Performance Evaluation of Transit Signal Priority in Multi-Directional Signal Priority Request Situations

By

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(Keywords: Transit Signal Priority, Ring Barrier Controller, Regression Analysis, Green Extension, Priority Progression, Priority Level, Detector Slack, Detector Adjust Threshold, Adjust Step)

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Scholarly Abstract

Ring Barrier signal controller in VISSIM traffic simulation software provides different options for configuring Transit Signal Priority. This controller emulator allows for considering arterial progression by Priority Progression parameter; preferring specific transit signal priority calls to other calls by Priority Level feature; providing more green split to the signal priority phase by Green Extension attribute. This study aims to evaluate the impact of these three parameters on the performance of transit signal priority. The study area is based on three signalized intersections of Prices Fork Road in Blacksburg, Virginia. A total of five transit lines are assumed to request signal priority. Green Extension and Priority Level were found to have significant influence on bus delays, whereas bus frequency is not a significant variable to affect TSP effectiveness (for reducing the transit delays).

This study also aims to identify the traffic conditions in which the adaptive feature of VISSIM Ring Barrier Controller can be most useful. Detector Slack, Detector Adjust Threshold, and Adjust Step are the parameters that should be hardcoded in the controller for activating the adaptiveness. The study area (Prices Fork Road in town of Blacksburg, VA) incorporates five bus lines are assumed eligible to request priority. This study revealed that transit service overlap can enhance or exacerbate each bus performance when transit signal priority is implemented, depending on the scheduled headways and the frequency of signal priority requests in each intersection.

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General Audience Abstract

Ring Barrier signal controller in VISSIM traffic simulation software provides different options for configuring Transit Signal Priority. This controller emulator allows for considering arterial progression by Priority Progression parameter; preferring specific transit signal priority calls to other calls by Priority Level feature; providing more green split to the signal priority phase by Green Extension attribute. This study aims to evaluate the impact of these three parameters on the performance of transit signal priority. The study area is based on three signalized intersections of Prices Fork Road in Blacksburg, Virginia. A total of five transit lines are assumed to request signal priority. Green Extension and Priority Level were found to have significant influence on bus delays, whereas bus frequency is not a significant variable to affect TSP effectiveness (for reducing the transit delays).

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To my parents and siblings,

I am always grateful of having you.

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CHAPTER 1: INTRODUCTION

1.1 Introduction

The operation of Transit vehicles can be improved by either modifying the geometry of the roadways in favor of the transit vehicles, or by using wireless technologies that enables the communication between transit vehicles and signal controllers. The latter is known as Transit Signal Priority (TSP), and is becoming a popular strategy in congested urban areas for reducing travel time or delay of the bus lines. TSP is categorized either as passive or active. Passive TSP assumes that buses of certain transit lines arrive at the intersections always at the same time, whereas active TSP operates based on transit vehicle detection and travel time. Active TSP activates the signal priority strategy upon detection of the bus upstream an intersection and manipulates the signal plans in favor of the transit vehicle. If an Active TSP considers the network traffic, it would become a traffic responsive TSP, which is known as Adaptive TSP.

1.2 Objective

While there has been lots of TSP algorithms offered by different researchers, there are still some features in the controllers that has not been thoroughly evaluated. Ring Barrier Controller (RBC) emulator of VISSIM software package contains some parameters that can deal with the conflicting transit signal priority requests that call for priority of green phase on one intersection, while at the same time maintains a minimum level of arterial progression in a coordinated corridor. The parameters are called Green Extension, Priority Level, and Priority Progression. Moreover, RBC suggests an Adaptive TSP algorithm. This algorithm deals with the travel time variabilities of the transit vehicles by introducing three parameters: Detector Slack, Detector Adjust Threshold, and Adjust Step. Detector slack is defined as a time by which a bus can arrive earlier or later than the controller's estimated travel time. If the transit vehicle passes the check-out detector earlier or later than the allowed estimated travel time and detector slack, the detector would gap or max out, respectively. If the consecutive number of gap or max out events reaches detector adjust threshold, the detector will update the travel time estimation by "Adjust Step" seconds (with an upper bound limit of 10 seconds).

The specific objectives of this thesis are as follow:

- To study the joint impact of Priority Progression, Priority Level, and Green Extension on the operation of the VISSIM RBC Controller and its effect on the network, when there are multi-directional TSP requests.
- To find a regression model that can predict delay as a dependent variable of the above-mentioned parameters and traffic condition.
- To investigate the capability of Adaptive TSP feature embedded in the VISSM RBC Controller in dealing with transit lines fluctuating performance.
- To assess whether there is any correlation between the benefits or negative impacts of implementing signal priority among conflicting or overlapping bus lines.

1.3 Organization of the Thesis

This thesis is written in manuscript format consisting of two papers that will be submitted soon to the Journal of Transportation Engineering, Part A: Systems. The thesis is divided into four chapters. Summary of each chapter is provided below:

Chapter 1: This chapter provided a general description about the significance of this effort, and explains the organization of this thesis.

Chapter 2: This chapter is co-authored by Dr. Montasir Abbas and will be submitted to the Journal of Transportation Engineering, Part A: Systems. The effect of implementing transit signal priority for conflicting requests on a coordinated-actuated corridor is described in this chapter.

Chapter 3: This chapter is co-authored by Dr. Montasir Abbas and will be submitted to the Journal of Transportation Engineering, Part A: Systems. The VISSIM ring barrier controller adaptive TSP feature is investigated in this chapter.

Chapter 4: This chapter provides a summary of the research done in chapters two and three and discusses about future research opportunities in the field of transit signal priority.

CHAPTER 2: EVALUATION OF TRANSIT SIGNAL PRIORITY FOR MULTI-DIRECTIONAL REQUESTS ON A HYPOTHETICALLY COORDINATED-ACTUATED ARTERIAL

Kianoush Kompany[1]; Montasir Abbas, Ph.D., P.E.[2]

2.1 Abstract

This study aims to evaluate and quantify the impact of three signal controller's parameters: Priority Progression, Priority Level, and Green Extension on TSP effectiveness. The study area (Prices Fork Road in town of Blacksburg, VA) incorporates six bus lines. Five bus lines are assumed eligible to request priority. Considering various traffic demands, the signal plans are optimized using VISTRO signal optimization software. VISSIM simulation software is employed to model the network and investigate the effect of the above mentioned parameters (Green Extension, Priority, and Priority Progression), which are embedded in the Transit Signal Priority menu of the Ring Barrier Controller. Two regression models that map the transit vehicle and side-street passenger car delay differences to the significant parameters are proposed. Green Extension and Priority Level were found to have significant influence on bus delays, whereas bus frequency is not a significant variable to affect TSP effectiveness (in terms of reducing the transit delays). This study helps traffic practitioners to gain more insight into appropriate configurations of signal controllers.

Keywords: Transit Signal Priority, Coordinated-actuated, Green Extension, Priority Progression, Priority Level, Ring Barrier Controller, Regression Analysis

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2.2 Introduction

Transit Signal Priority (TSP) is a cost-effective method for maintaining punctual bus operations. TSP is categorized either as passive or active. Passive TSP assumes that buses of certain transit lines arrive at the intersections always at the same time, whereas active TSP operates based on transit vehicle detection and travel time [1].

