce congestion and travel time on large arterial networks. The main research tasks were as follows:

1. Present a clear approach to generating realistic and accurate traffic scenarios to be used in the design of signal control systems.
2. Develop a procedure for designing TRPS control mode, using the 170-type controller's pattern-matching mechanism, in the Reston Parkway arterial network.
3. Compare the currently implemented TOD system to the proposed TRPS control in the Reston Parkway arterial network.
4. Present the pros and cons of the TRPS control mode of operation.

METHODS

The following sections show the methodology followed in this research. The text is organized into five sections. The following two sections summarize the concepts of TRPS control mode and a review of the state of the art in TRPS control. The third section presents the proposed approach to generating different traffic scenarios for the Reston Parkway network using the proposed significant critical movements' concept. The fourth section presents the steps of evaluating the performance of the TRPS control mode of operation (using pattern-matching mechanism) in the Reston Parkway large arterial network. Finally, the fifth section provides the conclusion and discusses the pros and cons of the proposed TRPS control mode.

BACKGROUND

Overview

Different modes of adaptive traffic signal control have been studied and analyzed to determine the most appropriate way to optimize the parameters required by each system. The first generation of successful responsive systems includes SCOOT and SCATS, which provide responses to real-time traffic by optimizing cycle lengths, phase splits, and offsets. These systems outperformed the best fixed-time control strategies, with a 6 to 20 percent savings in travel time at the network level.^{1,2}

Adaptive systems, however, require major investments in terms of infrastructure and communication hardware. Alternatively, existing controller features, such as TRPS, can be utilized to provide an operation that can theoretically be equivalent to adaptive control. Traffic responsive control mode, like any adaptive control mode, has the ability to switch timing plans being implemented in traffic networks according to traffic variations.³ This concept strives to apply the most appropriate timing plan for the existing traffic pattern to increase the overall system performance by minimizing delay and number of stops. There is a need for research to determine the design procedure for traffic responsive control mode parameters. This section presents the basics of traffic responsive control and a comprehensive literature review for the research conducted in this topic.

Traffic Responsive Control Concepts

In order to implement traffic responsive control mode, a set of system detectors should be spread on the traffic network being studied. The number of system detectors supported in traffic controllers differs among controller manufacturers. The selection of the number of system detectors should be appropriate, as for any adaptive control system, because the efficiency of the controlling system depends on the system detectors. Guidelines to selecting the number of system detectors for traffic responsive control were provided in a report by the Texas Transportation Institute (TTI) in addition to the limited guidelines provided by the Federal Highway Administration.³ Counts and occupancies of selected system detectors are collected. The treatment method for the collected detector data depends on the traffic responsive methodology in the traffic controllers operating the entire network.

Two methodologies can be followed to implement traffic responsive control in any traffic network as per The National Transportation Communications for Intelligent Transportation Systems Protocol (NTCIP) 1210 Field Management Stations Draft: threshold mechanism and pattern-matching mechanism.⁵ Each controller manufacturer provides one of these methodologies in their traffic controllers to implement traffic responsive control mode of operation. The required parameters to set up each methodology are different. For either methodology, different controller manufacturers might call traffic responsive parameters by different names.

The Threshold Mechanism

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

Different factors are used to aggregate counts and occupancies obtained from system detectors to form CC parameters then PS parameters. Three types of factors are generally used: scaling, weighting, and smoothing factors.^{6,7,8} Scaling factors—one for counts and another for

occupancies for each system detector—are used to convert counts and occupancies into a combined value ranging from 0 to 100 percent to indicate how close the approach is to its capacity. Each system detector is assigned a weighting factor, by which that system detector’s data are multiplied. Some controller manufacturers allow different weighting factors for counts and occupancies, while others apply the same weighting factor to occupancy and count.^{6, 7, 8}

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: a filtering approach and an averaging approach. The filtering 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 smoothing factor is determined by the traffic engineer to screen out any erratic detector data values, and is therefore site specific. The “averaging approach” averages the values of the detector data over the previous time intervals. The greater the number of previous time intervals used, the less sensitive the smoothed value is to changes.³

Most controller manufacturers use three PS parameters: an offset PS parameter, a cycle PS parameter, and a split PS parameter. Functions used to aggregate the CC parameters into PS parameters are, in most cases, predefined by the controller manufacturer. These functions are typically some sort of weighting averages.^{6, 7, 8} Each 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 controllers continually collect system detector data, track the values of different PS parameters (produced using scaling, weighting, and smoothing factors), and then compare the obtained PS parameters to the predefined set of thresholds. Different traffic patterns produce different values of PS parameters, causing the master traffic controller to switch timing plans when necessary.

Figure 1 illustrates the main concept of the threshold mechanism. The figure presents the threshold mechanism as a cube with three axes, with each axis representing a PS parameter. This large cube is then divided by the PS thresholds into 48 small cubes (4 x 4 x 3 levels). Each one of these small cubes represents a specific timing plan saved in the local traffic controllers. Thus, when the obtained PS parameters are calculated, the master controller maps their values in one of the small cubes and switches the currently implemented timing plan to the plan associated with the cube. The number of timing plans that can be stored in traffic controllers differs from one controller manufacturer to another.

Eagle and Naztec NEMA controllers are examples of traffic controllers that support the threshold mechanism for implementing traffic responsive control mode in traffic networks. Eagle controllers support up to 64 system detectors, 10 computational channel parameters, and 8 original timing plans. Eagle controllers also support an additional 8 timing plans using optional CC parameters called queue and occupancy CC parameters. Naztec controllers support only 3 CC parameters. However, combinations of these 3 CC parameters are used to calculate each of

the PS parameter levels. Naztec has 24 total timing plans that can be assigned to each one of 144 possible combinations of different PS parameter levels.⁴

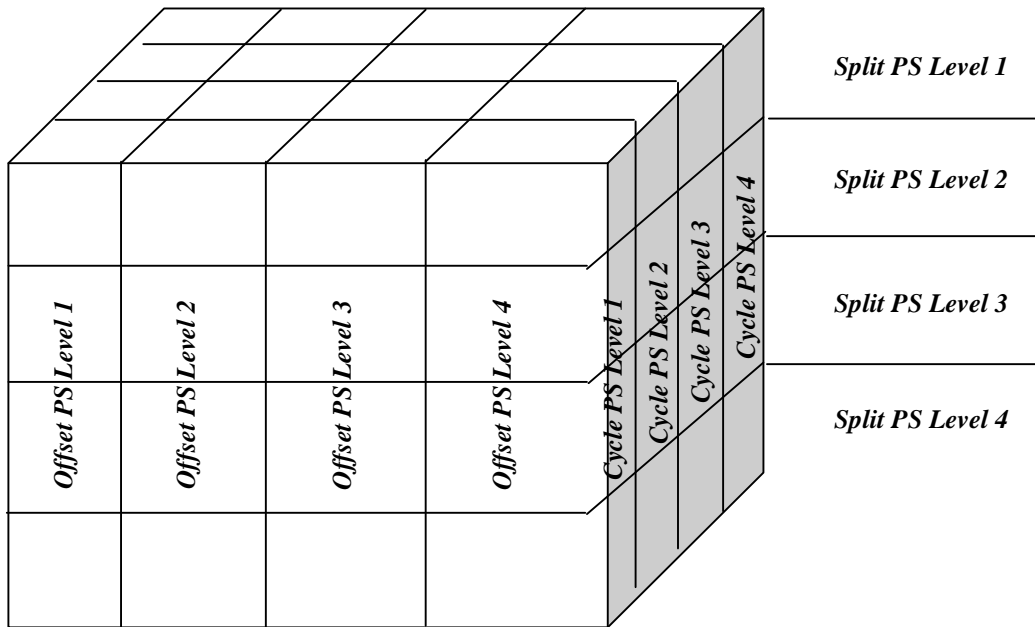


Figure 1. Threshold mechanism to implement traffic responsive control.

The Pattern-Matching Mechanism

The pattern-matching mechanism deals with detector data (counts and occupancies) in its row form. In other words, it does not aggregate system detector data to any CC parameters or PS 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 from the threshold mechanism. The master traffic controller switches the timing plan in traffic networks based on the sum of the deviations of individual count and occupancy values from those stored in the master controller for each timing plan. These stored counts and occupancies simulate the thresholds in the threshold mechanism.

Examining a 170 controller, which implements the pattern-matching mechanism of traffic responsive control mode, can clarify this method. Figure 2 summarizes the pattern-matching mechanism implemented in the 170 controller. All system detector counts and occupancies are combined together with the pre-programmed counts and occupancies into 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 the weighting factor (K), which is a global constant factor for all detectors, and the weight factors for each system detector;⁹ 170 controllers use the following formula to calculate different F_j plan values:⁹

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

where:

F_j = summation of the absolute value of the weighted difference between actual detector data and the pre-programmed counts and occupancies associated with each plan over all detectors

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-specified constant ranging between 0 and 100

W_i = a detector-specific weighting factor used to emphasize volumes and occupancies measured by selected detectors if their outputs are more important. These values are between 0 and 10.

A = a user defined constant with a value ranging between 0 and 1

F_c = the F value of the plan currently in use.

Theoretically, pattern-matching algorithms in general have more potential to differentiate between different traffic patterns. However, very limited research has been conducted to provide guidelines for determining the parameters of the pattern-matching mechanism. This research attempts to fill this gap in the literature.

Previous Research Efforts on Traffic Responsive Control

Several research efforts have been conducted to improve the overall performance of different adaptive control modes generally and traffic responsive control mode specifically. Approximate dynamic programming (ADP) is one of the methods attempted in the literature.¹⁰ ADP was the first attempt to optimize the traffic control objective functions dynamically through adaptive approximation of the value functions. The algorithm depends on the approximation of the value function progressively during operation while preserving the structural property of the control problem. That research concluded that the ADP strategy is as good as the best existing control strategies while being efficient and simple in computation.

Another research effort was aimed at minimizing congested situations via a traffic-responsive signal control mode founded on a hierarchical Petri net (PN) representation of the system.¹¹ 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 on the modular representation, switches among internal module structures so as to modify some parts of the model traffic system (e.g., signal plans, turning rates, etc.), depending on both state and time. The low-level control system, which acts on the DTPN representation, optimizes the performances of the traffic system by solving mathematical programming equations that 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 enables the use of the same modular/switching system to rule the traffic flows through the considered signalized intersections during the entire day.¹¹

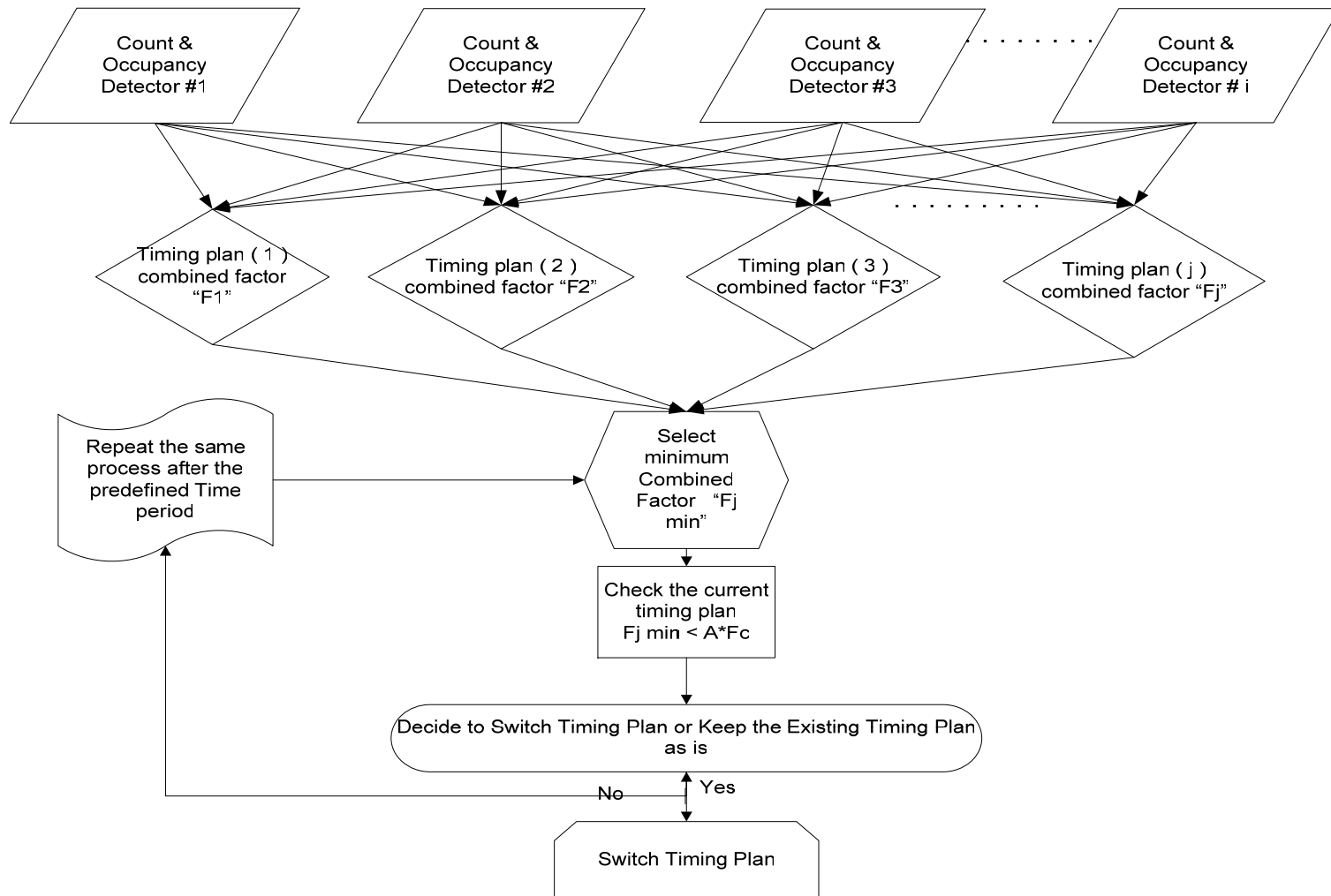


Figure 2. Pattern-matching traffic responsive control mechanism implemented in 170 controllers.

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 was conducted for a single intersection.^{12,13} This study showed that fuzzy logic can improve system performance by reducing delay and stops in a simulated network.

Research has also been performed to describe various techniques for determining the thresholds in traffic responsive threshold mechanism to achieve the best separation between different traffic scenarios.^{14, 15} These techniques included principal components and discriminant analysis,¹⁶ artificial neural networks and support vector machines,¹⁷ and decision-tree classifiers with various forms of nearest neighbor classification methods.¹⁸

A recent study introduced a step-by-step procedure for determining the thresholds for traffic responsive control mode.¹⁹ This research proposed a traffic state classification method using modified linear discriminant analysis (LDA). 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 improve the robustness of the traffic responsive control operation mode.

Another research effort provided general guidelines for the threshold mechanism of traffic responsive control mode.²⁰ A multi-objective evolutionary algorithm and a supervised discriminant analysis were used in the research to come up with the guidelines. In that research, three main movements were proposed for many traffic networks: 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 scenario probabilities were determined using the probability of occurrence of traffic volume in the major arterial direction; then given this probability, the probability of all other volumes in the other directions was determined. Multi-objective genetic algorithm optimization was used to select the timing plan to be implemented in the network out of many plans obtained from the 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 and resulted in a stable performance of traffic responsive control both in simulation and field tests. The limitation of the mechanism was that it assumed each original node produced equal numbers of trips and these trips were equally attracted by other nodes in the network. These assumptions are not necessarily true for most 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.²¹ The city of Milwaukee, Wisconsin, installed a closed-loop traffic responsive system to manage congestion and reduce traffic accidents.²² The study reported a reduction in adjusted frequency of

congestion-related intersection accidents. It also reported an increase in approach capacity and vehicle speed over system detectors.

Another simulation study was conducted in two networks in Lafayette, Indiana, and compares traffic responsive control and TOD modes.²³ Six different traffic scenarios were used for the analysis with the assumption that traffic responsive pattern change would occur at unexpected times for a typical day. Each scenario was run for 1 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 to configure the TRPS mode until it behaved as expected. As a consequence, the study reported that TRPS frequently resulted in unexpected time plan changes, reducing the overall system performance.²³

Summary

A review of the literature revealed that traffic responsive control mode can provide efficient control of arterial networks. However, limited research has been attempted to formalize an approach to implementing pattern-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 an approach. The research presented in this report was conducted to address these deficiencies.

DETERMINATION OF SIGNIFICANT CRITICAL MOVEMENTS TO GENERATE TRAFFIC SCENARIOS FOR LARGE ARTERIAL NETWORKS

Reston Parkway Network Description

The Reston Parkway arterial network (shown in Figure 3) is considered one of the most congested networks in Northern Virginia. The network consists of 14 intersections with a total length of 16,572 ft with spacing between intersections ranging from 524 ft to 3,309 ft. The speed limit for the main arterial is 45 mph and ranges from 15 mph to 45 mph for the side streets.

As shown in Figure 3, 11 intersections are four-leg intersections. Intersection 13 is a three-leg intersection, and intersections 6 and 7 are four-leg intersections with one-way side streets. Intersection 10 has only right-turn movements for the side streets (i.e., no through or left turns from the side streets).

Actual system detector data for this network were collected for a period of 1 month, from April 5, 2008, to May 6, 2008. Detectors cover nearly the entire network and record every 15 minutes.

The 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 weekdays and only one plan during weekends. The following sections present the details of the analysis done to implement traffic responsive control mode in the Reston Parkway network.

Currently, 170 traffic controllers are used to operate the entire network. The 170 controllers use pattern-matching algorithms for traffic responsive control mode. Thus, the final output for this section is the parameters required to set up such a mechanism in the Reston Parkway network in addition to optimum timing plans.

Proposed Approach Analysis Steps

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

Step 1: Data Clustering

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: Correlation Analysis

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: Synthetic Origin-Destination (O-D) Analysis

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 determined. This is a very important step to generate realistic traffic patterns.

Step 4: Critical Movement Analysis

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.