The Ring-Barrier Controller (RBC), embedded in VISSIM simulation software, provides numerous options for signal designers to configure the system based on network condition. Green Extension is an option that defines the upper bound for the amount of time that green phase can be extended in favor of transit vehicles. If no value is input, only Early Green strategy would be implemented. If the traffic designer wants to satisfy a minimum green band for the coordinated phases along the arterial during the signal priority service time interval, then the Priority Progression is the option to flag. Priority Level is the third parameter that is examined in this research. TSP default operation in VISSIM is to grant green phase to the transit vehicles that have the shortest estimated travel times between check-in and check-out detectors [2]. To evaluate the sensitivity of TSP operation to Priority Level, side over arterial priority and arterial over side priority are defined in order to assign higher importance to the transit vehicles that call for priority from side streets and arterials, respectively.

2.2.1 Objective

Although previous studies have investigated the impact of TSP on network performance, they have overlooked the joint impact of priority progression, priority level, and green extension variations on the performance of unconditional, active transit signal priority. This study aims to shed light on the combined effect of these three parameters, and suggests the most suitable input of these parameters into the signal controllers.

Considering the above mentioned parameters and the network fluctuations, the authors investigated the efficiency of TSP service for various volume-to-saturation flow rates of the arterial and side-streets (values considered are 0.1, 0.2, and 0.3), and for different bus frequencies. The study area is in the Virginia State Route 412, known as Prices Fork Road, a major corridor in Blacksburg, home of Virginia Tech University. The route includes 3 signalized intersections and 1 un-signalized intersection. In order to make the assumption of coordinated operation plausible, and due to the fact that the volumes on the un-signalized intersection is too low, only the signalized intersections are modeled in the network. Detailed description of the network is provided in the Study Area section of the paper. The remainder of this paper is as follows: 1) Literature Synthesis; 2) Study Area; 3) Methodology; 4) Results and Conclusions.

2.2.2 Study Area

The study site selected for this research is Virginia State Route 412, known as Prices Fork Road, which is a major roadway in Blacksburg. Students and university staff who live in the northern part of the town use this highway to commute to the university. Six bus lines operate along this stretch of the highway and the side-streets around it, from which the authors have assumed that five lines are eligible to request signal priority. Transit routes are shown in Figure 1.

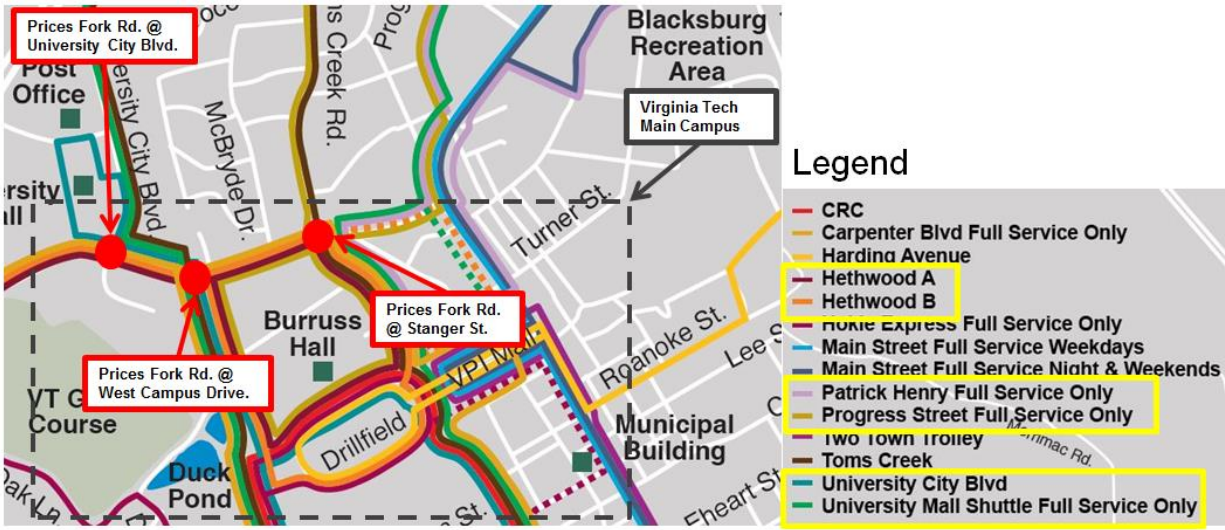

Figure 1: Bus routes of the study area [3]

Table 1 illustrates operating routes of each bus:

Table 1: Transit Routes

Bus Route	Description
Hethwood A (HWA)	Starts from Burrus Hall bus station and travels westbound towards West Campus Drive; makes a right turn to merge on the West Campus Drive, and finally turns left at the intersection of West Campus Drive and Prices Fork Road. On the way back to the campus, it travels eastbound on Prices Fork Road from Hethwood apartment community (west side of campus), and it turns right on the intersection of Prices Fork Road and Stanger Street.
Hethwood B (HWB)	Starts from Stanger Street time-check bus station and travels northbound towards Prices Fork Road; makes a left turn to merge on the Prices Fork Road, and travels westbound to Hethwood Community. On the way back to the campus, it eastbound on Prices Fork Road, and it turns right on the intersection of Prices Fork and West Campus Drive.
Patrick Henry (PHD)	Starts from Stanger Street time-check bus station and travels northbound towards Prices Fork Road; makes a right turn at the intersection of Prices Fork Road and Stanger Street to merge on Prices

	Fork Road. This bus route does not call for priority in the modeled network.
Progress Street	Enters the network from Toms Creek Road (north of Prices Fork Road and Stanger Street intersection) and travels southbound towards Stanger Street.
University City Boulevard (UCB)	Starts from Burrus Hall bus station and drives westbound towards West Campus Drive; makes a right turn to merge on the West Campus Drive and turns left at the intersection of West Campus Drive and Prices Fork, travels on Prices Fork for about 370 meters, and turns right at the intersection of Prices Fork and University City Boulevard. On the way back to the campus, it travels westbound on Prices Fork Road towards the intersection of Prices Fork and Stanger, and makes a left turn when it arrives to this intersection.
University Mall Shuttle (UMS)	Starts from Burrus Hall bus station and drives westbound towards West Campus Drive; makes a right turn to merge on the West Campus Drive. It travels northbound on the West Campus Drive and turns left at the intersection of West Campus Drive and Prices Fork Road. UMS travels on Prices Fork for about 460 meters, and turns right to Old Glade Road past the Prices Fork and University City Boulevard intersection. On the way back to the campus, it travels southbound on University City Boulevard, and turns left at the intersection of Prices Fork and University City Boulevard. After moving on Prices Fork for about 370 meters, it finally merges on West Campus Drive by making a right turn at the intersection of Prices Fork and West Campus.

2.3 Literature Synthesis

TSP is categorized as passive and active, where active TSP can be either rule-based or model-based [1]. Numerous studies have quantified and evaluated the impact of the TSP strategy on the overall traffic and transit lines within a transportation network. However, only few studies have considered the interaction of priority progression, priority level, and green extension parameters available in the signal controllers, on providing transit vehicles with signal priority.

A sensitivity analysis on an intersection in Changzhou, China, in which active TSP was assessed, revealed that TSP is mostly effective under high traffic conditions, though the volume to saturation flow rates were not mentioned [4]. Zhang and Rakha [5] also noted that the benefits of TSP on transit vehicles are the most in higher traffic demand conditions.

To overcome the conflicting priority requests of four directions in intersections of an arterial, Kim, Park [6] proposed a corridor-based multi-directional TSP algorithm that performed superior to the traditional first-come first-served priority algorithms for it reduced transit delay 2% further. The proposed method was studies on an arterial under various traffic demand conditions and it was found that a concentrated bus network (in which most of the bus lines pass the same intersection) benefits most from the proposed method [6].