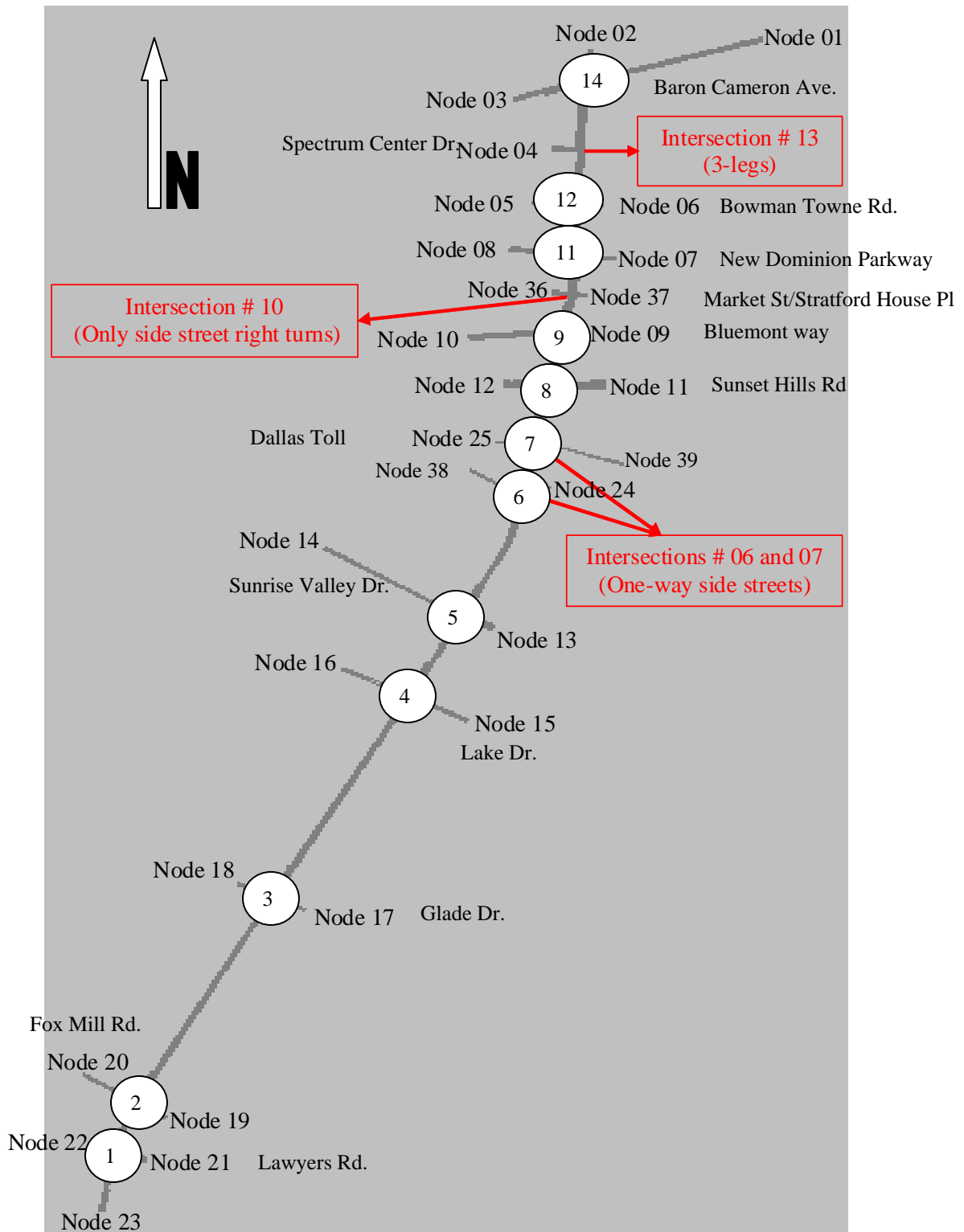


Figure 3. The Reston Parkway network in Northern Virginia.

Traffic Pattern Generation for Large Arterial Networks

In this section, the details of the proposed approach to deal with large arterial networks are presented. The four steps listed previously are performed in the Reston Parkway arterial network. The details of each step are presented here.

Traffic Level Determination (K-means Clustering)

The first step to generating 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 as well. Clustering can be based on the volumes of different link movements (i.e. left, through, and right) or link flow volumes. In this section, the traffic levels are based on the link flow volumes. The clustering analysis should be conducted for the main arterial as well as side streets separately as the side streets are not expected to have as high traffic levels as the main arterial.

K-means clustering is proposed to be used for the level determination. MATLAB was used to perform the entire analysis.²⁴ 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 numbers of clusters. The average silhouette value determines how good the clustering of data using a given number of clusters is. Finally, to determine the best number of clusters, a graph presenting the number of clusters versus its corresponding average silhouette value was used to select the optimal number of clusters corresponding to the maximum average silhouette value, as presented in Figure 4 for the main arterial and Figure 5 for side streets. Based on the k-mean analyses performed for the main arterial 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 were the recommended levels to be used to design traffic responsive control. Figures 6 and 7 show the silhouette values for each cluster's data points for the selected solution. In general, silhouette values closer to 1 indicate that the data points are very distant, and therefore very well separated, from neighboring clusters. Values closer to -1, indicate that the data points are probably assigned to the wrong cluster. The silhouette values in Figures 6 and 7, therefore, indicate that the data was well clustered. K-mean analysis results are in the form of a vector that includes each object and the cluster that this object is assigned to. This vector is used to determine the limit for each level. Figure 8 and Figure 9 show the limits for main arterial clusters and side-street clusters, respectively. The data points are shown in blue, where the limits that define different clusters are shown in red. Table 1 summarizes the cluster limits for both of main arterial and side streets.

Table 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.

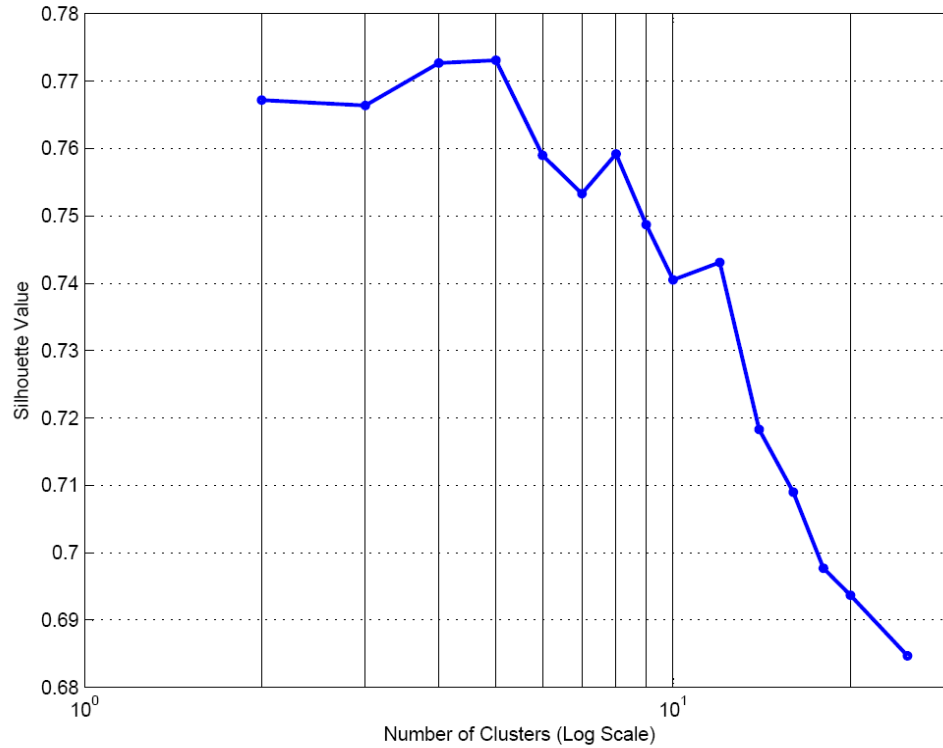


Figure 4. Silhouette value corresponding to different number of clusters for main arterial volumes.

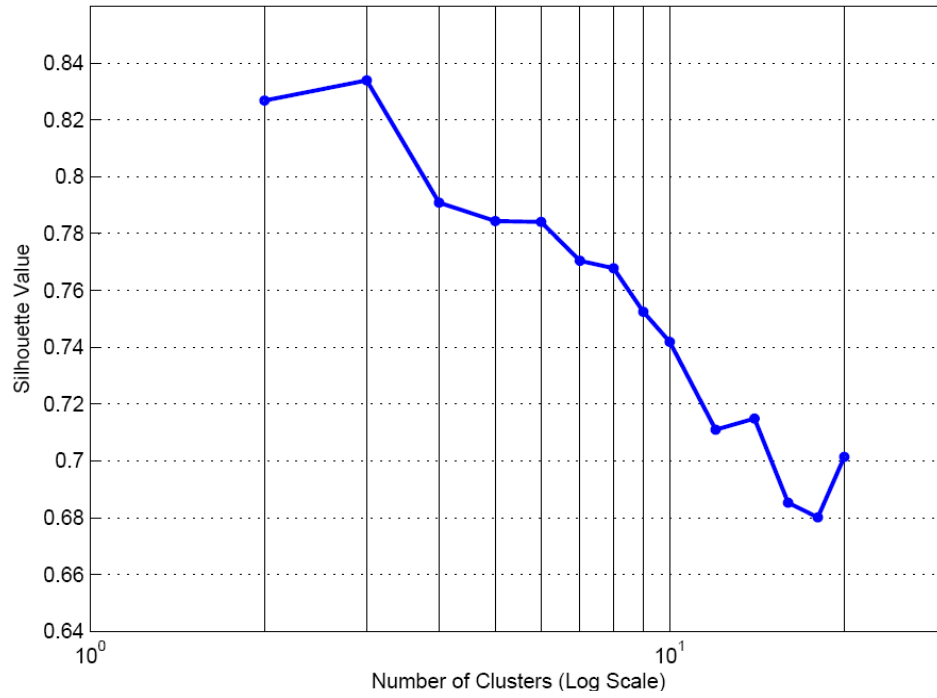


Figure 5. Silhouette value corresponding to different number of clusters for side street volumes.

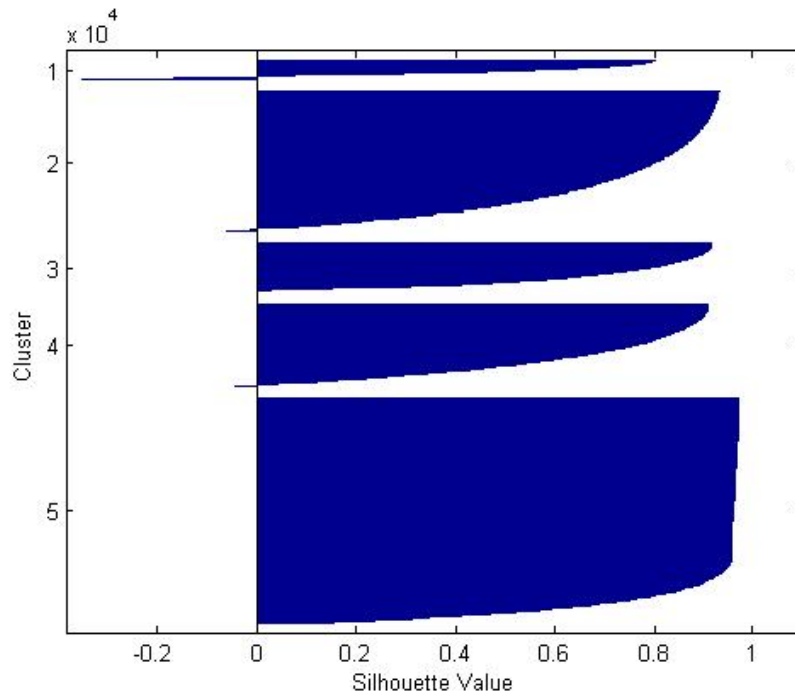


Figure 6. Silhouette plot for main arterial volumes.

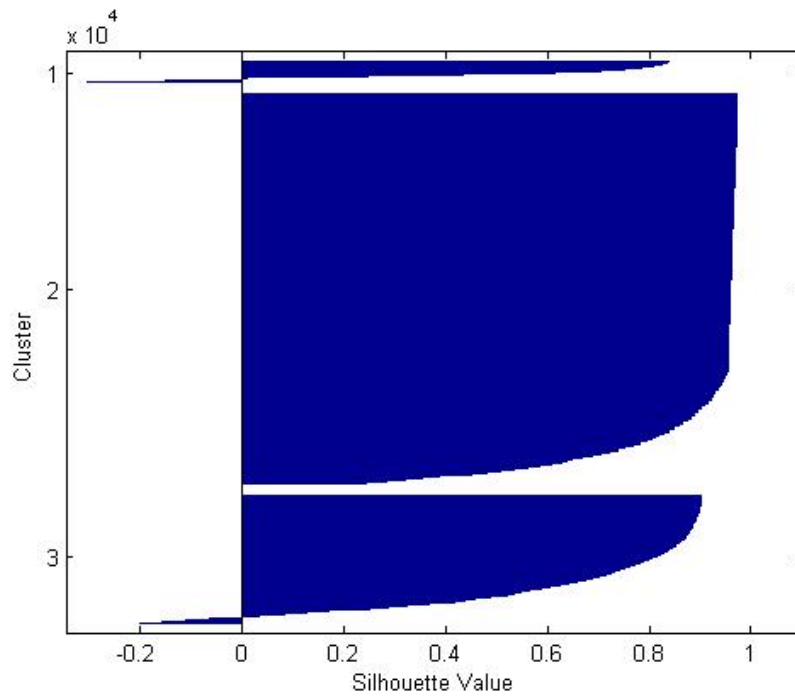


Figure 7. Silhouette plot for side street volumes.

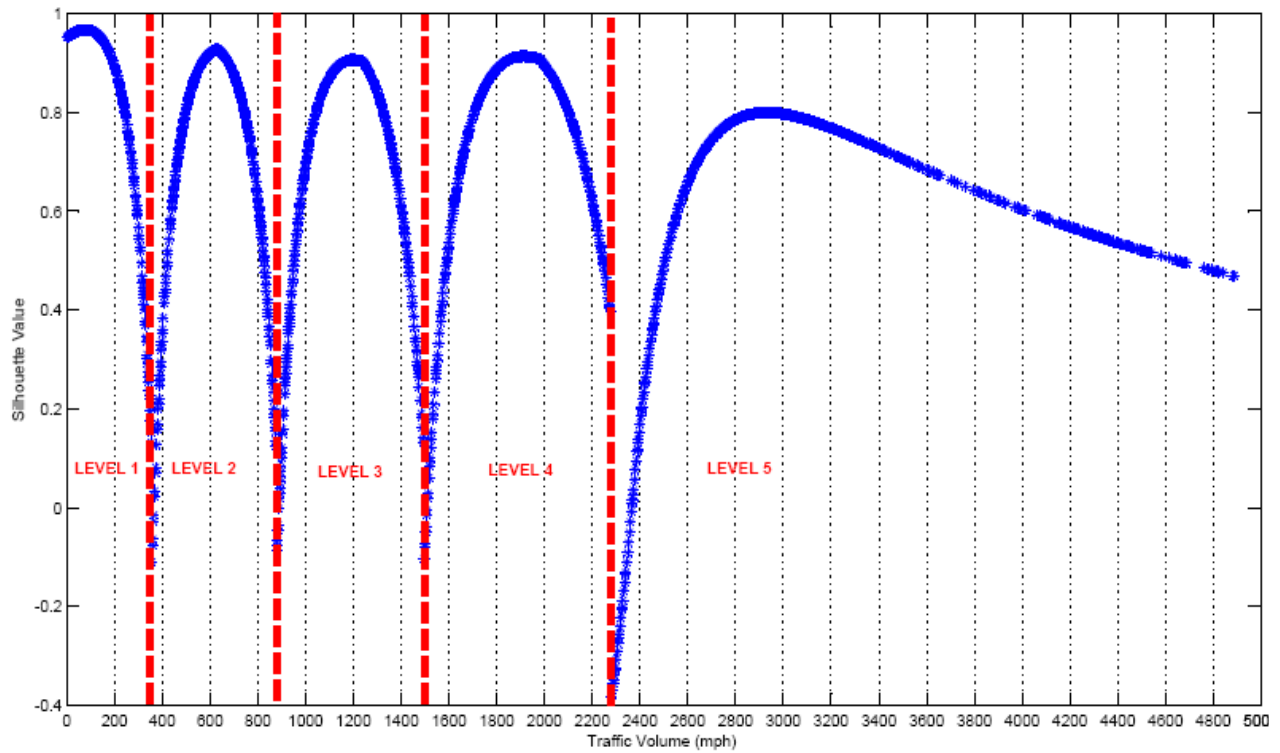


Figure 8. Link flow limits for clusters of the main arterial volumes.

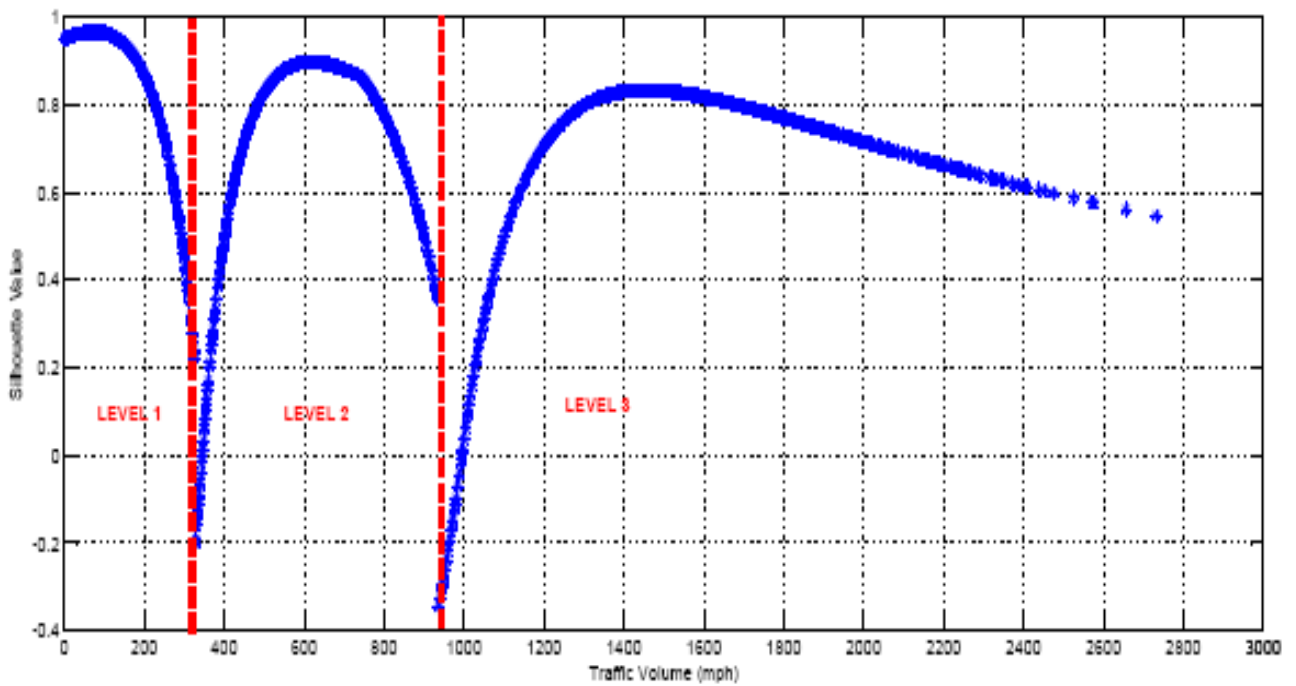


Figure 9. Link flow limits for clusters of side street volumes.

Correlation Analysis of Detector Data

As previously discussed, the primary method 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. At the same time, they have considerable traffic level variation. These movements will be used to generate the traffic patterns considered in the TRPS system 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 systematically highly correlated, which means if the traffic level for one of them increased, all traffic levels for highly correlated movements are going to increase and vice versa. The situation is different for the critical movements: if traffic level of one of the critical movements increases, 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 minimize the number of traffic movement combination considered.

Clearly, correlation analysis should be done for the detector data so that correlation factors between each movement and all other movements can be obtained. The SAS statistical package was used to determine the Pearson's correlation coefficients for all traffic movements in the entire network.²⁵ This correlation analysis should only consider movements entering the network either from the main arterial or from side streets. However, side-street through movements are also considered 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-street through movements.

For the Reston Parkway arterial network, the two correlation runs were performed using one month's data, and the correlation tables are presented in Table 2 for movements entering the network and Table 3 for side-street through movements. These correlation factors by themselves do not determine which movements can be considered highly correlated to other movements. Therefore, it is necessary to define a threshold that separates the highly correlated movements and uncorrelated movements. This threshold is found by running k-means clustering with only two clusters over all Pearson's correlation factors for both SAS runs. The K-means clustering analysis divided all movements into two groups, with a 0.50 threshold value for movements entering main arterial and 0.60 threshold value for side-street through movements. This means that for the movement entering the network, if the correlation factor between any two movements is more than 0.50, then these two movements should be considered highly correlated; otherwise they are not. In Table 2 and Table 3, the red cells represent the correlation factors more than 0.50 and 0.60, respectively.

It is obvious from Table 2 that there are almost five movements that have small correlations with other movements. Those movements are the 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 south bound through at the last intersection. Also it is clear from Table 3 that all side-street 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 any one of these movements affect the network significantly? The answer 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 constraint for the level of all movements of such links) and 2) if any one of these movements is found to be on a link having significant variation in its traffic level—if so then it is important to know at which level such movement is significant. Synthetic O-D analysis provides a clear answer for these two points.