In another study on an isolated intersection, the maximum delay in a conflicting transit signal priority request environment was calculated and the transit vehicle that experienced the highest delay on its route was granted priority. TSP operation was improved by assigning weights to bus services based on their mode and route level (local, rapid or express), preferring Green Extension to Early Green, and considering the current operation condition. The results showed that when TSP was used, compared to the base scenario, transit delay dcreased by 11 percent [7].

Applying TSP on the arterials improves bus performance by prioritizing transit vehicle movements while minimizing the negative impacts on the passenger cars progression on the main street (known as the arterial) and the harmonized movement of vehicle platoons [8],[9],[10].

Combining an arrival time prediction model and various priority signal timing scenarios, Ekeila et al. (2009) proposed a dynamic transit signal priority that accounts for traffic conditions and transit operation variations; when the proposed strategy was tested on a corridor including 17 signalized intersections in Vancouver, Canada, the results outperformed the conventional TSP models in decreasing transit travel time by 1.5 min, compared to NO TSP scenarios.

Diab, Bertini [11] investigated the effect of overlapping routes on TSP performance by applying regression methods for building bus headway delay model. It was found that the overlapping routes results in the increase of bus headway delay by 3.8 seconds [11].

It is necessary to evaluate the influence of different traffic demand levels and signal timing on the functionality of signal priority. Muthuswamy, McShane [12] selected a corridor of two intersections in Newark, NJ, to assess the network performance for current vs. future peak hours, existing vs. proposed signal timing, and normal vs. TSP operation. The authors found that optimizing signal timing plans can account for 17% of delay reduction when no TSP was implemented. When TSP and optimal signal timing plans were applied to the existing traffic conditions, the travel times of buses and passenger cars reduced by 21% and 20%, respectively; [12].

Winters and Abbas [13] examined the Impact of TSP implementation on Blacksburg Transit, bus service provider in Blacksburg, on three intersections of an uncoordinated under-saturated arterial. The transit delay reduced the most when maximum green extension time for the TSP phase was set to 20 seconds [13].

To the best of the authors' knowledge, although previous studies have investigated the impact of TSP on network performance, none of them have considered the joint impact of priority progression, priority level, and green extension parameters on the performance of unconditional, active transit signal priority. This study aims to shed light on the combined effect of these three parameters, and suggests the most suitable input of these parameters into the signal controllers. Not only green extension and early green strategies were considered, but also the impact of assigning higher priority to bus priority requests from the side-streets was evaluated. In addition, the Priority Progression effect on the network performance was assessed.

2.4 Methodology

2.4.1 Signal Plan Development

For each experiment scenario (scenarios will be explained in the Experiment Design section), appropriate traffic volumes were input into VISTRO signal optimization software and phase splits, cycle lengths, and offsets were optimized. The objective function was to minimize the total vehicle delays. Genetic algorithm was used to reach near optimal phase splits and cycle lengths to address this minimization problem. Because the distances between the intersections are less than 800 meters, the best practice is to operate the signal plans in coordinated-actuated mode [14]. Therefore, the cycle length of all the three intersections is equal.

The signal phases at the intersection of University City Boulevard and Prices Fork Road operate on the protected mode. This means that the left turn phases change to red once the controller terminates green splits for them, and the left turners cannot turn while their adjacent through movements are being served. However, phasing on the West Campus Drive intersection and Stanger Street intersection is protected permissive. This means that upon termination of the green split for the left turners, the signal head changes to a flashing yellow arrow. This allows for the left turn movements to pass through the intersection while the adjacent through movement is being served, given that there is no through movement from the opposite direction. Phase numbers and sequences of each intersection are shown in Figure 2 and 3:

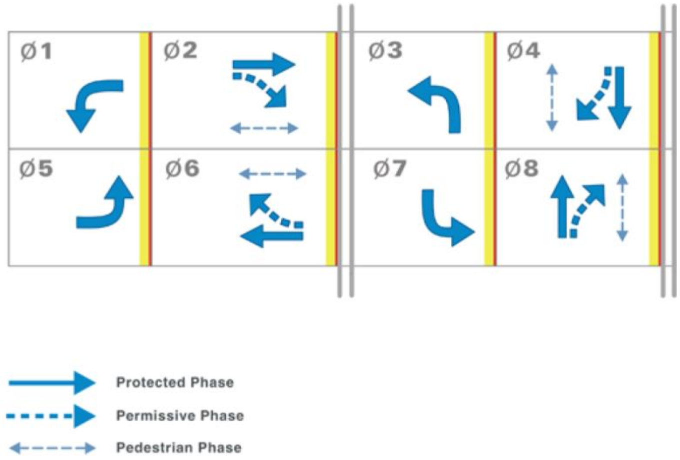

Figure 2: Ring Barrier Diagram of University City Boulevard Intersection at Prices Fork Road [15]

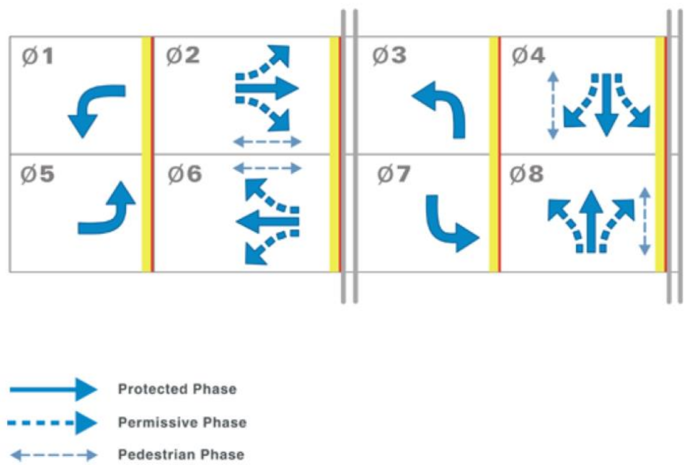

Figure 3: Ring Barrier diagram of West Campus Drive and Stanger Street intersections, at Prices Fork Road [15]

Yellow and red clearance time intervals, and lost time at each intersection were input based on the Institute of Traffic Engineers formulae [16]. The Maximum Recall option of the controller was selected for the eastbound and westbound movements to maintain the coordinated operation. Maximum Green and Minimum Green parameters were input based on the Traffic Signal Timing Manual [15]. When the optimized phase splits were higher than the Maximum Green, then the optimized phase splits were substituted for the Maximum Green.

2.4.2 Detectors Layout

Due to the fact that the speed limits on the network links are equal to or less than 35 mph, long loop presence detectors located at the stop lines were used to activate the phases. The length of the detectors for the through movement lanes was set to 12 meters, while the length of the detectors on left-turn lanes was set to 6 meters. The signal controllers' memory was set to non-locking mode, so that the permissive movements do not induce a phase change.

Check-in detectors for buses were placed right after the upstream intersection (i.e. the intersection immediately preceding the intersection that the bus sends priority call to) they passed, whereas check-out detectors were placed after the downstream stop lines.

Figure 4 shows the intersection of Prices Fork Road and Stanger Street, and the layout of the detectors.