Synthetic Origin-Destination Analysis

Synthetic O-D analysis aims to determine the distribution percentages for traffic entering the network from each origin node to all the 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 because they are highly correlated to each other. If any of these non-critical movements has a maximum observed k-means cluster level of one, 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 a number of observed traffic levels that is less than the maximum number of k-means cluster levels for such a link (in the Reston Parkway, three levels for side streets and five for main arterial), the maximum actual level on this link would be maintained in the analysis with higher traffic levels of other links.

For the critical movements, traffic levels for links where these movements belong vary regardless of the flow level on other links. This is also constrained by the maximum observed traffic level for links with these critical movements. This is a very important point, since small correlation between certain movements and other movements in the network does not mean that such movement affects network performance significantly. Small correlation might exist 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 2. Correlation factors between movements entering the 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		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			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				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					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						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							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								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									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										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											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												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													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														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															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																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																	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																		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																			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																				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																					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																						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																							1.00	0.38	0.18	0.65	0.71	0.52	0.53	0.66	0.59	0.31	0.51
9 WBR																								1.00	0.55	0.42	0.32	0.51	0.52	0.32	0.26	0.47	0.54
9 WBL																									1.00	0.42	0.26	0.57	0.60	0.30	0.22	0.55	0.60
10 EBR																										1.00	0.78	0.80	0.80	0.75	0.68	0.56	0.78
10 EBL																											1.00	0.66	0.68	0.76	0.72	0.43	0.66
10 WBR																												1.00	0.87	0.74	0.63	0.66	0.87
10 WBL																													1.00	0.73	0.61	0.70	0.89
13 EBR																														1.00	0.78	0.47	0.70
13 EBL																															1.00	0.37	0.61
14 SBT																																1.00	0.72
14 WBL																																	1.00

- Red cells (darker shaded) 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. Correlation factors between side-street through movements in the 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		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			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				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					1.00	0.51	0.57	0.53	0.61	0.62	0.37	0.71	0.63	0.73	0.74
5 EBT						1.00	0.91	0.92	0.92	0.34	0.49	0.83	0.77	0.83	0.77
5 WBT							1.00	0.89	0.91	0.29	0.75	0.86	0.78	0.83	0.80
8 EBT								1.00	0.86	0.25	0.70	0.81	0.85	0.85	0.80
8 WBT									1.00	0.70	0.69	0.89	0.77	0.87	0.84
9 EBT										1.00	0.75	0.80	0.65	0.34	0.30
9 WBT											1.00	0.46	0.63	0.77	0.55
10 EBT												1.00	0.79	0.89	0.87
10 WBT													1.00	0.87	0.87
14 EBT														1.00	0.94
14 WBT															1.00

- Red cells (darker shaded) 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 the maximum observed traffic level constraint to the five critical movements obtained from correlation analysis, it was found that the east bound left turn movement at the fourth intersection belonged 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, this needs further verification with synthetic O-D analysis. Synthetic O-D analysis provides the distribution percentages for each movement in the network, which consequently confirms 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 does not provide information 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 the Reston Parkway arterial network is performed based on the actual detector data. QUEENSO-D software was used to perform the required synthetic

analysis.²⁶ One run was 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 provides the distribution percentages for traffic entering the network from each origin node over all destination nodes. Figure 3 includes node numbers used in QUEENSO-D runs. These O-D percentages are important because they provide an idea of which major movements in the network are significant. These distribution percentages are expected to change throughout the day, and because time of day is represented here with the traffic level on the network at each time, these distribution percentages were determined for each traffic level. Table 4 through Table 7 present the distribution percentages for different traffic levels. This technique was later verified against the AM and PM peak turning percentages as will be shown in the following sections.

Determination of Significant Critical Movements

To finally determine the significant critical movements for the Reston Parkway network, both the correlation analysis and the synthetic O-D analysis were conducted to complement each others.

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 was excluded. The other four movements were considered critical.

Synthetic O-D analysis confirmed that the remaining four movements have a great effect on the network since each one of them has a high distribution percentage for the traffic coming from the link it belongs to. Tables 4 through 6 show the distribution percentages from origin to destination nodes. It can be seen in these tables that the west bound right at intersection number seven (node 39 as illustrated in Figure 3) is significant to the network. The distribution percentage for this movement is very high (more than 85 percent). In addition, it belongs to a link having three traffic levels. This movement was then confirmed with the Northern Virginia staff as being a significant critical movement. Synthetic O-D analysis also showed other movements that belong to links with two or three traffic levels and had high distribution percentages, such as east bound right turn movement at the third intersection, west bound left turn movement at the fourth intersection, and 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 because the correlation analysis showed that all these movements are highly correlated. In other words, their levels increase and/or decrease together; therefore they are considered non-critical movements from the beginning.

Table 4. Distribution percentages for side street: Traffic Level 1.

	DESTINATION 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	-	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	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	0.0	2.9	14.9	0.8	0.0	99.2

• The "-" sign refers to unavailable movement.

Table 5. Distribution percentages for side street: Traffic Level 2.

	DESTINATION 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 6. Distribution percentages for side street: Traffic Level 3.

	DESTINATION 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	-	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 7. Distribution percentages for main arterial: different traffic levels.

		DESTINATION 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
		Main Arterial Level 1																													
ORIGIN NODES	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
	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 NODES	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
	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 NODES	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
	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 NODES	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
	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 NODES	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
	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.

Thus, the final significant critical movements for the Reston Parkway network are as follows: north bound through and west bound right at the first intersection, west bound left at the fifth intersection, west bound right at the seventh intersection, and south bound through at the last intersection. Figure 10 shows the 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.

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 addressed in the following section. 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 during the AM and PM peak periods. This process will not result in the exact turning percentages at individual intersections, but would rather be useful in understanding and determining the critical traffic movement levels that drive the change in traffic patterns over the whole network. Table 8 and Table 9 show the obtained traffic patterns and the actual detector data for the AM peak period. Table 10 shows the absolute percent error between the two patterns. It should be noted that the high percentages correspond to very low traffic volumes and therefore can be considered practically insignificant.

Tables 11 through 13 show the same values but for the PM peak period. This analysis shows that the critical movement analysis can adequately represent the traffic patterns in the network.

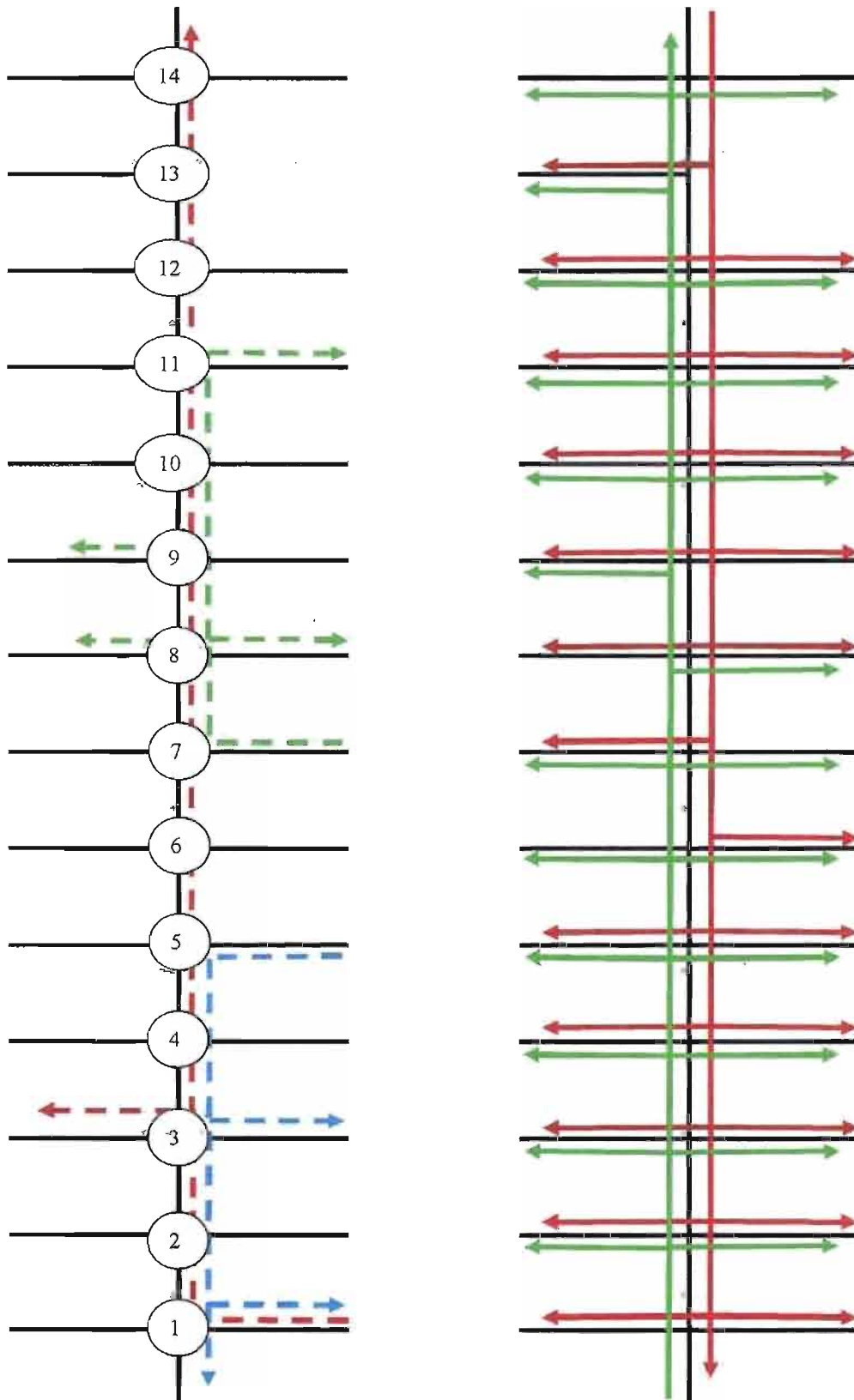


Figure 10. Major distributions of the critical traffic movements in the Reston Parkway network.

Table 8. Traffic patterns generated using proposed approach during the AM peak period.

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	107	1943	225	164	724	251
2	76	29	221	303	0	23	211	1762	303	23	615	43
3	128	95	103	129	37	160	197	1402	262	107	449	86
4	248	43	35	154	50	122	278	1253	159	124	453	240
5	210	101	15	24	56	246	84	1371	168	395	778	160
6	51	0	105	-	-	-	-	1218	609	0	1228	-
7	-	-	-	3	0	323	0	1339	-	-	1277	454
8	171	82	84	40	51	244	79	1466	124	688	1607	210
9	4	4	324	329	0	0	222	1541	118	3	1852	18
10	-	-	333	-	-	43	-	1183	321	-	1251	0
11	15	119	200	269	56	10	215	619	391	142	782	79
12	195	2	140	120	0	213	37	574	36	29	754	37
13	40	-	293	-	-	-	130	852	-	-	534	26
14	53	102	171	147	65	114	188	446	258	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 9. Actual traffic pattern obtained from detector data during the AM peak period.

Intersection	East Bound			West Bound			North Bound			South Bound		
	L	T	R	L	T	R	L	T	R	L	T	R
1	144	256	84	160	96	532	60	1568	312	372	584	40
2	415	9	292	12	12	100	256	2004	28	24	698	168
3	104	116	92	176	144	164	236	1650	581	84	628	36
4	168	120	44	188	308	472	136	1532	216	148	576	184
5	165	463	40	58	366	376	228	1818	112	709	756	1072
6	484	0	456	-	-	-	-	1858	554	0	2024	-
7	-	-	-	664	1	866	384	1996	-	-	1784	232
8	84	1116	324	252	448	188	560	1396	952	276	1464	148
9	12	8	136	32	1	16	408	1292	20	8	1678	44
10	-	-	21	-	-	9	-	1320	10	-	1804	3
11	24	160	236	220	224	150	428	736	216	148	1348	76
12	8	4	136	26	6	1	200	720	44	32	1420	68
13	12	-	52	-	-	-	64	648	-	-	1420	8
14	120	744	252	300	617	40	212	354	140	108	844	192

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

Table 10. Absolute percent error between modeled and actual patterns during the AM peak period.

Intersection	East Bound			West Bound			North Bound			South Bound		
	L	T	R	L	T	R	L	T	R	L	T	R
1	19	79	19	39	30	70	78	24	28	56	24	528
2	82	222	24	2425	-	77	18	12	982	4	12	74
3	23	18	12	27	74	2	17	15	55	27	29	139
4	48	64	20	18	84	74	104	18	26	16	21	30
5	27	78	63	59	85	35	63	25	50	44	3	85
6	89	-	77	-	-	-	-	34	10	-	39	-
7	-	-	-	100	-	63	-	33	-	-	28	96
8	104	93	74	84	89	30	86	5	87	149	10	42
9	-	50	138	928	-	-	46	19	490	-	10	59
10	-	-	1486	-	-	378	-	10	3110	-	31	-
11	38	26	15	22	75	-	50	16	81	4	42	4
12	2338	50	3	362	-	21200	82	20	-	9	47	46
13	233	-	463	-	-	-	103	31	-	-	62	225
14	56	86	32	51	89	185	11	26	84	53	71	68

Table 11. Traffic patterns generated using proposed approach during the PM peak period.

Intersection	East Bound			West Bound			North Bound			South Bound		
	L	T	R	L	T	R	L	T	R	L	T	R
1	421	82	430	98	67	161	35	725	116	555	2902	512
2	229	96	608	303	0	23	192	930	185	86	3058	122
3	288	73	572	529	70	334	126	888	168	163	2165	164
4	458	11	464	588	88	257	262	1165	83	265	1440	352
5	468	235	230	24	56	246	23	1655	202	738	1803	295
6	51	0	105					1529	840	0	2717	
7				107	36	790	10	1755			2717	892
8	213	263	471	402	303	238	329	1903	322	893	2736	585
9	433	0	505	329	0	0	256	1976	122	0	3380	21
10			727			43		2251	121		2385	0
11	28	336	578	712	192	40	441	1313	746	182	1095	106
12	195	2	140	120	0	213	14	1366	13	60	1132	75
13	40		293					121	1653		981	79
14	179	321	433	385	207	341	339	913	441	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 12. Actual traffic pattern obtained from detector data during the PM peak period.

Intersection	East Bound			West Bound			North Bound			South Bound		
	L	T	R	L	T	R	L	T	R	L	T	R
1	60	188	148	292	184	428	88	632	124	536	1604	192
2	264	8	280	60	40	120	292	740	20	40	1972	404
3	100	196	208	220	164	128	92	780	184	192	1932	68
4	308	256	196	220	248	280	40	764	178	420	1756	128
5	527	220	209	308	236	657	80	1190	132	424	1856	184
6	376	0	224	-	-	-	-	1868	568	0	2200	-
7	-	-	-	560	1	680	396	1804	-	-	2424	368
8	220	436	576	660	896	412	280	1728	432	200	1576	92
9	36	36	304	16	12	4	276	2052	4	24	1492	80
10	-	-	192	-	-	8	-	2100	16	-	1500	8
11	132	208	360	176	172	279	360	1468	304	160	992	64
12	48	4	256	28	12	28	200	1620	4	16	976	76
13	48	-	156	-	-	-	172	1528	-	-	904	56
14	272	752	160	244	798	112	432	787	326	120	528	172

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

Table 13. Absolute percent error between modeled and actual patterns during the PM peak period.

Intersection	East Bound			West Bound			North Bound			South Bound		
	L	T	R	L	T	R	L	T	R	L	T	R
1	602	56	191	66	64	62	60	15	6	4	81	167
2	13	1100	117	405	-	81	34	26	825	115	55	70
3	188	63	175	140	57	161	37	14	9	15	12	141
4	49	96	137	167	65	8	555	52	53	37	18	175
5	11	7	10	92	76	63	71	39	53	74	3	60
6	86	-	53	-	-	-	-	18	48	-	24	-
7	-	-	-	81	-	16	-	3	-	-	12	142
8	3	40	18	39	66	42	18	10	25	347	74	536
9	-	100	66	1956	-	-	7	4	2950	-	127	74
10	-	-	279	-	-	438	-	7	656	-	59	-
11	79	62	61	305	12	-	23	11	145	14	10	66
12	306	50	45	329	-	661	93	16	-	275	16	1
13	17	-	88	-	-	-	30	8	-	-	9	41
14	34	57	171	58	74	204	22	16	35	58	54	65

EVALUATION OF PATTERN-MATCHING TRAFFIC RESPONSIVE CONTROL MODE IN THE RESTON PARKWAY LARGE ARTERIAL NETWORK

Analysis Steps for the Reston Parkway Network

The major analysis steps followed to evaluate traffic responsive control in the Reston Parkway network are presented in this section. The details of each step are presented in the following sections of this section. 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.

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.²⁷ The Virginia Department of Transportation (VDOT) requested that the existing phase sequences (i.e., lead-lead, lag-lag, lead-lag, or lag-lead) be kept the same as the sequence implemented in the current TOD control operation because this sequence is governed by the geometry at each intersection. Thus, the optimization of the PASSER V phase sequence feature was not used.

It was important to develop the timing plans such that they had cycle lengths that were factors of the periods that the master controller used to collect traffic samples. In the Reston Parkway network, this period was 15 minutes (900 seconds). Thus, only timing plans with cycle lengths of 90, 100, 150, and 180 seconds were considered. Therefore, for each traffic scenario, there were four timing plans that could be implemented in the traffic responsive control mode. As a result, 2,700 timing plans were generated (675 traffic scenario x 4 cycle lengths).

Selection of Best Timing Plans

The multi-objective algorithm found that in order to minimize frequent transitioning between timing plans, and to minimize delay and stops, a maximum of five plans should be stored in traffic controllers in addition to the exiting plans being used in TOD operation. VDOT required that the plans being used in the TOD operation be included in the final set of timing plans.

Evaluation of 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 in PASSER V 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.²⁸ The PASSER V initial selection analysis was necessary since CORSIM runs would take a very long time if performed for all plan-scenario combinations (2,700 plans x 675 scenarios).

The degree of detachment (DOD) introduced by Abbas et al. was used to select the best five plans out of the 2,700 obtained plans.³ The multi-objective genetic algorithm optimization was used to select the five best plans based on an optimization of delay, stops, and DOD. The delay and stops were the estimated values obtained from PASSER V.

Figure 11 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.

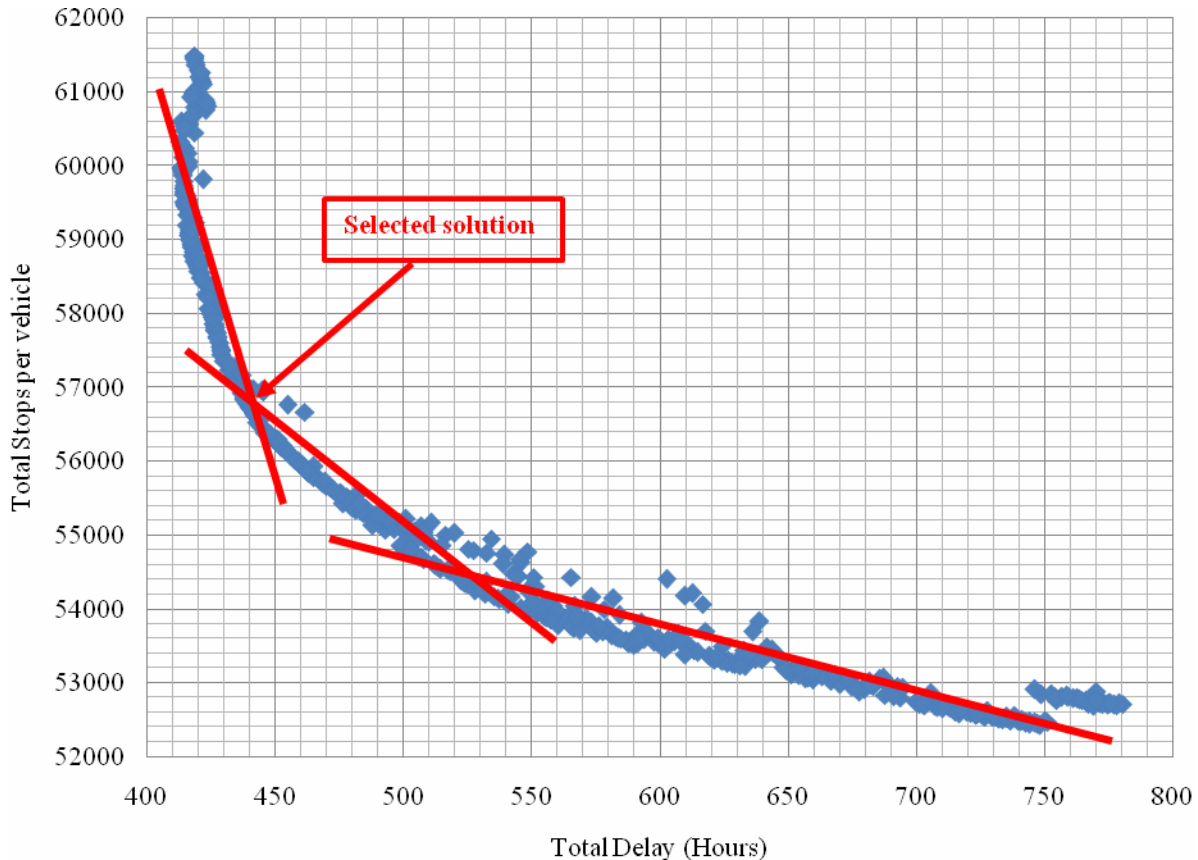


Figure 11. Results of the multi-objective genetic algorithm optimization and the selected solution.

As described previously, VDOT requested adding the developed plans to the current TOD plans. However, current TOD plans were modified to make their cycle lengths a factor of the 900 seconds proposed for use in traffic responsive control. This modification increased the cycle length to the four cycle lengths indicated previously. The timing plans were modified by allowing SYNCHRO²⁹ to redistribute the green splits using the pre-determined cycle length. One of the modified TOD plans (with cycle length of 150 seconds) was found to be almost identical to one of the four plans obtained from the multi-objective optimization. Table 10 shows the four plans obtained from the multi-objective genetic algorithm optimization and the five modified TOD plans. It is clear from Table 14 that the fourth new plan is the same as the second modified TOD plan.

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 the pattern-matching mechanism in 170 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 to 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 and 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 times 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. The last two variables are the counts and occupancies for each system detector associated with different timing plans. The rationale for 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 timing plan. The least distance would indicate the timing plan that matches the existing pattern—hence the pattern-matching nomenclature.

Eleven system detectors were used in the Reston Parkway network. The locations of these system detectors are shown in Figure 12. 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. The detectors shown in red are those used by the traffic responsive control, while the ones in white are the ones that were not used, as is discussed here.

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 14. Proposed four timing plans and modified time of day plans.

Scheme #	New				Modified TOD				
	1	2	3	4	5	6	7	8	9
Intersection No. 1									
Cycle (sec.)	100	90	90	150	180	150	180	150	150
Offset (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
Offset (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
Offset (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
Offset (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
Offset (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
Offset (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. 8									
Cycle (sec.)	100	90	90	150	180	150	180	150	150
Offset (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
Offset (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
Offset (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
Offset (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
Offset (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
Offset (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. 7									
Cycle (sec.)	100	90	90	150	180	150	180	150	150
Offset (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

Intersection No. 14									
Cycle (sec.)	100	90	90	150	180	150	180	150	150
Offset (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

A special evolutionary code using genetic algorithm and supervised discriminant analysis was used to determine the required pattern-matching parameters. This code has the formula by which 170 controllers implement traffic responsive control 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 patterns based on CORSIM results, which consider oversaturation for different links.

Different K factors, ranging from 0 to 100, were input to the evolutionary code one at a time so that the Pareto front for each K was obtained. Delay, stops, and classification error corresponding to the optimum solutions of different K factors were determined and plotted versus the K factor in order to determine the optimum K factor to be used. Figure 13 through Figure 15 present the optimum values for delay, stops, and classification error, respectively, for different K factors.

It was observed that the classification error improved with increasing K factor. For K factor equal to zero (i.e., neglecting system detector occupancies), the classification error was highest, which means that including occupancies improves pattern recognition. Moreover, for K factors more than 50 percent, stops did not affect the selection as it became almost constant with negligible variation.

It was also clear that for small K factors (up to 50 percent), the stops and classification error were very high. Therefore, K factors less than 50 percent were not considered optimum. From these figures and the previous discussion, a K factor of 90 percent was selected to be the optimum K as it corresponded to the minimum delay and minimum classification error (with the same number of stops).

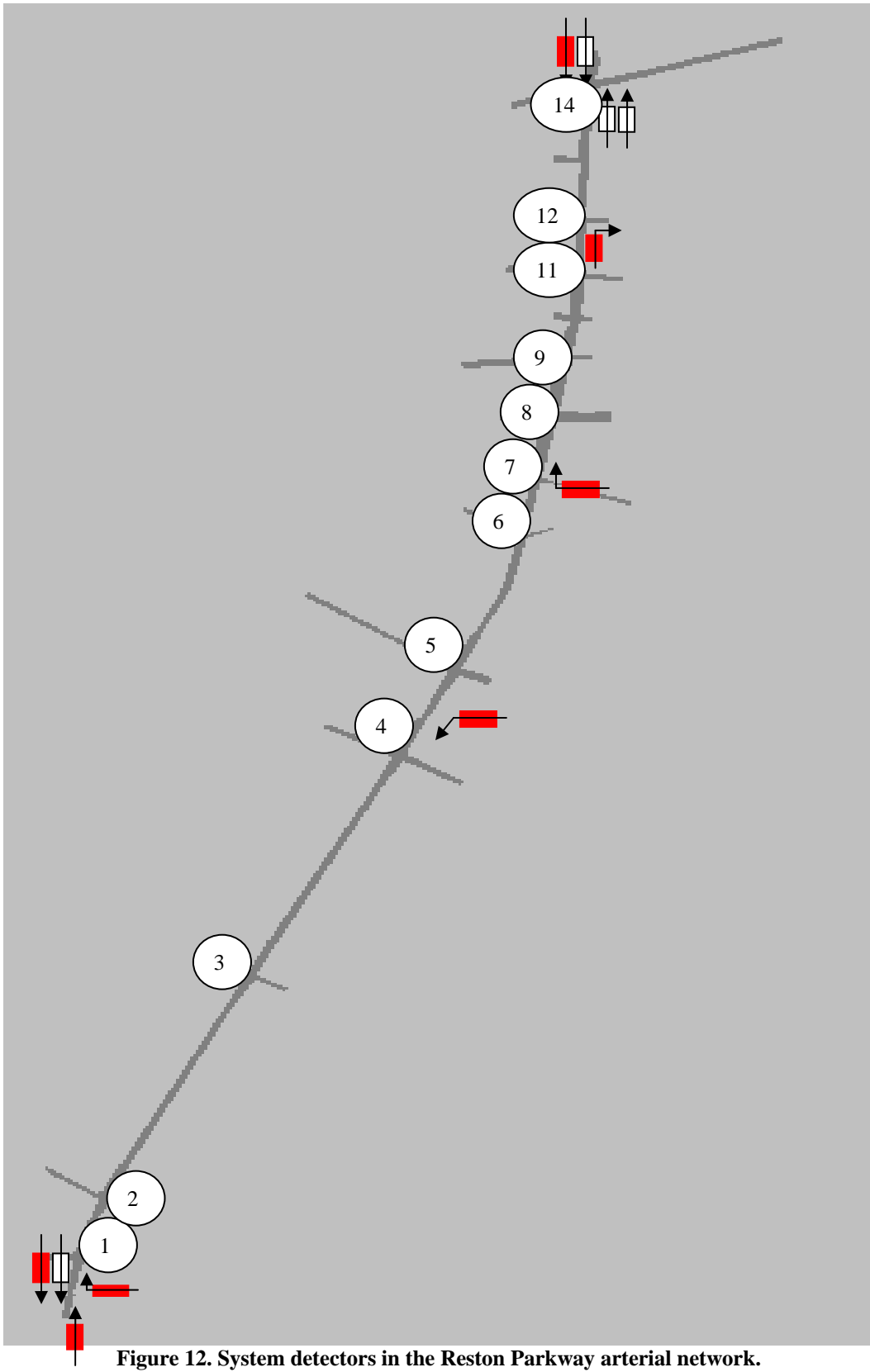


Figure 12. System detectors in the Reston Parkway arterial network.

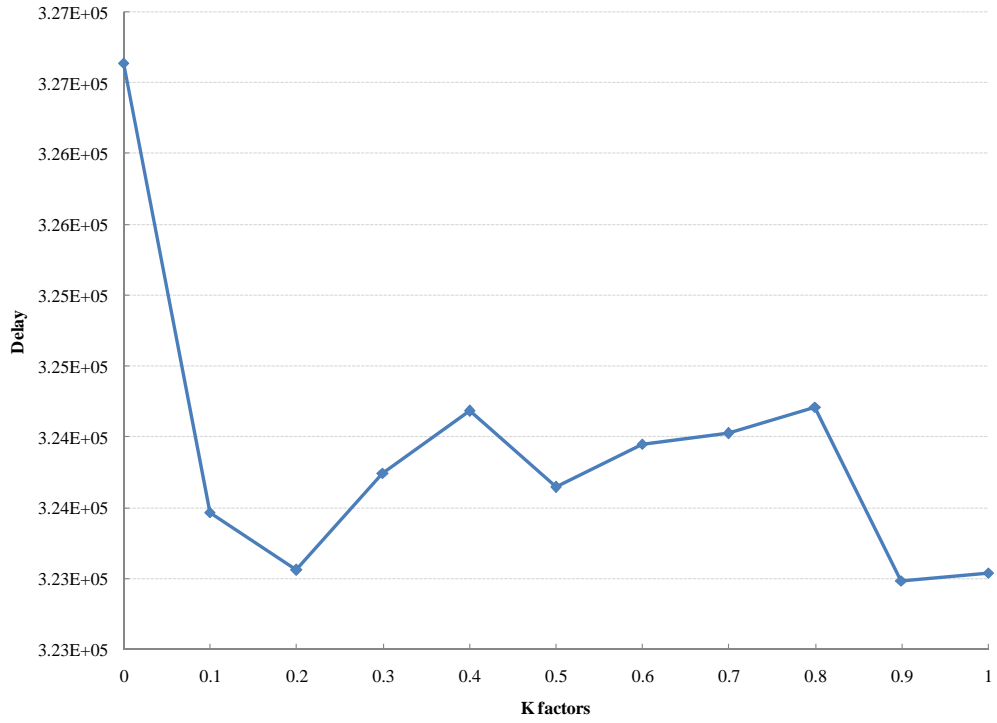


Figure 13. Optimum delay values for different K factors.

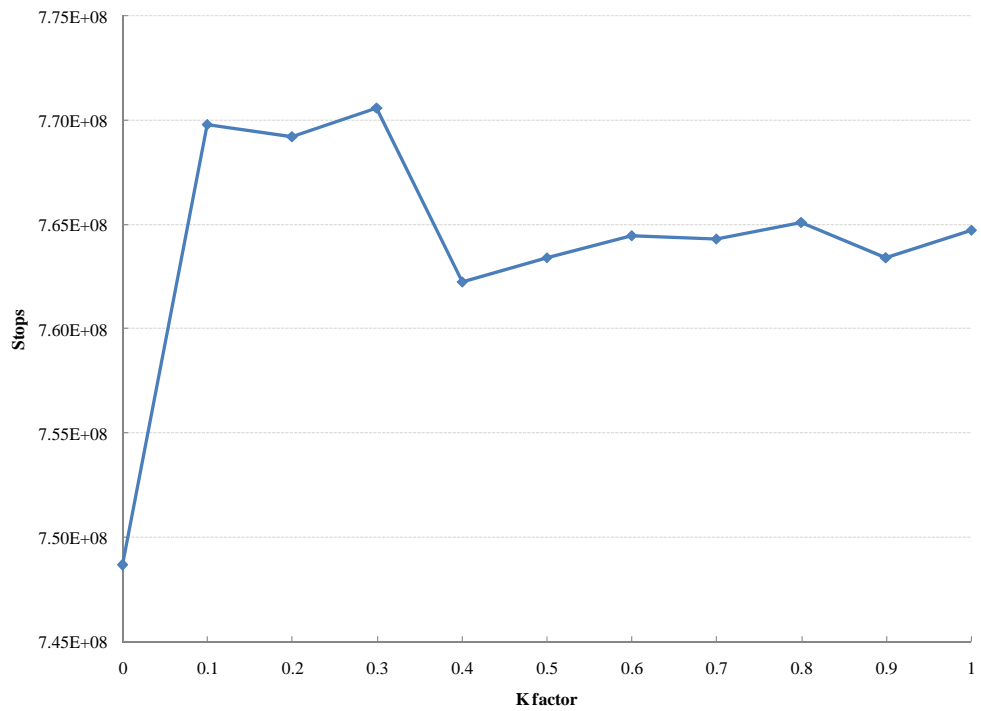


Figure 14. Optimum stop values for different K factors.

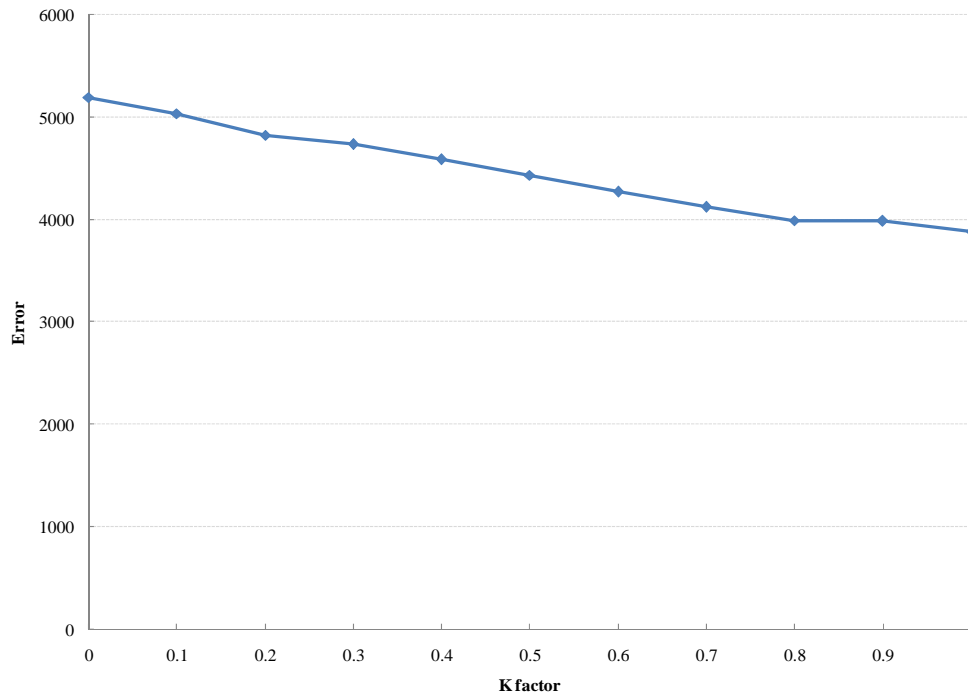


Figure 15. Optimum classification error values for different K factors.

Figure 16 through Figure 19 show the Pareto front for the K factor of 90 and the selected optimum solution for this K factor.

It can be observed 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 delay, stops, and classification error are plotted to show the improvement in results. Figure 20 through Figure 22 show that the number of generations used in the run is enough to achieve the required stability in the results. This means that the obtained optimum solution cannot be improved any further.

Table 15 shows the system detector weighting factors determined using the GA code, for K = 90 percent. It should be noted that detectors 2, 4, 5, and 7 have weighting factors of zero, which means they should not be considered in pattern recognition because their data do not improve the recognition process.

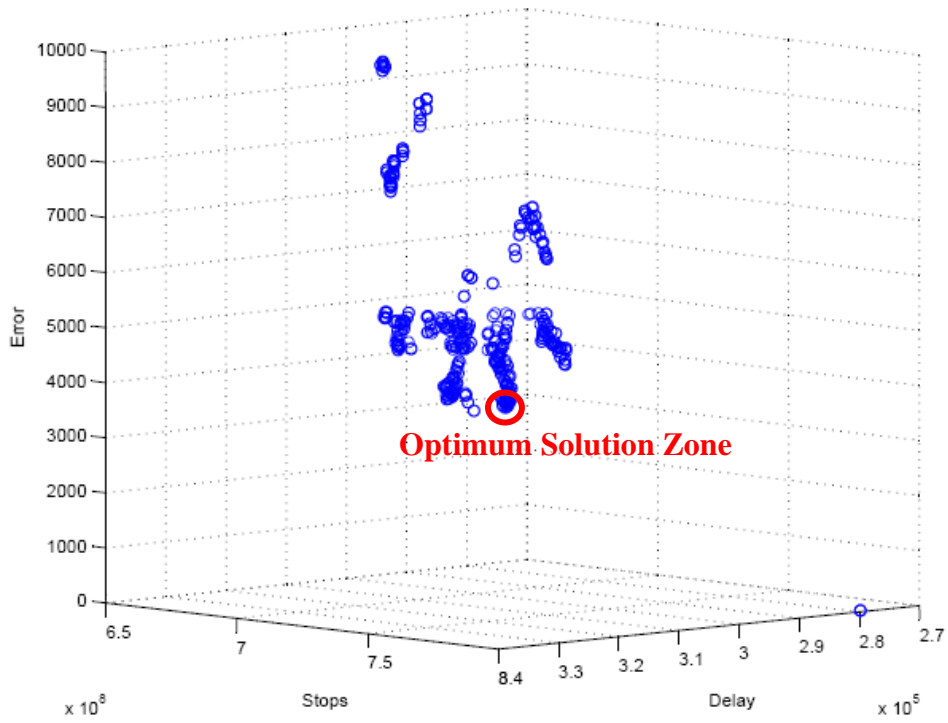


Figure 16. Pareto front for 170 controller's evolutionary code ($K = 90\%$).

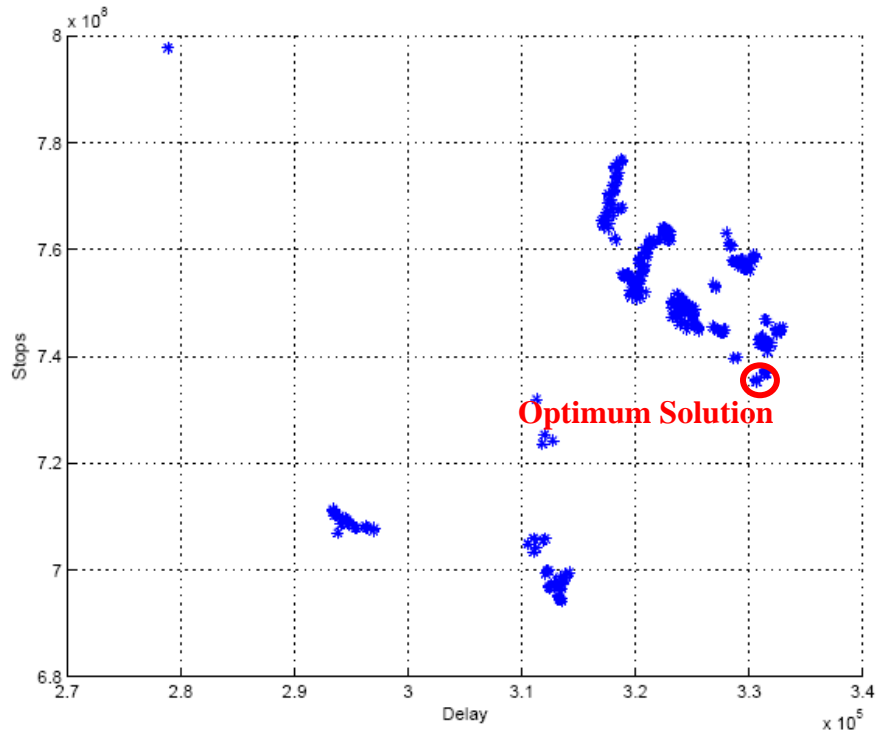


Figure 17. Delay-stops plan ($K = 90\%$).