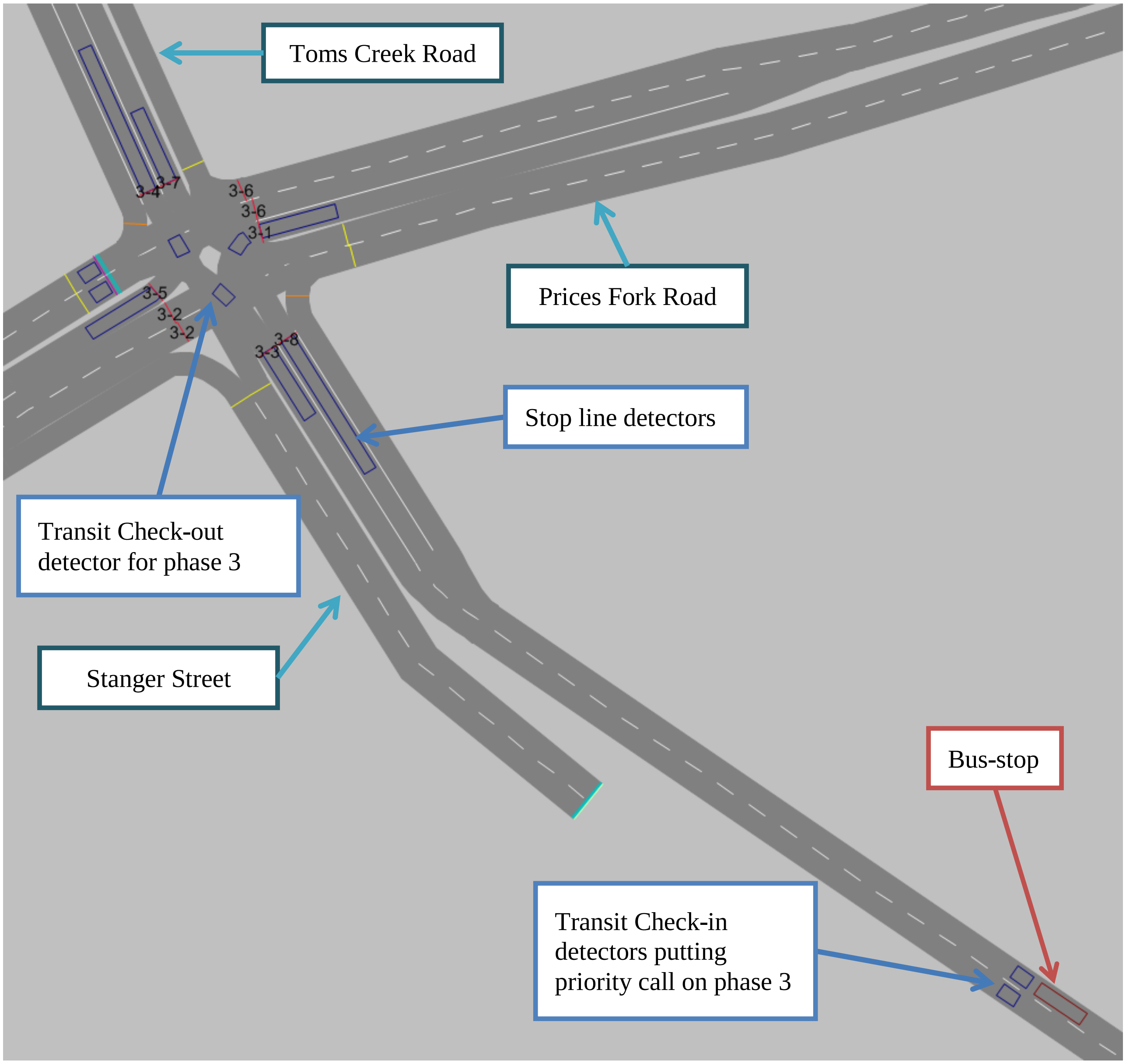

Figure 4: Detectors layout at Stanger Street and Prices Fork Road intersection

2.4.3 Experiment Design

The arterial consists of three signalized intersections, and the total length of the arterial is approximately 2,500 meters. Since studying the functionality of TSP in variable network conditions was of interest, SAS JMP Pro statistical software was used to obtain all the scenarios that can result in statistically valid interpretation of the simulations [17].

Table 2 shows the parameter values for each scenario. The variables employed in this study are explained below:

Arterial Bus Frequency (BF-Art) refers to the frequency of the arterial transit vehicles. Arterial buses include HWA and HWB because their major travel paths are on the arterial. The values are: 1, 2, 4, and 6 vehicles per hour (complying with Blacksburg Transit schedule for Reduced Service, Intermediate Service, Full Service Off-peak Hours, and Full Service Peak Hours, respectively.

BF-Side: Side-street Bus Frequency refers to the frequency of the side-street transit vehicles. Side-street buses include those buses that operate on ProgressSt. , UCB, PHD, UMS routes. The values are: 1, 2, 4, and 6 vehicles per hour (complying with Blacksburg Transit schedule for Reduced Service, Intermediate Service, Full Service Off-peak Hours, , and Full Service Peak Hours, respectively.

V/S-Art: Volume to Saturation Flow Rate on Arterial defines the ratio of the vehicles that enter the network from the two extreme ends of the modeled arterial roadway compared to the saturation flow rate. The values include: 0.1, 0.2, and 0.3.

V/S-Side: Volume to Saturation Flow Rate on Side-street defines the ratio of the vehicles on the side-streets compared to the saturation flow rate. The values include: 0.1, 0.2, and 0.3.

PP: Priority Progression is a binary variable (0 if inactive, 1 if active) that defines whether or not the minimum arterial progression will be met.

PL: Priority Level is a categorical variable that defines how important the calls of different phases would be in case of conflicting transit signal priority requests:

- 0: Signal controllers of the intersection serve the priority calls based on their default logic.
- 1: Signal controllers serve the priority calls received from phases 2 and 6 (arterial through movements).

  2: Signal controllers assume higher priority for phases 1, 3, 4, 7, and 8.

GE: Green Extension defines how long the green phase can elapse beyond its designated green split. The values include: 5, 10, 15, and 20. Value of 0 denotes that the only priority option is Early Green.

PHDDelDiff: Delay difference (percent) between without TSP and with TSP scenarios for Patrick Henry Drive Transit Line.

UMSDelDiff: Delay difference (percent) between without TSP and with TSP scenarios for University Mall Shuttle transit line.

UCBDelDiff: Delay difference (percent) between without TSP and with TSP scenarios for University City Boulevard transit line.

ProgressDelDiff: Delay difference (percent) between without TSP and with TSP scenarios for Progress Street transit line.

HWBDelDiff: Delay difference (percent) between without TSP and with TSP scenarios for Hethwood B transit line.

HWADelDiff: Delay difference (percent) between without TSP and with TSP scenarios for Hethwood A transit line.

Priority Bus Delay Diff: Average delay difference (percent) of transit lines that are eligible to request signal priority, between without TSP and with TSP scenarios.

Side-street Passenger Car Delay Diff: Average delay difference (percent) of passenger cars that traverse side streets, between without TSP and with TSP scenarios.

Arterial Passenger Car Delay Diff: Average delay difference (percent) of passenger cars that travel on the arterial, between without TSP and with TSP scenarios.

Table 2: Design of Experiment

Variable	Variable description	Input Values	Unit
BFArt	Frequency of Arterial Bus Lines	2, 4, 6	vehicles/hr.
BFSide	Frequency of Side-street Bus Lines	2, 4, 6	vehicles/hr.
VSArt	Volume to Saturation Flow Rate of Arterial	0.1, 0.2, 0.3	-
VSSide	Volume to Saturation Flow Rate of Side Streets	0.1, 0.2, 0.3	-
GE	Green Extension	5, 10, 15, 20	seconds
PL	Priority Level	0, 1, 2	-
PP	Priority Progression	0, 1	seconds

The time it takes the transit vehicles to enter the modeled network was input to the simulation by estimating the travel time between the time-check bus station (outside the model) and the network, and a dwell time of 20 seconds was considered if there were any bus stations in between. Equation 1 represents the formula used for the estimation of transit vehicle entrance time to the network:

$$ET_i = \frac{D_i}{v_{mean}} + DT_{mean} \times N_i \qquad (1)$$

Where,

ET_i = entrance time of bus i to the network

D_i = closest distance between the time-check bus station (outside the network) of bus i and the modeled network

v_{mean} = bus average speed (assumed to be 50 km/hour)

DT_{mean} = average dwell time of transit vehicles at bus stops (assumed to be 20 seconds)

N_i = number of bus stops that transit vehicle i stops at before entering the network

After the experiments were modeled in VISSIM and RBC controllers were configured, each model was run 10 times using 10 different random seeds, for both of the “No TSP” and “with TSP” scenarios. Simulation durations were set to 75 minutes and the first 15 minutes of run time was for warming up the network; therefore, the networks were analyzed for one hour.

2.5 Results

In order to get a comprehensive inference from the Transit Signal Priority operation in multi-directional priority call environment, the response of each transit line against the parameters was studied. This helps to understand which parameters affect the network performance significantly, and to find any unexpected results that are due to unobserved factors. For this purpose, the delay differences of each transit line, depending on whether or not TSP was implemented on the network, were plotted against each experiment in Figure 5.

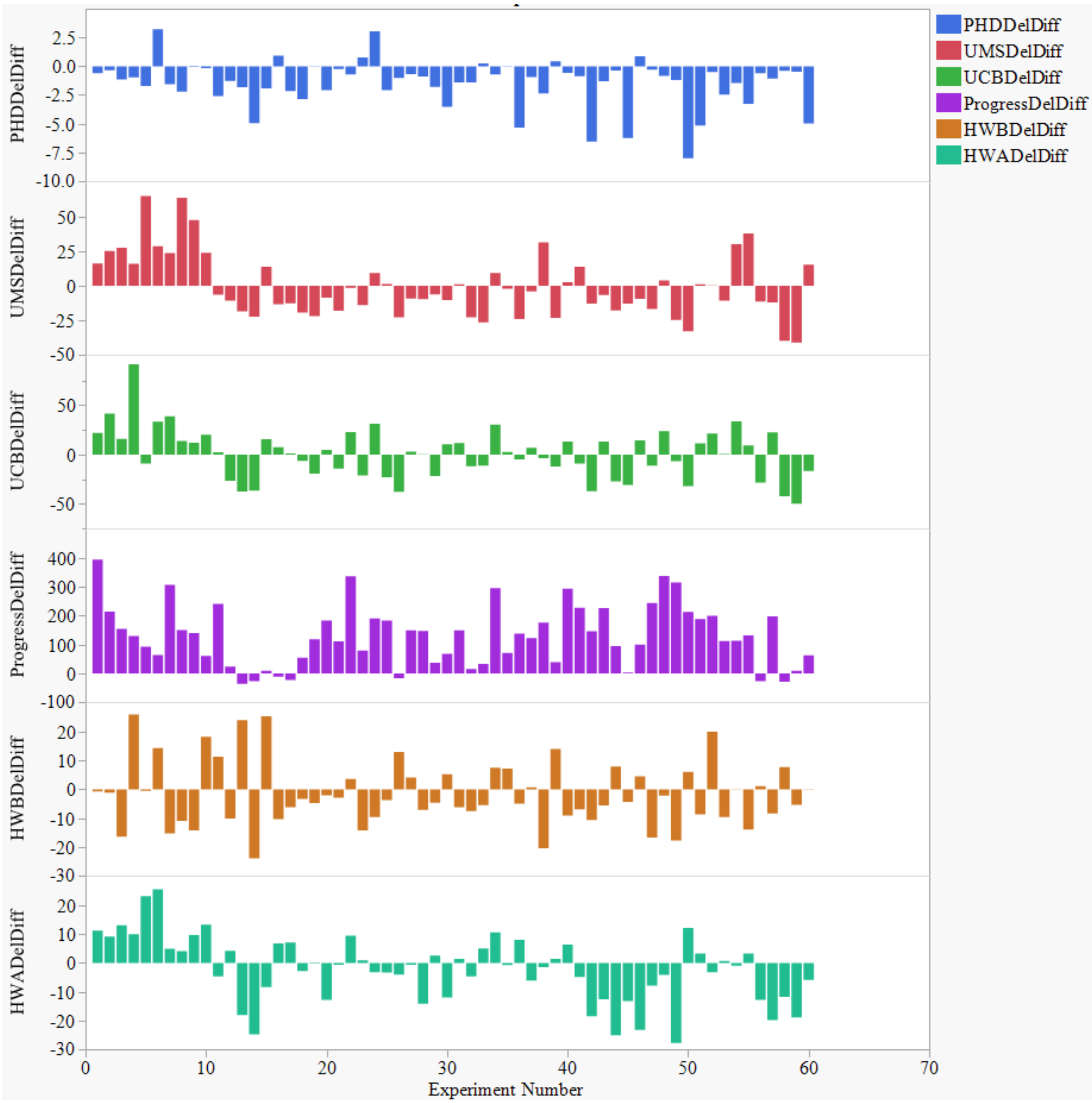

Figure 5: Transit lines delay difference between "with TSP" and "without TSP" scenarios (percent)

Based on Figure 5, it can be intuitively understood that the delay of Progress St. transit line always increases when TSP is implemented on the controllers. By looking at the simulation, it was noticed that the check-in detector for this transit line (associated with signal head number 4) was much closer to the intersection than the check-in detectors of the other transit lines; this makes the priority level parameter ineffective because the calls for priority from this transit line is received by the controller always after the signal controller has already granted priority to another transit priority request. Due to the fact that Progress Street delay is a dependent variable of its check-in detector distance, this line is excluded from further analysis. Figure 6 illustrates how the priority calls from other phases impose additional delay on the "Progress Street" transit line in "with TSP" scenarios.