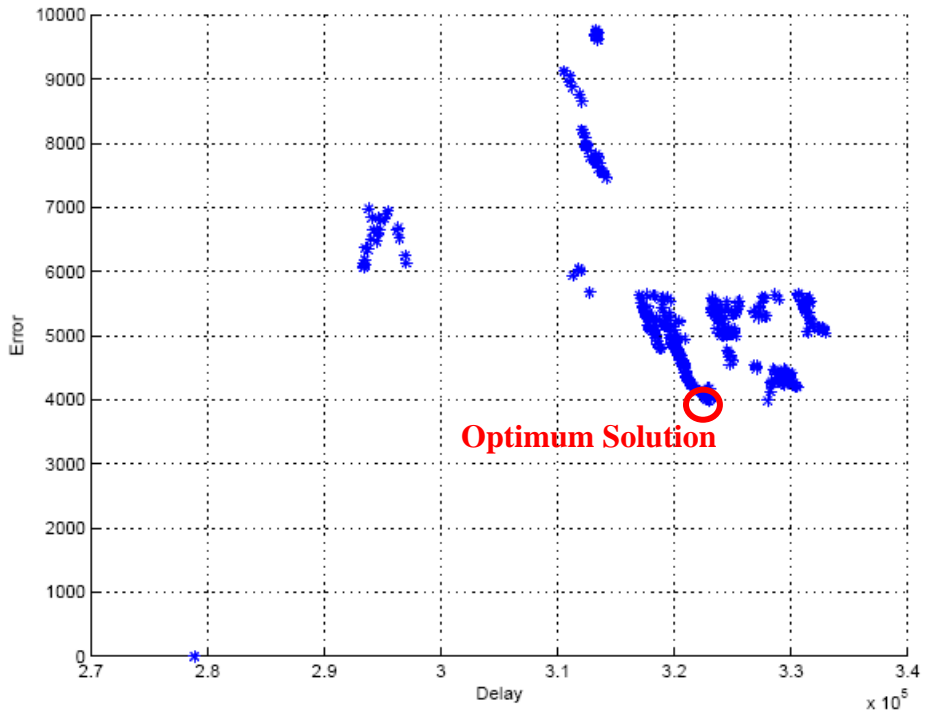


Figure 18. Delay-error plan (K = 90%).

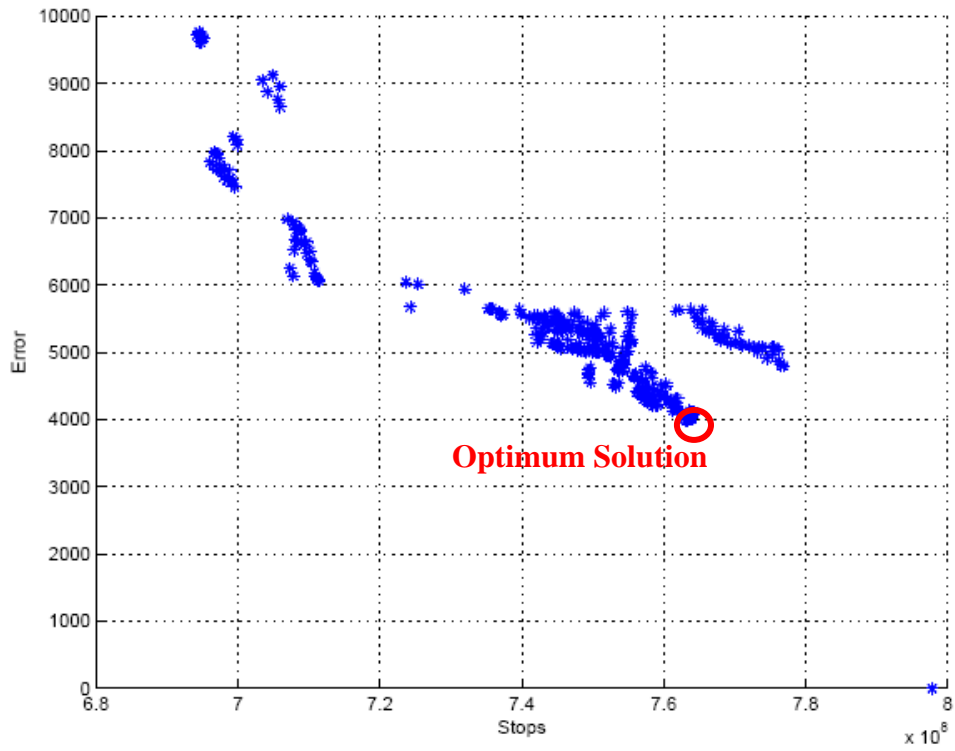


Figure 19. Stops-error plan (K = 90%).

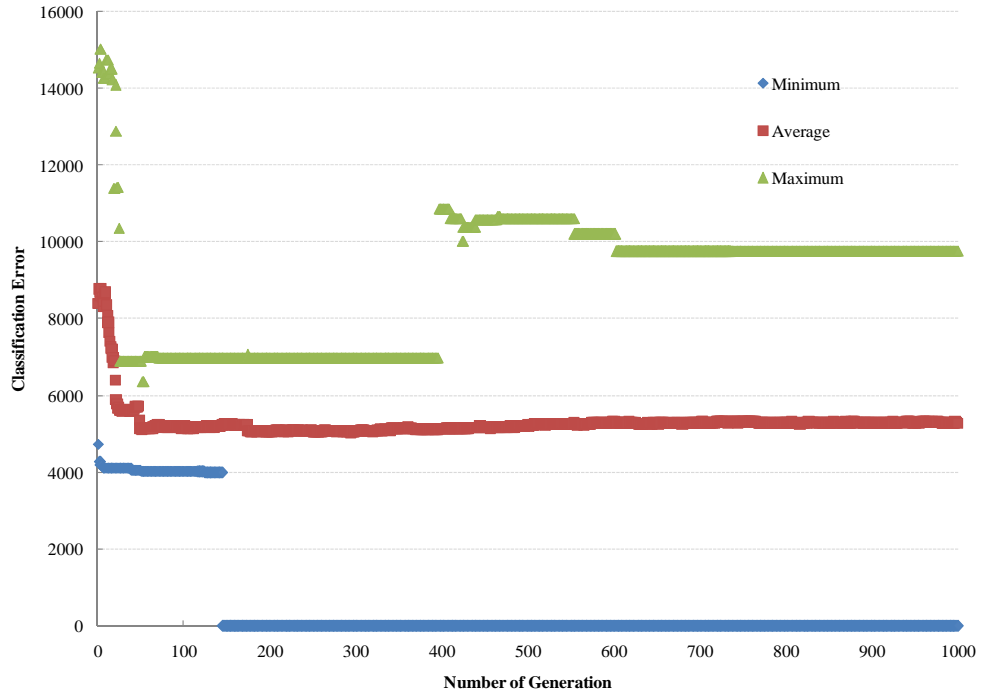


Figure 20. Range for the classification error (K = 90%).

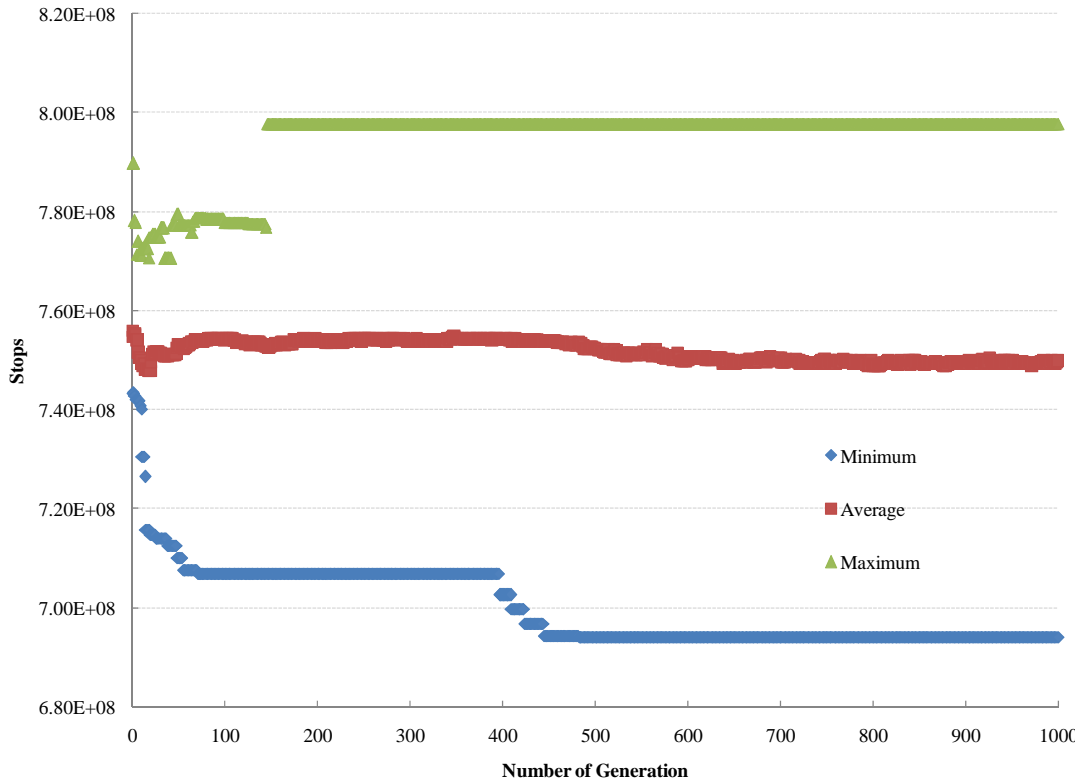


Figure 21. Range for stops (K = 90%).

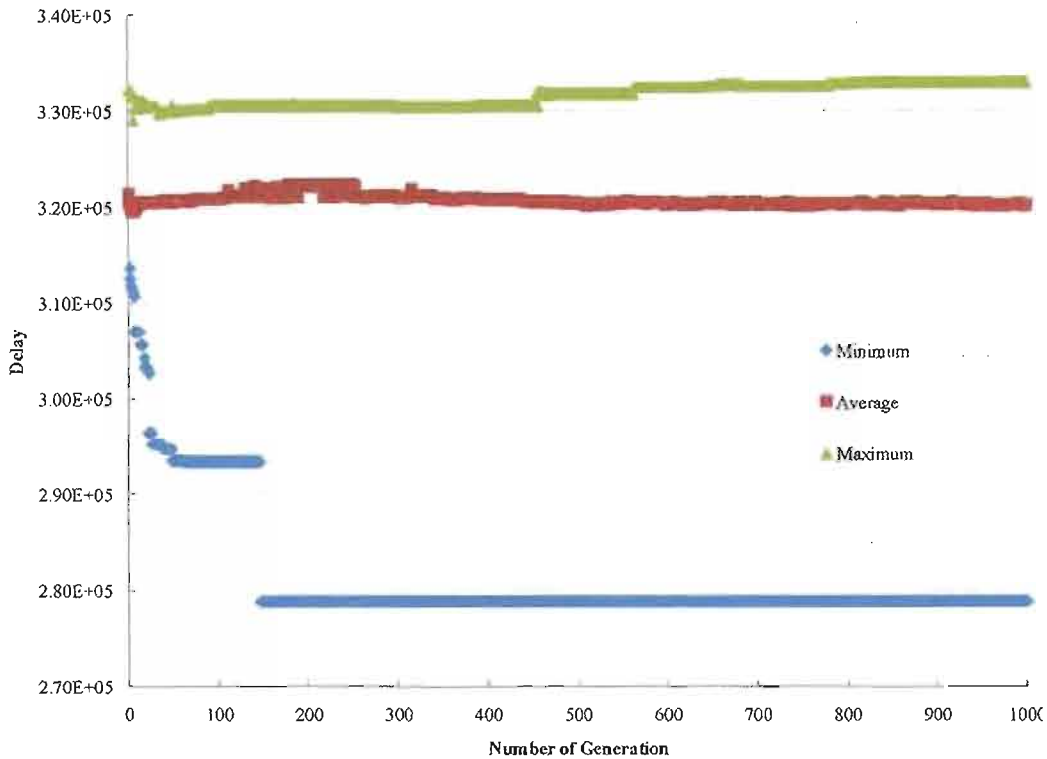


Figure 22. Range for delay (K = 90%).

Table 15. 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 previously, the evolutionary code reassigns timing plans to different traffic scenarios based on oversaturation results from CORSIM. For the selected optimum solution at K = 90 percent, it was found that timing plan number 8, one of the VDOT modified plans, was not included in the new assignment. This means that this plan was no longer needed for the proposed traffic responsive system due to its similarity to some of the other selected plans.

Table 16 and Table 17 present counts and occupancies, respectively, for each active system detector with each selected timing plan.

Table 16. Counts for active system detector associated 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 17. Occupancies for active system detector associated 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

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 weekday and one weekend day to confirm that the system worked as it should and to determine the effect of implemented traffic responsive control in the Reston Parkway before the actual implementation of the proposed system.

Wednesday, April 9, 2008, and Saturday, April 5, 2008, were selected as examples of 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.³⁰ Vehicle actuated program (VAP) script was used to simulate the 170 controllers in VISSIM runs.³¹ One VAP file was generated for each controller.³²

Using the obtained values for traffic responsive variables and actual traffic scenarios for the selected days, timing plans implemented during the whole day were determined. Figure 23 and Figure 24 show the traffic responsive timing plan versus TOD plan for the selected weekend and weekday, respectively. In these figures, timing plan number 10 refers to the free control mode. These simulation runs showed stable performance and smooth transitioning. The performance measures associated with these plans are shown in the Results section.

RESULTS

Table 18 and Table 19 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 weekday, 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.

The results of the simulation show 62.45 seconds/vehicle average delay and 1.73 stops/vehicle average number of stops for the TOD control in weekend (i.e., April 5, 2008). 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, representing expected savings of about 26.94 percent in delay and 14.45 percent in number of stops.

For the weekday April 9, 2008, it was found that, using TOD control mode, the average delay was 150.42 seconds/vehicle and the average number of stops was 2.84 stops/vehicle. 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 percent savings on delay and 21.13 percent savings in stops are expected.

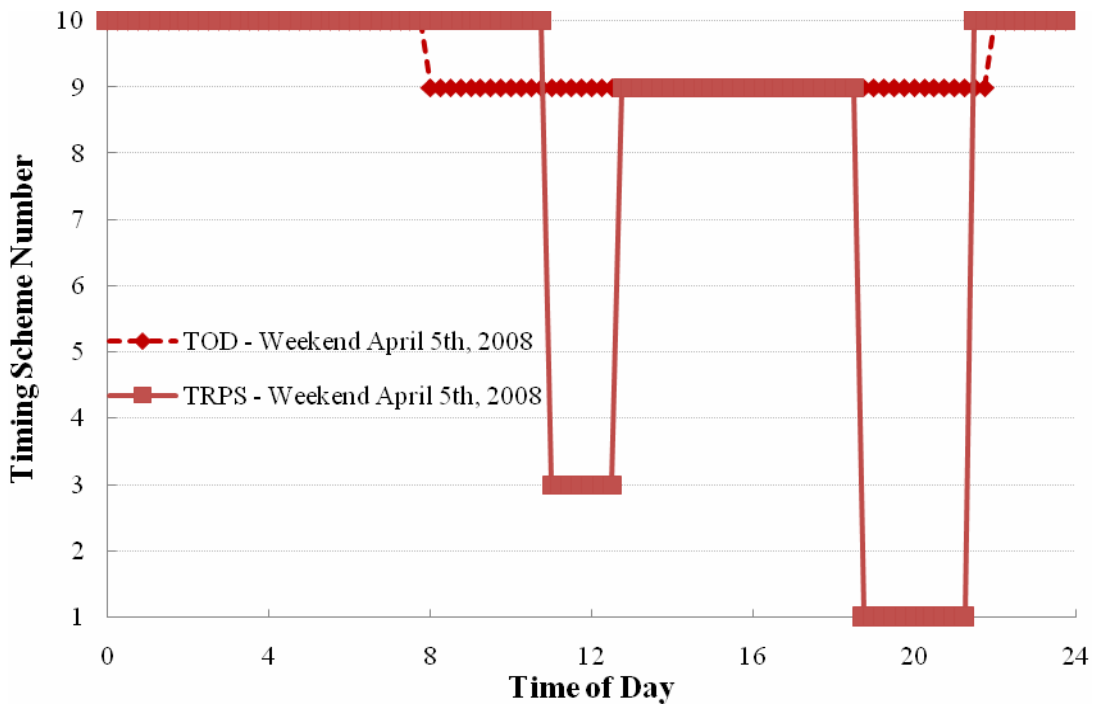


Figure 23. Timing plans for traffic responsive control versus TOD for weekend.

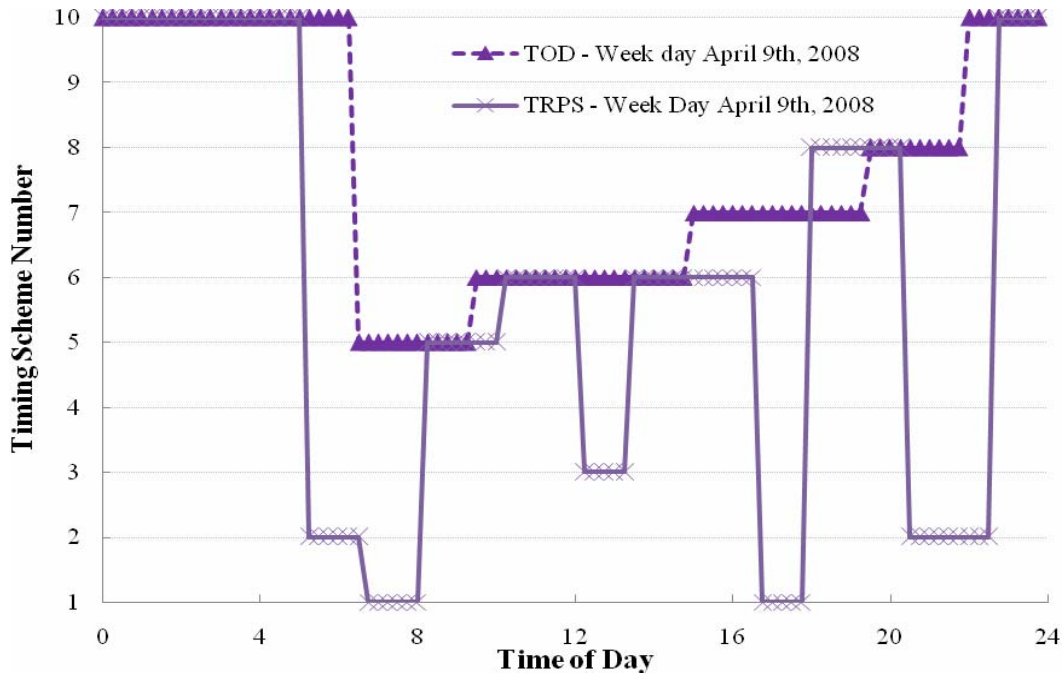


Figure 24. Timing plans for traffic responsive control versus TOD for weekday.

Tables 20 through 23 show the travel time, delay, and total stops by hour of day for each traffic bound. The table lists all the MOEs for TRPS and TOD operation. Figures 25 through 28 show the detailed comparison trends between the TRPS and the TOD Measures of Effectiveness (MOEs) for each of the north, south, east, and west bounds from 6:00 a.m. to 10 p.m. on a weekday.