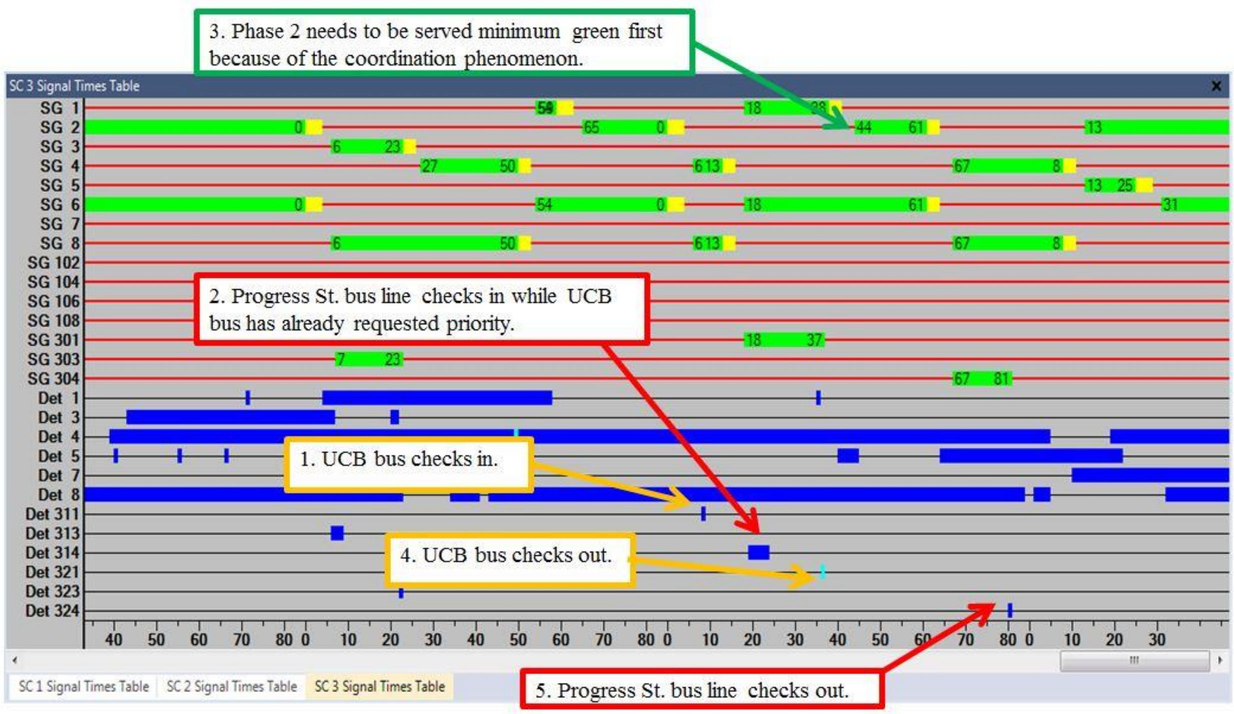

Figure 6: Illustration of SG 304 (Progress Street bus line TSP phase) losing priority to SG 301

2.5.1 Regression Analysis

To find the significant variables that influence the performance of TSP, linear regression models were fit to the results and the significant factors were captured by using standard least squares method. Table 3 to 6 shows the parameter estimation results.

Table 3: Summary of Fit for Bus Delay Difference Regression Model

RSquare	0.89
RSquare Adj.	0.65
Root Mean Square Error	7.36
Mean of Response	-3.17
Observations	60

Table 4: ANOVA Test for Bus Delay Difference Model

Source	DF	Sum of Squares	Mean Square	F Ratio
Model	40	8044.326	201.108	3.72
Error	19	1028.201	54.116	Prob. > F
C. Total	59	9072.527		0.002

Table 5: Parameter Estimate for Bus Delay Difference Regression Model

Term	Estimate	Std. Error	t Ratio	Prob. > |t|
Intercept	-13.470	7.646	-1.760	0.094
GE	-0.545	0.170	-3.200	**0.005**
BF-Art	0.379	0.660	0.570	0.572
BF-Side	-1.419	0.777	-1.830	0.084
V/S-Art	21.066	16.858	1.250	0.227
V/S-Side	11.682	20.227	0.580	0.570
PP[0]	-2.431	1.354	-1.800	0.089
PL[0]	3.730	1.859	2.010	0.059
PL[1]	4.419	1.796	2.460	**0.024**
(GE-9.92)*(GE-9.92)	0.091	0.034	2.650	**0.016**
(GE-9.92)*(BF-Art-3.32)	0.074	0.085	0.870	0.398
(BF-Art-3.32)*(BF-Art-3.32)	0.276	0.527	0.520	0.606
(GE-9.92)*(BF-Side-3.33)	-0.042	0.108	-0.390	0.701
(BF-Art-3.32)*(BF-Side-3.33)	1.282	0.368	3.480	**0.003**
(BF-Side-3.33)*(BF-Side-3.33)	1.226	0.480	2.550	**0.020**
(GE-9.92)*(V/S-Art-0.2)	2.382	2.647	0.900	0.380
(BF-Art-3.32)*(V/S-Art-0.2)	-1.391	8.803	-0.160	0.876
(BF-Side-3.33)*(V/S-Art-0.2)	-3.364	9.351	-0.360	0.723
(V/S-Art-0.2)*(V/S-Art-0.2)	404.832	255.263	1.590	0.129
(GE-9.92)*(V/S-Side-0.2)	-2.672	2.778	-0.960	0.348
(BF-Art-3.32)*(V/S-Side-0.2)	6.920	8.134	0.850	0.406
(BF-Side-3.33)*(V/S-Side-0.2)	-16.278	11.530	-1.410	0.174
(V/S-Art-0.2)*(V/S-Side-0.2)	-33.997	194.192	-0.180	0.863
(V/S-Side-0.2)*(V/S-Side-0.2)	-227.088	319.985	-0.710	0.487
(GE-9.92)*PP[0]	0.053	0.168	0.320	0.753
(BF-Art-3.32)*PP[0]	-0.040	0.664	-0.060	0.953
(BF-Side-3.33)*PP[0]	0.372	0.770	0.480	0.634
(V/S-Art-0.2)*PP[0]	-41.275	23.436	-1.760	0.094

(V/S-Side-0.2)*PP[0]	-4.751	17.592	-0.270	0.790
(GE-9.92)*PL[0]	0.008	0.249	0.030	0.974
(GE-9.92)*PL[1]	0.051	0.269	0.190	0.852
(BF-Art-3.32)*PL[0]	0.101	1.303	0.080	0.939
(BF-Art-3.32)*PL[1]	-3.195	1.588	-2.010	0.059
(BF-Side-3.33)*PL[0]	-0.377	1.249	-0.300	0.766
(BF-Side-3.33)*PL[1]	2.722	1.173	2.320	**0.032**
(V/S-Art-0.2)*PL[0]	57.728	25.223	2.290	**0.034**
(V/S-Art-0.2)*PL[1]	-59.793	26.933	-2.220	**0.039**
(V/S-Side-0.22)*PL[0]	2.871	25.342	0.110	0.911
(V/S-Side-0.22)*PL[1]	-6.426	22.668	-0.280	0.780
PP[0]*PL[0]	2.379	1.901	1.250	0.226
PP[0]*PL[1]	-1.542	2.248	-0.690	0.501

Note: Bold numbers indicate significant variables in 95% confidence interval.

As the parameter estimation in Table 3 reveals, the significant variables of priority bus delay difference include: GE, PL, BF-Art, BF-Side, and VS-Art. PP influences the delays in a negligible manner; however, VS-Side does not considerably affect the TSP influence on priority bus delay. PP was not significant mainly because the number of intersections that the priority buses traversed were limited.

It is essential for a signal designer to know the effect of manipulating signal controller's parameters on the passenger car delay. Figure 7 shows that the delay of the passenger cars traveling on the arterial did not significantly increase, while side-street passenger car delay increase is not negligible; the analysis indicates that the variable that can predict side-street passenger car delay increase include: GE, BF-Side, and VS-Side (Table 6). Therefore, during the signal design procedure, GE and PL should be set in such a way that the bus delay is reduced and the increase of side-street passenger car delay is kept on the lowest level.