Figure 25, for instance, shows that the travel time on the north bound (NB) under TRPS mode is comparable to the TOD mode during the day, until 6 p.m. At that time, the TRPS switches to plan 8 one hour earlier than the TOD, as can be seen in Figure 24. This action results in a 75 percent reduction in travel time and 86 percent reduction in the number of stopped vehicles at 7:00 p.m. Figure 26 shows that the travel time on the SB direction also reduces by 78 percent due to this earlier switching at 6:00 p.m.

Figures 25 and 26 (for NB and SB traffic) show significant reductions in the number of stopped vehicles under the TRPS operation. The figures show that the number of stopped vehicles is consistently low during the day, unlike the variation in the number of stopped vehicles under the TOD operation. This low MOE is due to the fact that the TRPS timing plans were chosen to reduce the number of stopped vehicles while minimizing the delay with the multi-objective optimization approach. It can also be observed in these two figures that the TRPS operation mode is superior to the TOD mode as far as the delay and travel times are concerned.

Figures 27 and 28 show the MOEs for the EB and WB traffic during the day. As with the previous figures, the TRPS mode is clearly superior to the TOD mode, with reduction in travel time ranging between 75% and 96%. The largest reduction in the MOEs for the side streets can be observed in the EB number of stopped vehicles during the peak periods.

Table 18. MOEs for selected weekend.

Intersection #	Movement		MOEs for TOD		MOEs for Traffic Responsive		Intersection #	Movement		MOEs for TOD		MOEs for Traffic Responsive		
	From	To	Average Delay (sec.)	Average Stops	Average Delay (sec.)	Average Stops		From	To	Average Delay (sec.)	Average Stops	Average Delay (sec.)	Average Stops	
1	North	South	10.60	1.05	6.95	0.26	8	North	South	13.00	4.27	7.78	2.66	
	North	West	7.10	0.72	0.76	0.00		North	West	8.28	2.66	3.40	1.12	
	North	East	7.80	0.31	3.92	0.30		North	East	30.19	8.66	24.29	7.21	
	South	North	6.90	0.68	1.60	0.22		South	North	41.27	11.68	34.88	10.55	
	South	West	11.00	1.22	2.07	0.47		South	West	8.13	9.91	5.66	8.55	
	South	East	7.00	0.65	0.00	0.00		South	East	7.82	9.15	5.82	8.36	
	West	South	4.20	0.40	0.95	0.21		West	South	12.32	5.07	5.28	3.82	
	West	North	11.40	1.48	7.85	0.83		West	North	22.93	0.83	18.03	0.52	
	West	East	13.60	1.46	5.75	0.58		West	East	9.49	8.99	6.22	8.32	
	East	South	9.80	0.59	2.93	0.50		East	South	23.20	14.91	19.02	14.06	
	East	North	5.60	0.55	2.52	0.15		East	North	32.52	11.33	30.38	10.65	
	East	West	8.00	0.61	3.30	0.60		East	West	9.64	7.04	3.23	5.86	
2	North	South	19.10	1.15	14.90	0.54	9	North	South	18.80	16.11	13.11	14.67	
	North	West	6.40	0.04	0.32	0.00		North	West	34.28	15.95	30.64	14.60	
	North	East	11.30	0.58	4.43	0.41		North	East	25.95	8.45	19.60	7.15	
	South	North	11.90	0.86	6.83	0.32		South	North	5.20	7.77	0.12	6.86	
	South	West	8.50	1.09	2.69	0.37		South	West	40.46	10.23	34.10	9.46	
	South	East	5.40	0.11	0.35	0.00		South	East	18.39	10.05	12.12	9.22	
	West	South	11.00	0.93	1.66	0.34		West	South	8.19	4.71	0.90	2.94	
	West	North	63.40	1.03	57.04	0.84		West	North	21.59	7.85	19.20	6.78	
	West	East	72.80	1.84	64.71	0.91		West	East	12.44	4.39	7.63	3.50	
	East	South	58.10	1.39	51.28	0.92		East	South	26.61	3.05	24.11	1.82	
	East	North	5.60	1.08	0.97	0.18		East	North	31.02	13.08	24.52	12.15	
	East	West	47.60	1.04	45.15	0.93		East	West	39.36	6.83	33.56	5.67	
3	North	South	20.50	3.55	15.80	0.57	10	North	South	9.47	14.46	1.64	13.94	
	North	West	14.30	1.18	6.41	0.46		North	West	38.94	13.12	32.91	12.24	
	North	East	11.90	0.14	3.25	0.00		South	North	6.25	9.90	1.55	9.22	
	South	North	18.00	1.12	13.20	0.51		South	East	24.74	12.19	19.52	11.41	
	South	West	18.60	1.82	12.59	0.84		West	North	25.42	12.53	20.97	11.63	
	South	East	4.40	0.26	0.42	0.00		East	South	13.68	3.15	6.89	2.87	
	West	South	6.40	0.70	1.72	0.26		11	North	South	19.96	13.50	16.86	12.86
	West	North	28.00	1.33	25.84	0.84		North	West	5.33	1.12	2.40	0.01	
	West	East	34.50	2.14	27.74	1.26		North	East	18.43	2.00	12.50	1.50	
	East	South	29.50	1.52	22.46	0.75		South	North	10.27	0.38	2.71	0.06	
	East	North	8.20	0.59	1.86	0.18		South	West	40.94	0.87	34.87	0.13	
	East	West	37.90	1.92	34.70	0.95		South	East	19.61	15.14	12.40	13.51	
4	North	South	25.60	1.13	20.11	0.77	12	West	South	21.12	2.76	17.69	1.59	
	North	West	16.40	0.81	12.75	0.64		West	North	10.65	4.48	3.85	3.15	
	North	East	2.50	0.36	0.43	0.00		West	East	15.21	11.21	12.35	10.49	
	South	North	23.80	0.80	16.81	0.55		East	South	23.21	9.16	20.54	7.30	
	South	West	28.20	1.43	19.55	0.93		East	North	23.14	11.70	18.82	11.27	
	South	East	6.40	0.56	0.35	0.00		East	West	30.29	3.58	28.03	1.99	
	West	South	6.70	0.89	3.44	0.19		North	South	37.06	9.10	29.30	8.17	
	West	North	31.40	1.51	28.18	0.86		North	West	19.74	5.23	17.09	3.78	
	West	East	34.45	1.32	30.22	1.07		North	East	36.38	1.51	30.65	0.67	
	East	South	54.40	2.06	48.50	1.14		South	North	38.38	8.97	32.80	8.60	
	East	North	13.60	0.43	5.57	0.22		South	West	15.52	15.22	13.45	13.92	
	East	West	54.60	1.61	47.92	1.13		South	East	21.15	3.66	16.14	2.47	
5	North	South	52.00	1.68	43.35	1.67	13	West	South	24.27	10.88	20.12	9.70	
	North	West	13.40	1.03	8.92	0.51		West	North	38.02	16.10	34.63	14.17	
	North	East	3.70	0.52	0.65	0.00		West	East	22.56	5.93	17.98	4.66	
	South	North	25.00	1.16	18.18	0.91		East	South	10.98	2.00	7.72	0.89	
	South	West	7.90	0.43	4.51	0.42		East	North	27.85	13.69	20.89	12.67	
	South	East	2.00	0.24	0.00	0.00		East	West	3.07	3.38	0.02	2.79	
	West	South	26.00	1.05	17.58	0.45		North	South	15.32	13.68	13.08	12.61	
	West	North	42.80	1.84	37.79	0.84		North	East	26.54	13.14	19.13	11.93	
	West	East	42.10	1.77	36.02	0.83		South	North	7.57	5.36	4.63	4.26	
	East	South	20.80	16.95	15.40	16.80		South	East	18.05	12.63	10.20	10.95	
	East	North	8.30	1.14	1.89	0.21		East	South	31.28	14.14	23.45	13.23	
	East	West	29.80	27.40	25.34	26.80		East	North	34.53	4.85	28.00	4.58	
6	North	South	34.44	10.97	26.99	10.91	14	North	South	36.20	15.51	32.14	14.66	
	North	West	34.51	0.92	27.64	0.82		North	West	4.63	6.80	1.05	5.64	
	South	North	16.77	4.29	14.60	4.05		North	East	17.04	3.49	10.71	2.65	
	South	West	19.17	12.74	13.93	11.79		South	North	28.52	10.48	24.46	9.84	
	East	South	16.46	11.01	10.63	10.51		South	West	30.51	5.66	23.93	3.83	
	East	North	34.27	14.42	29.66	14.17		South	East	13.60	4.58	6.76	3.70	
7	North	South	17.12	7.91	13.14	7.53	15	West	South	35.11	9.38	28.28	8.33	
	North	East	18.51	10.42	9.68	10.32		West	North	28.82	4.19	24.18	2.76	
	South	North	37.52	0.45	31.63	0.09		West	East	35.81	10.67	33.10	9.28	
	South	East	17.62	10.79	14.13	10.28		East	South	42.49	10.62	35.49	9.24	
West	South	39.03	8.10	31.71	7.92	East	North	21.08	0.41	14.46	0.32			

Table 19. MOEs for selected weekday.

Intersection #	Movement		MOEs for TOD		MOEs for Traffic Responsive		Intersection #	Movement		MOEs for TOD		MOEs for Traffic Responsive			
	From	To	Average Delay (sec.)	Average Stops	Average Delay (sec.)	Average Stops		From	To	Average Delay (sec.)	Average Stops	Average Delay (sec.)	Average Stops		
1	North	South	47.91	4.17	40.76	0.41	8	North	South	13.36	7.90	8.09	3.58		
	North	West	19.14	4.80	12.31	0.23		North	West	51.59	7.28	46.71	1.63		
	North	East	34.30	3.45	26.38	1.20		North	East	20.56	12.85	16.30	8.88		
	South	North	51.92	5.13	42.62	0.29		South	North	31.84	14.79	24.95	11.24		
	South	West	40.07	4.45	36.04	1.08		South	West	21.02	15.28	16.35	9.23		
	South	East	17.30	3.50	8.49	0.08		South	East	29.02	11.58	23.47	8.11		
	West	South	50.49	6.11	43.28	0.33		West	South	46.28	6.63	37.29	4.61		
	West	North	29.42	5.16	22.68	1.21		West	North	28.07	4.10	23.14	0.76		
	West	East	51.28	6.55	47.23	1.54		West	East	53.78	14.50	45.32	8.61		
	East	South	15.38	3.57	8.79	0.78		East	South	45.22	16.21	38.06	15.03		
	East	North	51.60	5.30	46.11	0.45		East	North	10.94	14.12	7.24	11.29		
	East	West	20.41	5.20	10.18	1.55		East	West	41.36	10.21	37.45	6.55		
	2	North	South	26.64	3.78	21.32		1.51	9	North	South	27.36	16.93	19.84	15.36
		North	West	46.16	2.20	40.76		0.91		North	West	19.50	20.32	14.38	14.36
		North	East	25.12	6.02	23.36		0.45		North	East	19.16	14.14	14.90	7.82
		South	North	28.67	7.95	23.20		1.08		South	North	19.65	13.71	13.83	6.44
South		West	53.97	4.83	44.46	1.31	South	West		16.28	15.24	13.96	8.92		
South		East	39.14	4.55	35.41	0.00	South	East		40.63	16.48	31.57	9.95		
West		South	22.44	6.19	16.25	0.39	West	South		53.50	7.95	45.23	3.21		
West		North	34.06	6.83	23.72	0.92	West	North		44.67	12.41	37.43	7.85		
West		East	28.65	7.88	21.98	1.47	West	East		14.39	10.06	6.94	3.99		
East		South	19.34	4.41	15.17	1.60	East	South		39.91	4.66	32.60	2.47		
East		North	50.57	4.79	41.98	0.42	East	North		34.55	17.11	28.36	11.65		
East		West	32.81	7.83	27.15	1.46	East	West		32.36	9.88	24.04	5.74		
3		North	South	19.88	2.82	17.24	1.35	10		North	South	19.08	17.58	11.21	13.57
		North	West	45.48	3.64	40.79	1.35			North	West	51.55	19.56	45.30	13.35
		North	East	16.12	6.90	10.51	0.39			South	North	37.73	13.08	31.59	9.02
		South	North	25.23	6.96	21.81	1.39			South	East	33.55	17.56	29.99	12.28
	South	West	21.20	2.83	16.93	1.29	West		North	47.85	16.43	41.17	11.33		
	South	East	36.43	2.16	31.83	0.50	East		South	53.09	8.24	46.48	2.96		
	West	South	16.82	2.54	11.06	0.86	11		North	South	9.77	17.57	4.55	13.48	
	West	North	26.42	2.31	23.92	1.13			North	West	37.51	6.24	34.12	0.34	
	West	East	48.75	7.63	38.32	1.70			North	East	17.57	8.22	11.67	0.95	
	East	South	49.75	6.15	40.82	1.00			South	North	21.94	7.57	18.71	1.02	
	East	North	19.43	5.11	14.48	0.90			South	West	43.66	5.97	38.74	0.06	
	East	West	15.96	5.48	11.94	1.02			South	East	48.40	17.80	42.77	14.41	
	4	North	South	31.65	6.34	25.04			1.70	West	South	18.70	3.70	15.04	1.66
		North	West	42.90	4.76	39.61			0.93	West	North	23.23	5.30	19.35	3.46
		North	East	27.65	2.44	19.86			0.22	West	East	13.51	15.55	6.59	11.49
		South	North	13.28	6.60	9.03			0.70	East	South	15.98	14.45	13.53	8.59
South		West	43.27	8.33	35.78	1.46		East	North	44.39	14.50	41.82	11.61		
South		East	28.00	2.66	26.78	0.22		East	West	31.66	5.36	22.99	1.96		
West		South	46.53	7.50	39.49	0.82		12	North	South	35.11	12.72	28.50	9.13	
West		North	20.53	7.28	11.52	1.21			North	West	33.47	9.93	28.90	4.54	
West		East	24.22	4.50	17.33	1.39			North	East	37.79	4.69	32.79	0.68	
East		South	43.59	3.70	35.88	1.45			South	North	47.17	12.20	37.55	8.51	
East		North	11.14	3.37	7.46	0.56	South		West	33.31	19.22	28.59	14.96		
East		West	43.06	7.55	34.94	1.94	South		East	48.16	9.96	44.79	2.27		
5		North	South	54.33	9.13	47.42	2.36		West	South	30.58	16.94	22.77	10.05	
		North	West	28.32	3.80	21.63	0.74		West	North	21.90	22.10	13.07	14.87	
		North	East	30.72	1.91	25.90	0.58		West	East	22.99	12.06	18.84	5.27	
		South	North	53.83	6.43	46.50	1.76		East	South	32.26	8.38	26.59	1.19	
	South	West	48.30	2.37	40.57	1.36	East		North	16.62	19.11	10.82	12.68		
	South	East	42.28	1.62	35.92	0.39	East		West	28.08	4.72	20.65	3.18		
	West	South	35.89	3.97	30.00	0.57	13		North	South	14.56	15.49	9.73	12.99	
	West	North	22.41	2.93	19.05	1.70			North	East	21.17	16.21	17.30	12.65	
	West	East	53.61	7.30	47.95	0.90			South	North	39.36	11.32	31.88	3.60	
	East	South	12.46	21.38	10.14	16.93			South	East	43.40	18.24	39.42	11.46	
	East	North	54.73	5.09	49.34	0.55		East	South	47.37	18.46	45.32	12.74		
	East	West	19.95	32.22	14.71	27.19		East	North	39.05	12.54	34.46	4.95		
	6	North	South	47.40	13.73	38.88		11.78	14	North	South	51.65	19.18	43.03	15.56
		North	West	25.87	4.68	18.02		1.82		North	West	17.29	7.69	14.96	6.03
		South	North	27.88	7.00	21.37		4.83		North	East	31.43	7.10	24.64	3.53
		South	West	33.27	15.56	23.72		12.35		South	North	35.88	16.30	30.77	9.83
East		South	37.60	17.37	27.27	11.27		South		West	22.94	7.63	15.86	4.86	
East		North	41.96	17.11	38.00	15.08		South		East	30.47	10.71	21.38	3.84	
7		North	South	46.31	12.69	41.65		7.71		West	South	54.06	13.56	48.86	8.71
		North	East	27.73	15.65	22.93		10.84		West	North	29.84	4.89	26.09	2.88
		South	North	24.81	2.99	22.74		0.76		West	East	29.67	14.80	19.74	9.59
		South	East	29.94	17.83	25.16		11.10		East	South	30.06	15.49	23.84	9.32
		West	South	26.75	15.37	22.10	8.62	East		North	42.20	7.50	33.41	0.88	

Table 20. North Bound Traffic MOEs by Hour of Day.

Time	Week Day						Week End					
	Travel Time (secs)		Delay (secs/veh)		Total Stops		Travel Time (secs)		Delay (secs/veh)		Total Stops	
	TRPS	TOD	TRPS	TOD	TRPS	TOD	TRPS	TOD	TRPS	TOD	TRPS	TOD
6:00 AM	398.2	405.2	93.4	126.5	55.0	43.0	376.4	376.4	75.1	75.1	4.0	4.0
7:00 AM	414.6	445.9	118.6	120.0	119.0	5155.0	337.7	457.7	50.9	98.4	1.0	12.0
8:00 AM	441.5	495.2	144.2	161.4	237.0	9515.0	385.4	483.6	78.2	136.1	36.0	38.0
9:00 AM	418.6	528.6	118.7	135.7	148.0	251.0	431.1	563.9	130.5	135.7	68.0	48.0
10:00 AM	420.6	406.1	122.4	135.6	55.0	2302.0	415.9	551.5	117.5	97.9	88.0	261.0
11:00 AM	482.8	452.3	177.7	200.3	81.0	2802.0	445.3	645.6	143.5	151.7	59.0	9.0
12:00 PM	482.9	431.2	176.4	223.2	117.0	80.0	392.8	616.0	93.9	223.2	54.0	184.0
1:00 PM	519.5	446.6	150.2	183.3	90.0	125.0	422.3	605.6	150.2	183.3	85.0	78.0
2:00 PM	479.0	427.9	170.3	183.5	24.0	918.0	384.7	568.2	81.7	129.7	57.0	145.0
3:00 PM	479.6	427.1	180.9	180.3	131.0	4870.0	471.8	652.1	168.7	119.7	122.0	109.0
4:00 PM	405.8	458.7	105.1	250.3	80.0	692.0	421.6	671.9	122.3	157.7	90.0	79.0
5:00 PM	468.5	476.7	169.7	235.9	157.0	1037.0	398.5	634.4	99.8	143.7	89.0	5.0
6:00 PM	434.3	457.8	135.0	180.3	44.0	2708.0	385.9	566.2	85.9	0.0	31.0	54.0
7:00 PM	887.3	3582.2	586.2	620.4	206.0	1496.0	426.8	1047.2	121.0	0.0	39.0	125.0
8:00 PM	464.3	0.0	162.6	180.3	91.0	3963.0	446.7	627.0	146.5	0.0	24.0	44.0
9:00 PM	480.5	480.5	0.0	0.0	65.0	65.0	381.0	381.0	0.0	0.0	1.0	1.0
10:00 PM	0.0	0.0	0.0	0.0	1.0	1.0	435.9	435.9	0.0	0.0	1.0	1.0

Table 21. South Bound Traffic MOEs by Hour of Day.