Table 6: Parameter Estimate of Side-street Passenger Car Delay Difference Regression Model

Term	Estimate	Std. Error	t Ratio	Prob. > |t|
Intercept	-68.556	50.645	-1.350	0.192
GE	-3.098	1.128	-2.750	**0.013**
BF-Art	-8.015	4.374	-1.830	0.083

BF-Side	14.743	5.146	2.870	**0.010**
V/S-Art	-65.752	111.664	-0.590	0.563
V/S-Side	599.789	133.983	4.480	**0.000**
PP[0]	3.494	8.970	0.390	0.701
PL[0]	-2.825	12.316	-0.230	0.821
PL[1]	4.375	11.898	0.370	0.717
(GE-9.92)*(GE-9.92)	0.529	0.228	2.330	**0.031**
(GE-9.92)*(BF-Art-3.32)	1.010	0.563	1.790	0.089
(BF-Art-3.32)*(BF-Art-3.32)	3.981	3.488	1.140	0.268
(GE-9.92)*(BF-Side-3.33)	-1.046	0.718	-1.460	0.162
(BF-Art-3.32)*(BF-Side-3.33)	-3.151	2.437	-1.290	0.212
(BF-Side-3.33)*(BF-Side-3.33)	-2.099	3.182	-0.660	0.517
(GE-9.92)*(V/S-Art-0.2)	5.895	17.536	0.340	0.740
(BF-Art-3.32)*(V/S-Art-0.2)	84.321	58.309	1.450	0.164
(BF-Side-3.33)*(V/S-Art-0.2)	-49.444	61.938	-0.800	0.435
(V/S-Art-0.2)*(V/S-Art-0.2)	-854.398	1690.820	-0.510	0.619
(GE-9.92)*(V/S-Side-0.2)	-27.977	18.400	-1.520	0.145
(BF-Art-3.32)*(V/S-Side-0.2)	-4.047	53.880	-0.080	0.941
(BF-Side-3.33)*(V/S-Side-0.2)	167.556	76.374	2.190	**0.041**
(V/S-Art-0.2)*(V/S-Side-0.2)	-2396.826	1286.293	-1.860	0.078
(V/S-Side-0.2)*(V/S-Side-0.2)	-1113.249	2119.524	-0.530	0.606
(GE-9.92)*PP[0]	1.456	1.110	1.310	0.205
(BF-Art-3.32)*PP[0]	5.329	4.398	1.210	0.240
(BF-Side-3.33)*PP[0]	-1.368	5.101	-0.270	0.791
(V/S-Art-0.2)*PP[0]	-76.188	155.235	-0.490	0.629
(V/S-Side-0.2)*PP[0]	-159.209	116.527	-1.370	0.188
(GE-9.92)*PL[0]	-0.244	1.650	-0.150	0.884
(GE-9.92)*PL[1]	-0.487	1.782	-0.270	0.788
(BF-Art-3.32)*PL[0]	-6.007	8.634	-0.700	0.495
(BF-Art-3.32)*PL[1]	9.707	10.516	0.920	0.368
(BF-Side-3.33)*PL[0]	-5.067	8.274	-0.610	0.548
(BF-Side-3.33)*PL[1]	7.096	7.773	0.910	0.373
(V/S-Art-0.2)*PL[0]	48.991	167.071	0.290	0.773
(V/S-Art-0.2)*PL[1]	20.074	178.402	0.110	0.912
(V/S-Side-0.2)*PL[0]	121.446	167.860	0.720	0.478
(V/S-Side-0.2)*PL[1]	-95.351	150.146	-0.640	0.533
PP[0]*PL[0]	-10.018	12.590	-0.800	0.436
PP[0]*PL[1]	5.661	14.892	0.380	0.708

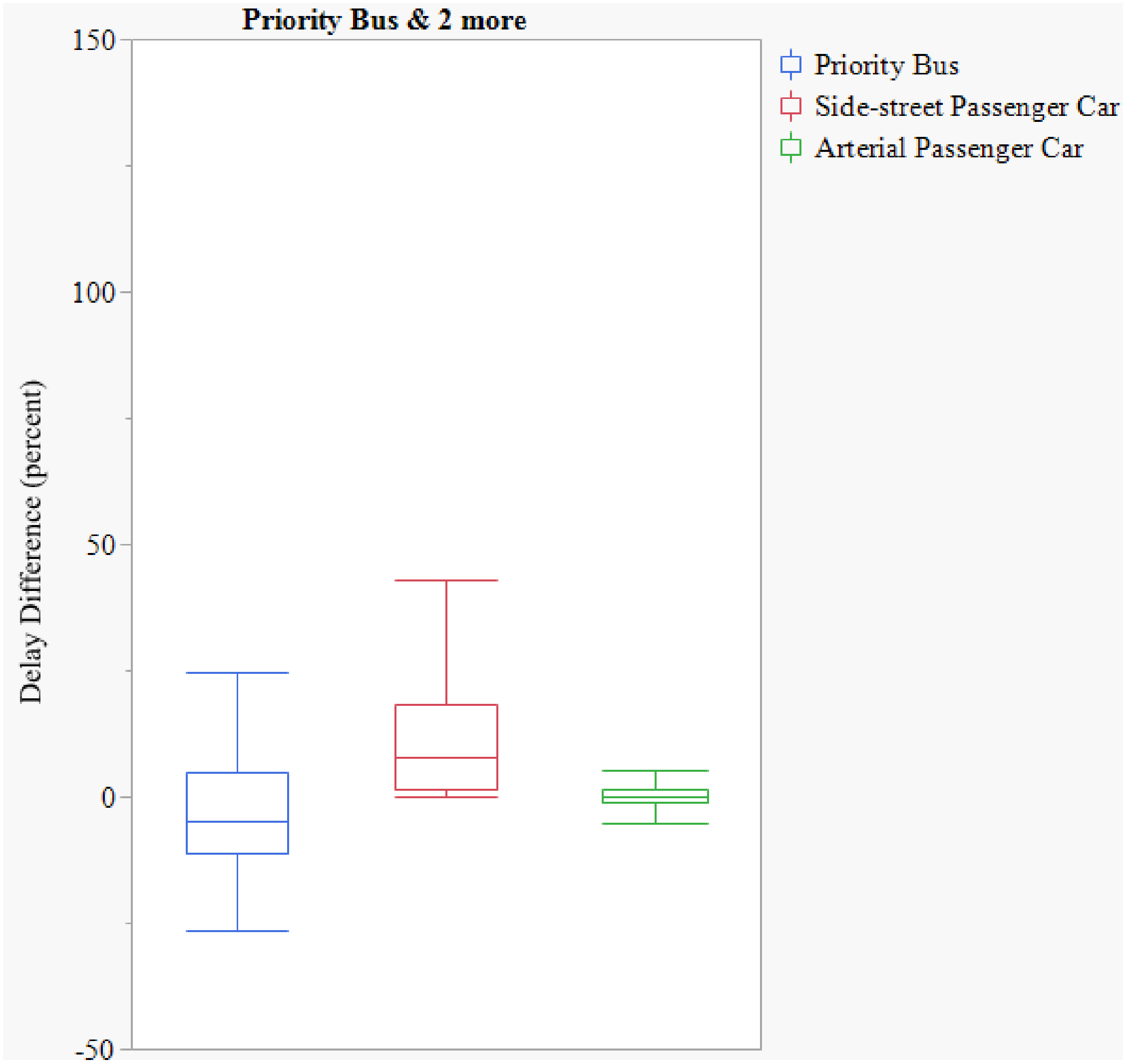

Figure 7: Box plots of priority bus, side-street and arterial passenger car delay difference