Time	Week Day						Week End					
	Travel Time (secs)		Delay (secs/veh)		Total Stops		Travel Time (secs)		Delay (secs/veh)		Total Stops	
	TRPS	TOD	TRPS	TOD	TRPS	TOD	TRPS	TOD	TRPS	TOD	TRPS	TOD
6:00 AM	388.8	441.6	88.3	90.2	31.0	813.0	368.1	368.1	54.4	54.4	7.0	7.0
7:00 AM	454.5	430.7	156.2	180.3	171.0	9015.0	377.7	558.0	65.2	139.7	12.0	20.0
8:00 AM	447.1	483.5	149.0	168.8	327.0	261.0	402.4	515.8	98.2	168.8	34.0	54.0
9:00 AM	426.7	445.3	99.2	107.1	261.0	317.0	434.0	541.1	99.2	107.1	104.0	114.0
10:00 AM	451.9	420.8	153.5	190.3	127.0	6658.0	474.1	664.4	168.7	88.4	132.0	254.0
11:00 AM	606.3	451.3	301.0	305.8	206.0	7645.0	484.5	790.3	178.7	174.6	259.0	405.0
12:00 PM	735.3	431.9	430.9	500.0	359.0	1500.0	508.5	1008.5	208.4	196.7	145.0	385.0
1:00 PM	1150.1	462.8	847.3	923.4	571.0	2124.0	522.8	1446.2	221.8	160.6	147.0	123.0
2:00 PM	1484.0	472.1	1182.3	1268.9	1118.0	4442.0	541.7	1810.6	243.5	133.7	175.0	157.0
3:00 PM	897.8	533.3	599.8	605.3	630.0	2057.0	590.4	1195.7	284.6	341.0	348.0	624.0
4:00 PM	479.0	501.7	181.6	341.7	156.0	1637.0	571.0	912.7	273.5	279.0	248.0	798.0
5:00 PM	489.4	505.3	193.6	302.6	117.0	1089.0	484.7	787.3	182.8	191.8	101.0	501.0
6:00 PM	654.0	657.1	358.1	398.4	104.0	8760.0	417.4	815.8	118.0	0.0	66.0	328.0
7:00 PM	1603.2	0.0	1297.3	1405.3	858.0	3934.0	469.4	1874.7	168.2	0.0	101.0	271.0
8:00 PM	933.9	0.0	633.2	670.7	383.0	1274.0	518.2	1188.9	206.4	0.0	59.0	43.0
9:00 PM	517.7	517.7	0.0	0.0	39.0	39.0	471.2	471.2	0.0	0.0	1.0	1.0
10:00 PM	0.0	0.0	0.0	0.0	1.0	1.0	436.0	436.0	0.0	0.0	1.0	1.0

Table 22. East Bound Traffic MOEs by Hour of Day.

Time	Week Day						Week End					
	Travel Time (secs)		Delay (secs/veh)		Total Stops		Travel Time (secs)		Delay (secs/veh)		Total Stops	
	TRPS	TOD	TRPS	TOD	TRPS	TOD	TRPS	TOD	TRPS	TOD	TRPS	TOD
6:00 AM	58.1	84.8	27.6	117.5	44.9	621.0	29.3	29.3	3.0	3.0	4.6	4.6
7:00 AM	256.1	196.2	197.7	186.0	141.2	947.0	30.6	216.0	4.1	186.0	12.6	191.9
8:00 AM	169.1	202.1	118.0	124.7	230.7	1217.0	35.9	159.5	8.9	124.7	38.6	367.6
9:00 AM	153.8	176.1	114.1	128.3	224.6	912.0	41.3	169.2	15.0	128.3	78.9	621.1
10:00 AM	105.2	186.9	73.9	89.2	118.3	939.0	57.7	146.6	31.5	89.2	105.1	444.8
11:00 AM	67.5	156.0	33.6	125.0	141.5	1156.0	71.8	196.2	41.6	125.0	124.9	333.1
12:00 PM	75.2	147.5	37.5	158.0	203.7	4610.0	132.5	290.0	102.5	158.0	157.3	780.6
1:00 PM	70.0	152.4	34.7	119.0	152.9	828.0	107.9	226.6	78.1	119.0	141.4	446.6
2:00 PM	62.4	131.6	28.9	85.2	140.4	823.0	107.7	192.5	77.8	85.2	140.4	908.6
3:00 PM	121.2	166.7	90.3	144.6	174.8	1383.0	84.7	228.5	54.3	144.6	109.2	540.7
4:00 PM	145.2	180.5	109.6	191.3	225.2	1303.0	121.1	311.9	91.1	191.3	113.9	542.7
5:00 PM	191.5	194.4	153.7	196.8	271.4	1611.0	135.1	331.2	104.8	196.8	121.0	1091.1
6:00 PM	162.3	211.9	137.5	113.5	189.5	1219.0	125.0	237.3	94.1	113.5	120.2	629.2
7:00 PM	124.7	519.9	85.4	276.9	191.4	2839.0	88.5	365.1	58.4	276.9	99.1	575.2
8:00 PM	66.2	363.4	35.7	308.2	69.9	1748.0	56.1	352.6	30.2	308.2	56.2	489.7
9:00 PM	44.0	258.5	51.2	51.2	47.9	479.0	90.8	90.8	51.2	51.2	20.1	20.1
10:00 PM	21.7	21.7	1.2	1.2	2.9	29.0	38.0	38.0	1.2	1.2	0.9	0.9

Table 23. West Bound Traffic MOEs by Hour of Day.

Time	Week Day						Week End					
	Travel Time (secs)		Delay (secs/veh)		Total Stops		Travel Time (secs)		Delay (secs/veh)		Total Stops	
	TRPS	TOD	TRPS	TOD	TRPS	TOD	TRPS	TOD	TRPS	TOD	TRPS	TOD
6:00 AM	63.7	98.4	32.6	111.8	40.5	67.5	34.0	34.0	75.3	6.8	3.4	3.4
7:00 AM	123.3	191.0	89.7	188.8	165.7	181.3	43.1	231.9	104.0	188.8	11.0	331.9
8:00 AM	127.8	243.0	94.4	312.3	272.0	241.2	46.3	358.6	137.9	312.3	33.1	501.8
9:00 AM	126.9	181.7	93.5	108.2	180.2	171.3	55.6	163.8	237.5	108.2	64.5	895.6
10:00 AM	106.3	136.6	72.5	91.7	89.8	114.8	59.2	150.8	279.5	91.7	89.1	1060.9
11:00 AM	70.9	152.6	37.1	95.2	80.0	113.7	73.0	168.3	435.6	95.2	108.9	1057.8
12:00 PM	89.7	167.2	56.1	141.7	100.1	112.8	157.0	298.8	1362.1	141.7	153.5	784.6
1:00 PM	92.0	174.9	58.3	149.8	162.3	252.5	125.0	274.8	1008.8	149.8	151.9	1086.5
2:00 PM	84.0	173.6	50.4	118.2	130.7	200.8	129.0	247.2	1052.5	118.2	149.3	912.7
3:00 PM	122.7	217.7	89.1	172.4	117.4	146.4	106.2	278.6	797.8	172.4	135.0	904.2
4:00 PM	170.0	196.9	136.9	141.8	162.9	144.5	129.1	270.9	1053.0	141.8	151.1	1191.5
5:00 PM	187.4	227.1	154.6	185.0	189.2	193.5	147.6	332.6	1258.9	185.0	133.9	743.2
6:00 PM	176.8	189.3	143.7	133.8	160.5	99.3	145.6	279.5	1235.8	133.8	127.4	478.6
7:00 PM	142.3	433.8	108.6	42.5	137.5	150.7	107.7	150.2	815.3	42.5	119.7	581.3
8:00 PM	62.9	86.6	29.0	77.3	66.4	32.0	59.1	125.0	323.0	77.3	56.6	731.5
9:00 PM	52.5	184.2	12.9	12.9	42.8	42.8	59.2	59.2	141.8	12.9	6.4	6.4
10:00 PM	15.8	15.8	1.5	1.5	2.6	2.6	42.3	42.3	16.8	1.5	0.9	0.9

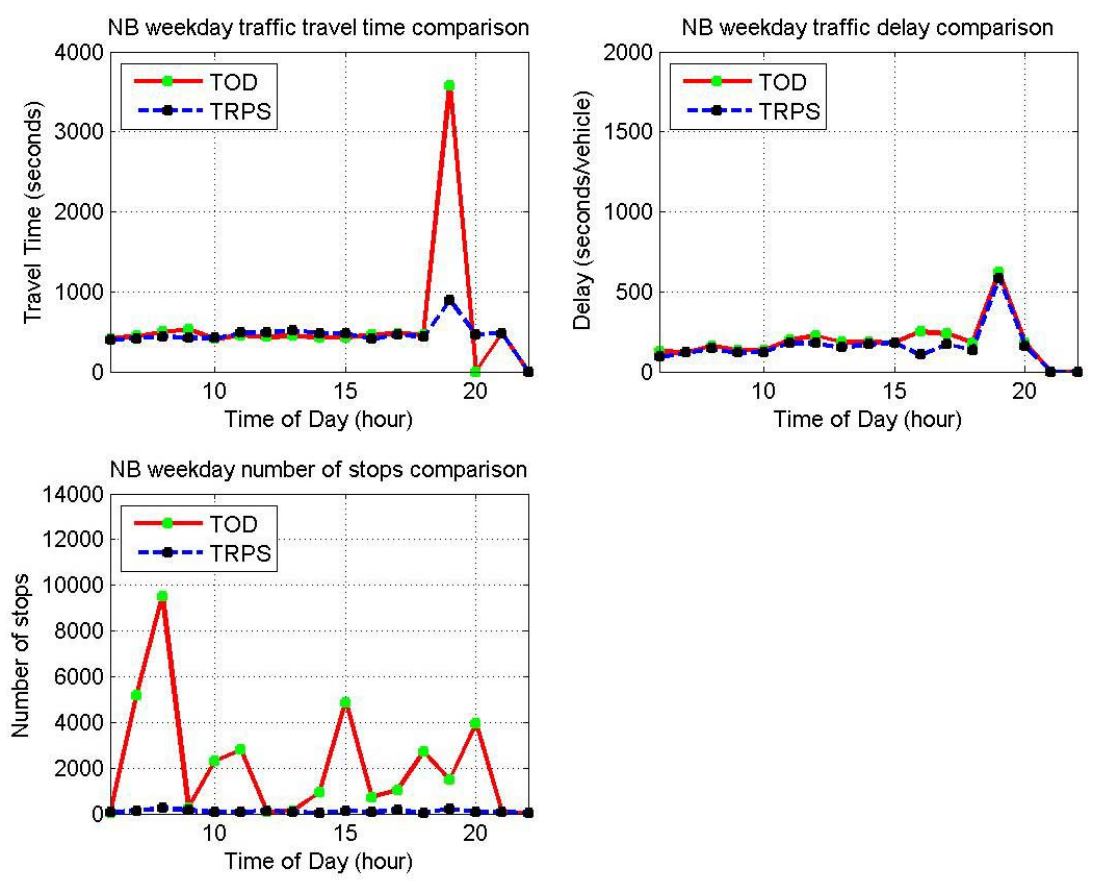


Figure 25. North bound Measures of Effectiveness for TRPS control versus TOD for weekday.

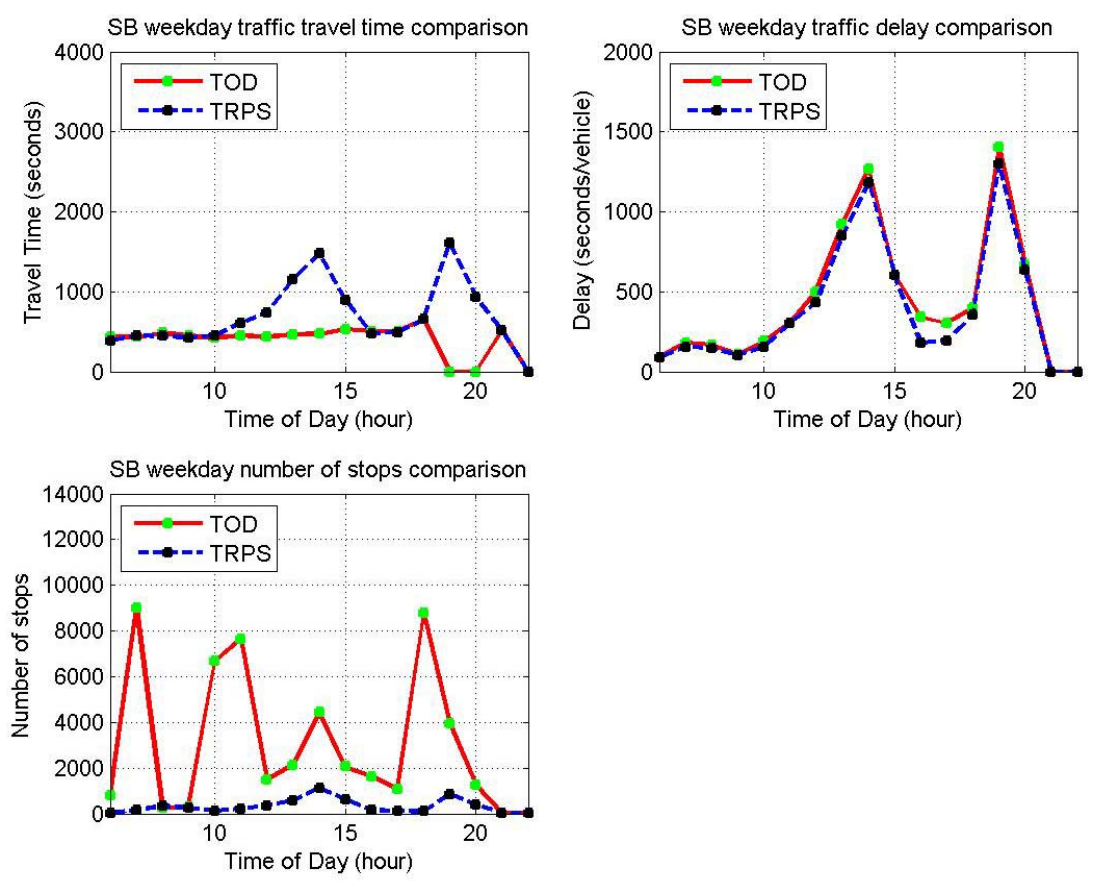


Figure 26. South bound Measures of Effectiveness for TRPS control versus TOD for weekday.

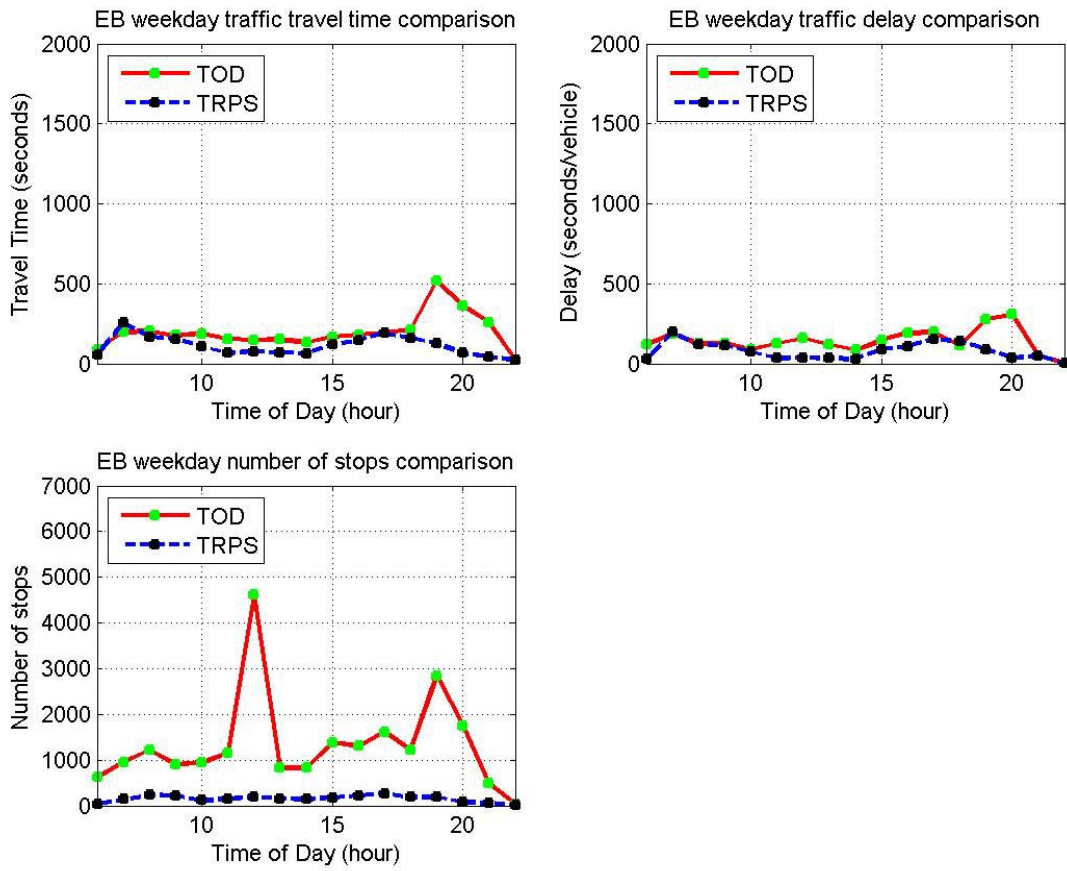


Figure 27. East bound Measures of Effectiveness for TRPS control versus TOD for weekday.

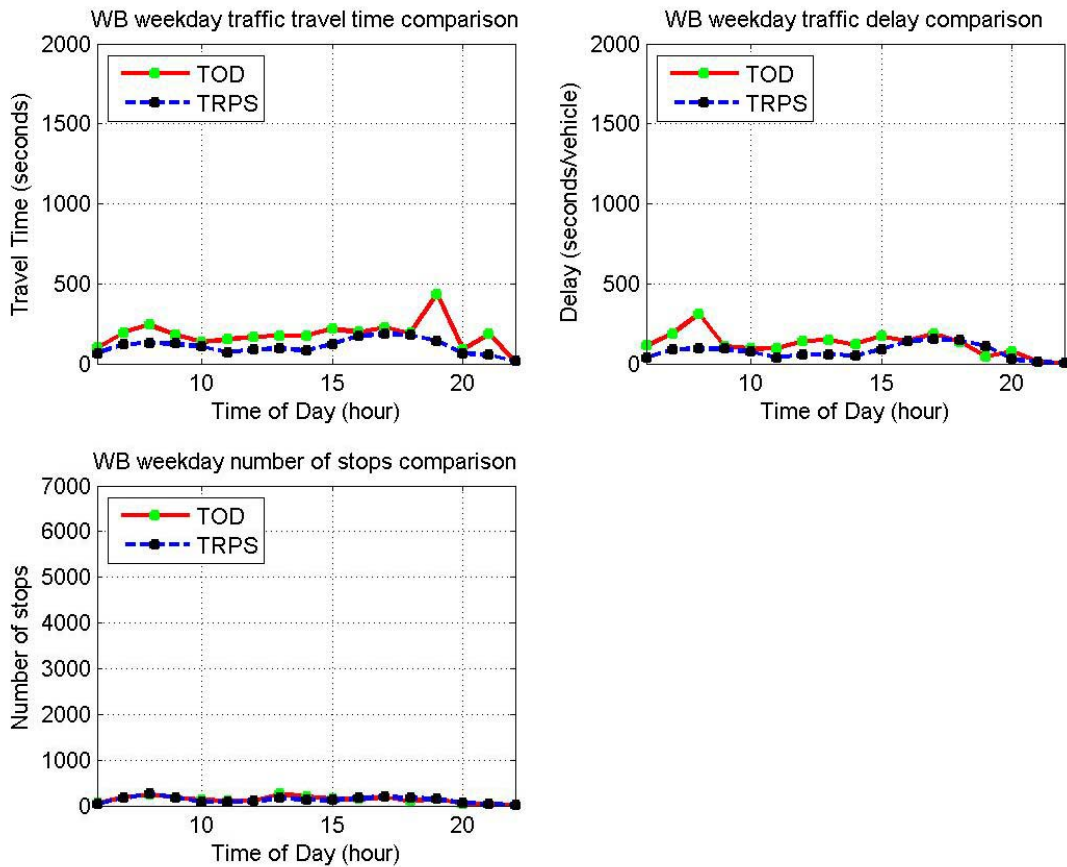


Figure 28. West bound Measures of Effectiveness for TRPS control versus TOD for weekday.

Figures 29 and 30 show the comparison between the TRPS and TOD modes of operation for the NB and SB traffic during the weekend. It could be observed that the NB travel time under the TRPS control is consistently outperforming the TOD operation during the whole day, with the largest reduction of 59% for the NB traffic travel time occurring during the P.M. peak period and the largest reduction for the SB traffic travel time of 70 percent and 74 percent occurring during both peak periods, respectively. It should be noted that the TRPS mode results in higher delay during the PM peak period, but lower number of stopped vehicles (and travel time) during that same period. This is due to the fact that the TRPS timing plans were selected to favor the reduction of stops, while it appears that the TOD old plans were selected to favor the reduction of delay. This is an important point to highlight that traffic engineers can favor one MOE over others when designing or selecting their timing plans.

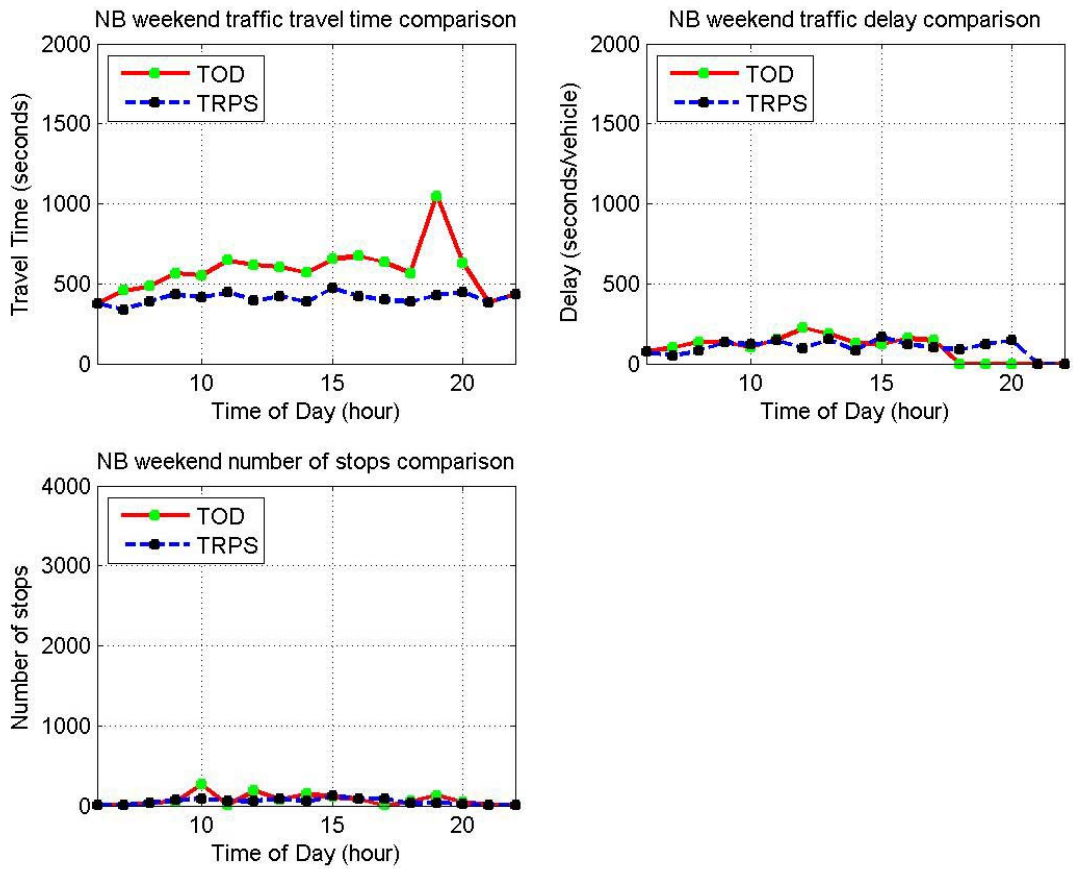


Figure 29. North bound Measures of Effectiveness for TRPS control versus TOD for weekend.

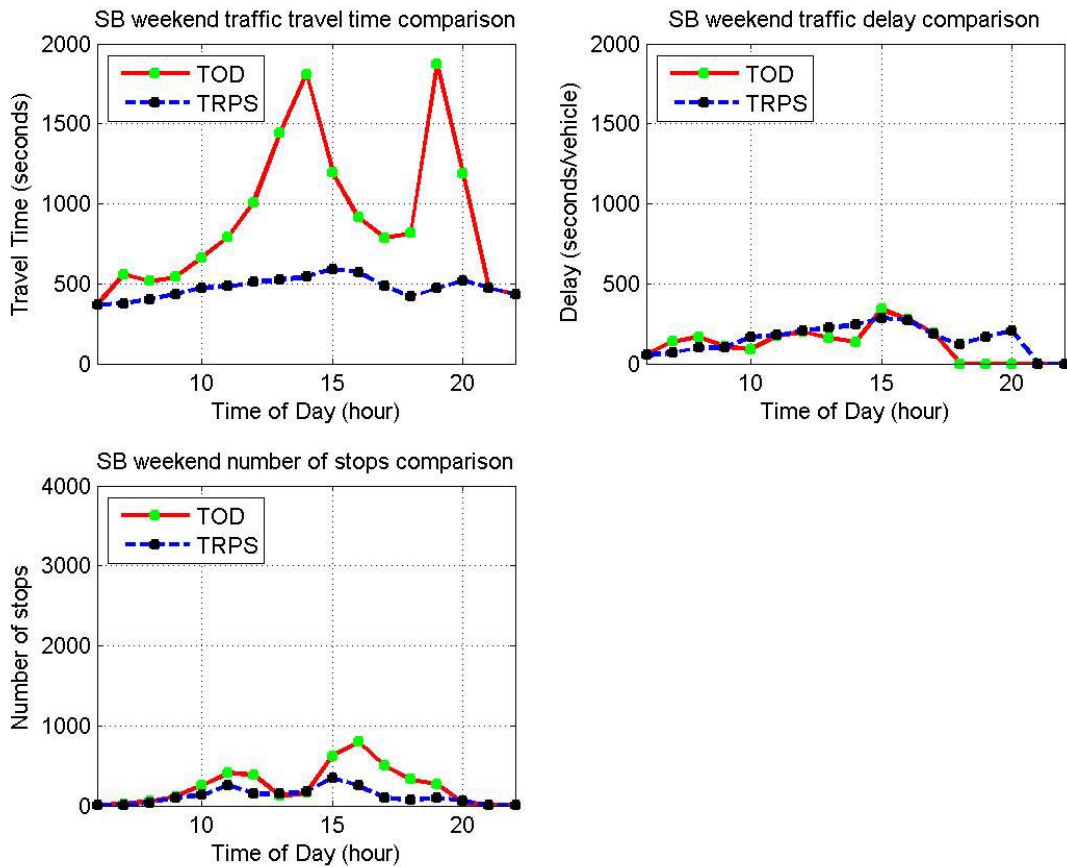


Figure 30. South bound Measures of Effectiveness for TRPS control versus TOD for weekend.

Figures 31 and 32 show the performance comparison for the EB and WB traffic (the side streets). The TRPS outperformed the TOD operation in all MOEs for the EB traffic. The TRPS also outperformed the TOD operation in travel time and number of stopped vehicles in the WB traffic, but resulted in increased delay for the WB traffic for most of the day.

It appears from these figures that the TOD plans were designed well, and were fine-tuned to minimize delay. Overall, the TRPS operation outperformed the TOD operation in travel time and number of stopped vehicles. It also outperformed the TOD operation in delay for most of the approaches, but resulted in an increase in delay for the WB approaches during some periods of the day.

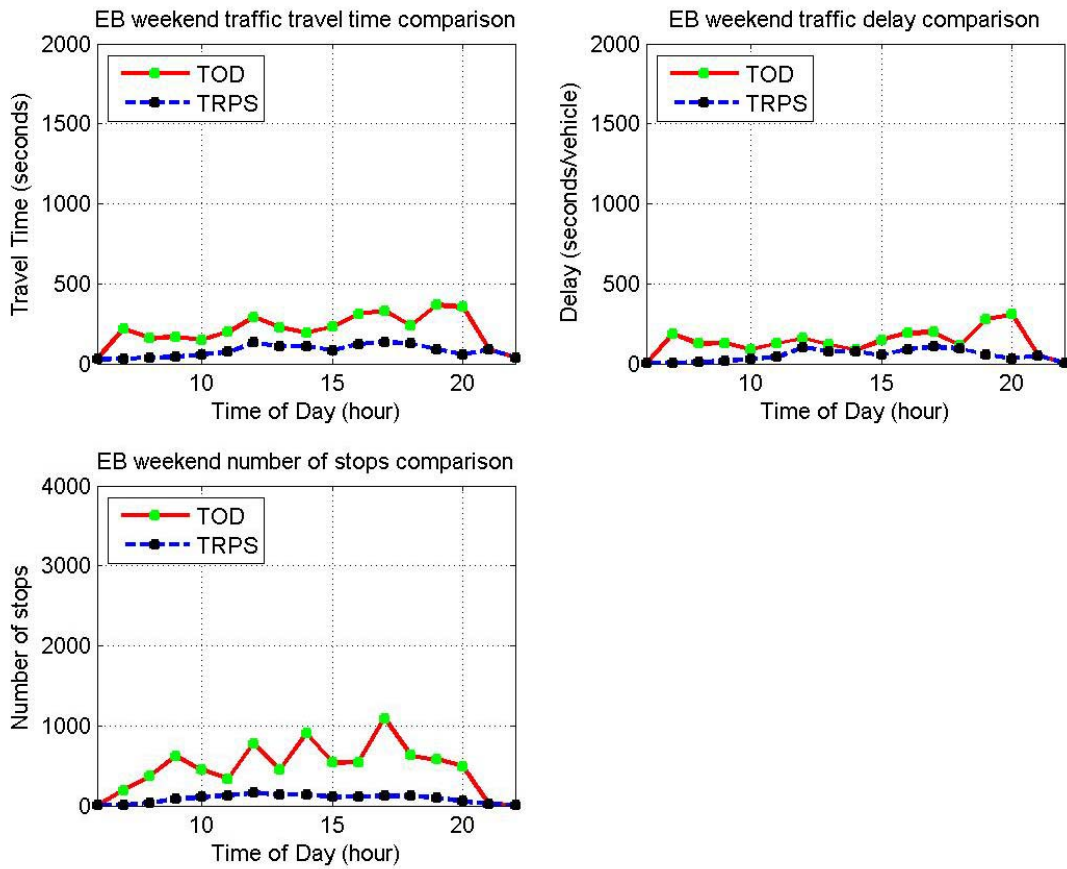


Figure 31. East bound Measures of Effectiveness for TRPS control versus TOD for weekend.

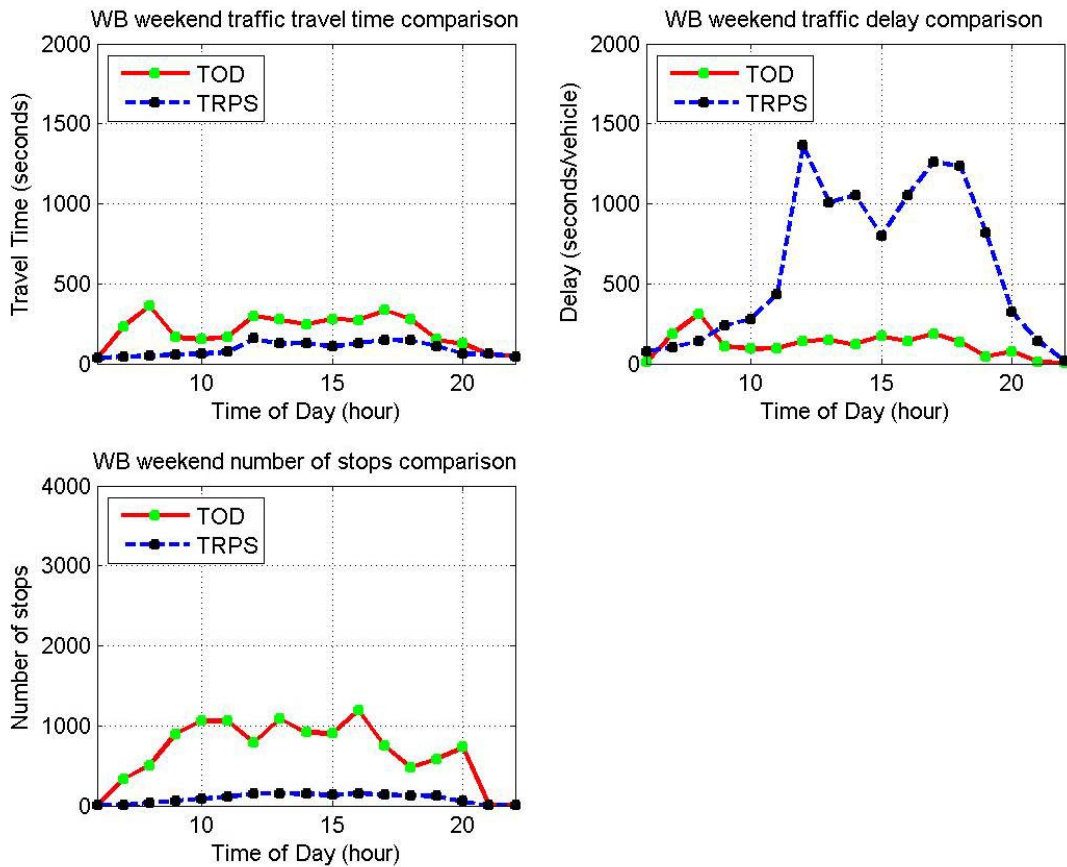


Figure 32. West bound Measures of Effectiveness for TRPS control versus TOD for weekend.

DISCUSSION

The work conducted in this research project developed a comprehensive methodology to implement traffic responsive control on the Reston Parkway arterial network in Northern Virginia, using the pattern-matching mechanism adopted in 170 controllers. This report documents a systematic, novel methodology for robust and optimal selection of TRPS pattern-matching parameters. The approach is based on the following steps:

1. *Data clustering.* This step includes clustering of detector counts for both the main arterial and side streets to determine the traffic levels for all movements entering the network.
2. *Correlation analysis.* In this step, correlation analysis between different movements in the network is conducted to quantify their relationships.
3. *Synthetic O-D analysis.* This step is used to determine the distribution percentages of traffic from each origin node to all destinations.

4. *Critical movement analysis.* This step combines the results of the previous three steps to determine the significant critical movements that control the entire network to determine the design traffic patterns.
5. *Generation of optimum timing plans.* In this step, timing plans are generated for each traffic scenario using PASSER V software.
6. *Selection of the best timing plans.* In this step, all combinations of timing plans and traffic scenarios are evaluated. A multi-objective optimization is performed to select the final number of timing plans.
7. *Determination of the TRPS parameters.* In this step, the selected timing plans are evaluated with all traffic scenarios with CORSIM simulation to account for the effect of oversaturation and actuated control. A multi-objective optimization is conducted to determine the optimal TRPS parameters.
8. *System validation.* In this step, VISSIM simulation is conducted to compare the performance of TOD to TRPS performance.

The methodology resulted in a verification of the benefit of TRPS and suggested that TRPS resulted in savings of up to 27 percent in delay and 14 percent in stops for weekends, and 18 percent in delay and 21 percent in stops for weekdays at this site.

However, it should be noted that the research conducted in this project did not consider the effect of pedestrian demands on the operation of TRPS. In addition, the methodology followed here did not account for any interruption in system operation (e.g., due to preemption). It should also be noted that there are other practical factors that need to be considered for field implementation, such as detector accuracy issues, maintenance issues, and public expectations. These issues should be looked at in future work.

CONCLUSIONS

The research documented in this report developed a new methodology for selection of optimal timing plans to be used with the TRPS control in addition to selection of pattern-matching TRPS parameters for robust performance. VISSIM VAP simulation was conducted and showed a 26.94 percent saving in delay and a 14.45 percent savings in number of stops by changing from existing TOD control to the proposed TRPS system during a typical weekend at this site. Simulation runs conducted for a typical weekday showed a 17.72 percent savings on delay and a 21.13 percent savings in stops at this site. The research conducted in this project indicated that TRPS operation is superior to TOD operation. The overall framework, systematic procedure and steps documented in this report can be used to address the common known limitations of TRPS control mode, and should therefore be used when implementing TRPS on other sites. There are, however, some challenges associated with actual field implementation, including the difficulty of maintaining the system with the existing 170 controller infrastructure. One of the challenges associated with 170 controllers is the lack of an intuitive and easy user interface to input control parameters. However, this should not be a challenge to experienced users.

RECOMMENDATIONS

The research conducted in this project indicated that TRPS operation is superior to TOD operation. This research used simulation to compare between the TOD and TRPS operation. Although the simulation results were found to be promising, actual field implementation is needed to evaluate field implementation issues. The methodology documented in this report should be followed to implement TRPS control on large arterials in an optimal and stable manner. Optimal and stable operation of TRPS could significantly reduce congestion, while capitalizing on existing traffic control infrastructure. The following is a specific list of recommendations that build on the outcome of the project.

1. VDOT should implement TRPS operation on several arterial systems and collect before-and-after field data and document their findings. One potential implementation site could be Route 21.
2. The Virginia Transportation Research Council (VTRC) should consider sponsoring research to develop a more user-friendly approach that builds on the comprehensive methodology developed in this project to simplify field implementation and evaluation. This research should conduct sensitivity and robustness analysis using field detector data to produce simplified guidelines in terms of charts or tables that can be directly used to implement TRPS operation mode.
3. VTRC should consider sponsoring research to extend the methodology developed in this project to address further operational issues in Northern Virginia as viable future extensions of the effort. These issues include:
 - effect of preemption within the TRPS framework as would be the case if TRPS is implemented in Northern Virginia since one of the intersections is frequently preempted
 - effect of pedestrian operation and requirements on signal system performance within the TRPS framework.
4. The results of this research effort should be transferred to other districts, and changes in requirements due to different controller types should be addressed.

COSTS AND BENEFITS ASSESSMENT

Estimation of Annual Delay Savings

The calculation of the delay savings was based on the total network delay reduction obtained from the VISSIM simulation results over all 24 hours a day. The typical weekday savings were multiplied by 261 normal weekdays and the typical weekend savings were multiplied by 104 weekend days. A cost of \$17.02 per-person hour of travel and a 1.25 average

number of people in a vehicle were used to translate the savings into a dollar value.³³ The total dollar amount of the delay savings was, therefore, calculated as $17.02 \times 1.25 \times (859.2 \text{ veh-hour/weekday} \times 261 + 386.2 \text{ veh-hour/weekend day} \times 104) = \$ 5,625,450$.

Estimation of Annual Delay Costs

The costs associated with the configuration of TRPS control will vary depending on the level of expertise of the signal operation staff, data availability, and the complexity of the arterial system. Some of the steps outlined in this report might not need to be conducted in such details if the arterial system traffic patterns are known or can be simply estimated (e.g., if the critical movements are already known by the system operator). Implementation of TRPS operation will require additional personnel time during the setup of the system, but less personnel time afterward. The U.S. Department of Transportation's ITS Joint Program Office estimated that the cost of optimizing traffic signal plans to range from \$2,500 to \$3,500 per intersection.³⁴ For the purpose of comparison, one can assume that for a relatively simple system, the cost of configuring a TRPS system will increase the optimization cost from \$2,500 to \$3,500 per intersection. In such a case, the additional cost of configuring a TRPS system in an arterial with 14 intersections will be \$14,000. In extreme situations, where complex analysis is needed, one can assume that the project can be undertaken by a university or equivalent institute for the cost of this project (\$122,000).

The least benefit-cost ratio will, therefore, be 46:1 ($5,625,450/122,000$).

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