2.5.2 Regression Formula

After defining the significant variables, prediction models for priority bus and side-street passenger car delay difference variables can now be constructed. The prediction formulae for estimating these dependent variables based on the significant independent variables are as follow:

$$Y_1 = -3.85 + X_1 - 0.55 \times GE + 0.06 \times (GE - 9.92)^2 + 0.99 \times (BFArt - 3.32) \times (BFSide - 3.33) + 0.56 \times (BFSide - 3.33)^2 + X_2 \times (BFSide - 3.33) + X_3 \times (VSArt - 0.2) \quad (2)$$

$$Y_2 = -113.96 - 3.29 \times GE + 12.47 \times BFSide + 574.50 \times VSSide + 0.79 \times (GE - 9.92)^2 + 79.22 \times (VSSide - 0.20) \times (BFSide - 3.33) \quad (3)$$

Where,

Y_1 = priority bus delay difference (percent)

Y_2 = side-street passenger car delay difference (percent)

X_1, X_2, X_3 = coefficients dependent on priority level value (proper values are shown in Table 6)

Table 7: Values of X_1, X_2, and X_3 Based on Priority Level

	PL = 0	PL = 1	PL = 2
X_1	2.46	4.98	-7.43
X_2	-0.13	1.44	-1.32
X_3	35.7	-28.98	-6.72

Profiling priority bus delay difference against its corresponding significant variables provides a helpful visualization for the practitioners to initially observe the influence of PL on the delay considering the traffic condition and transit level of operation (Figure 8). After this initial observation, signal designers can apply Equations 2 and 3 to obtain the best GE value.

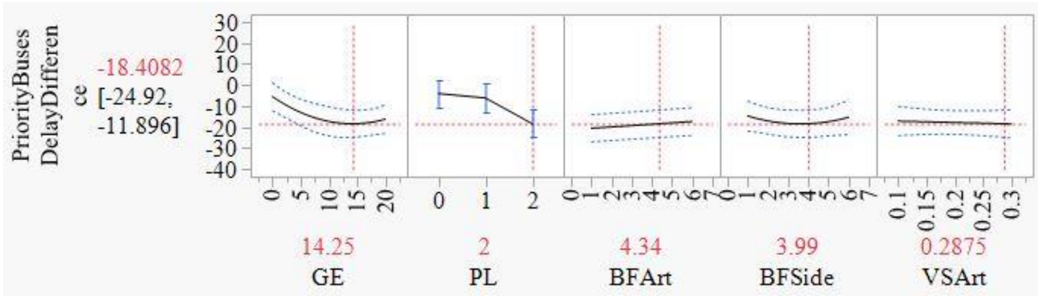

Figure 8: Sensitivity of Priority Bus Del Diff to the significant variables

Interestingly, it was noticed that when the frequency of side-street buses was high, an optimal GE value minimized both the priority bus delay reduction and side-street passenger car delays. This result was expected for the priority bus delay as TSP is an improvement strategy for transit vehicles. Regarding side-street passenger car, the result is primarily due to the fact that in a coordinated-actuated corridor, higher frequency of side street priority calls provides more green time to the side-street vehicles and the optimal GE values is able to reduce congestion (when GE is less than the optimal value) and starvation (when GE is higher than the optimal value) of side streets. Figure 9 shows the response of priority bus and side-street passenger car delay differences.

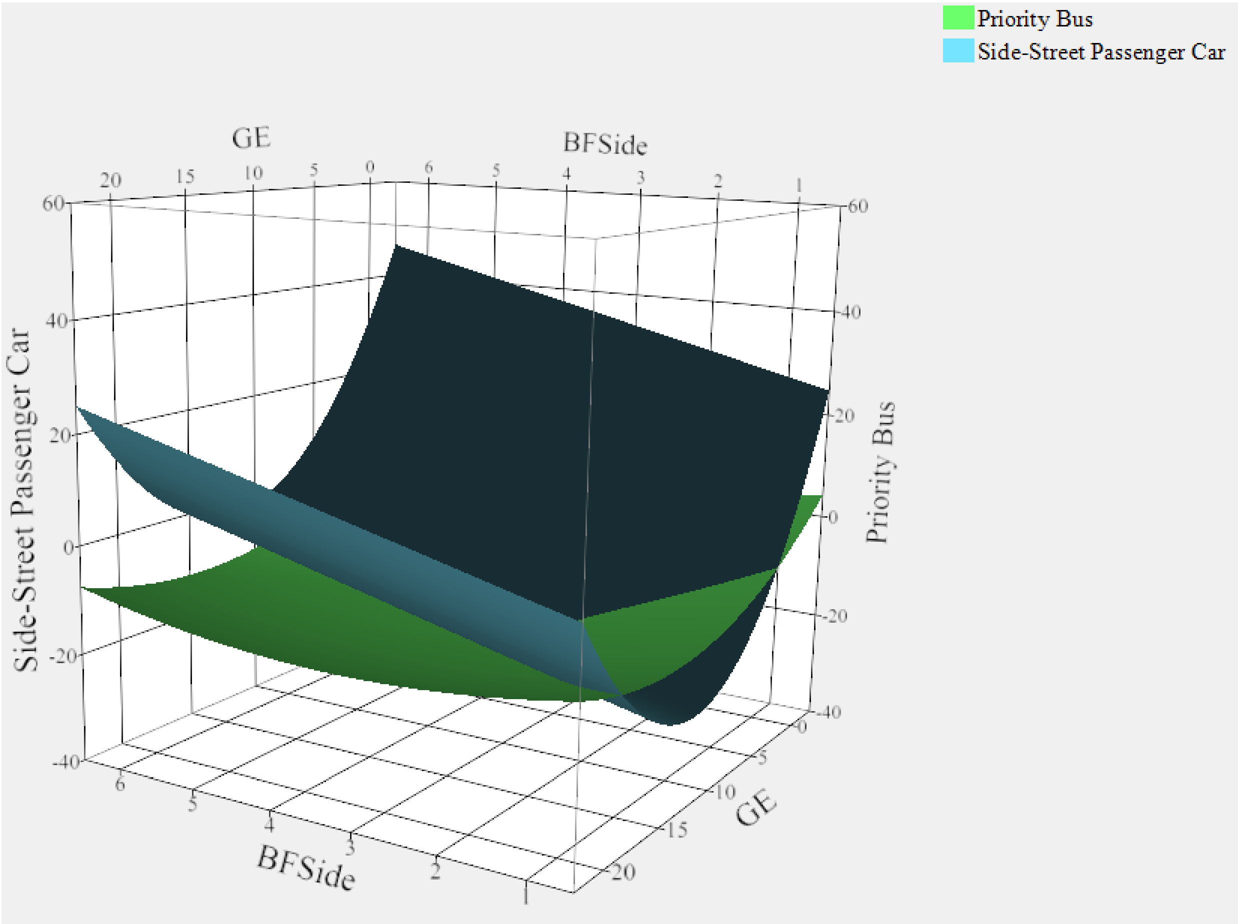

Figure 9: surface plot of delay differences against BF-Side and GE

Another noticeable observation was that the priority bus delay slightly increased as the traffic demand on the arterial grew. This is because the left turners on the arterial induce more calls on the signal controllers and this limits the signal controllers' ability in implementing a flexible priority, both in terms of timing and strategy. On the other hand, side-street passenger cars are always delayed more in higher ratios of traffic on the side streets, due to the queue built-up. Figure 10 shows the effect of travel demand variation on the dependent variables.

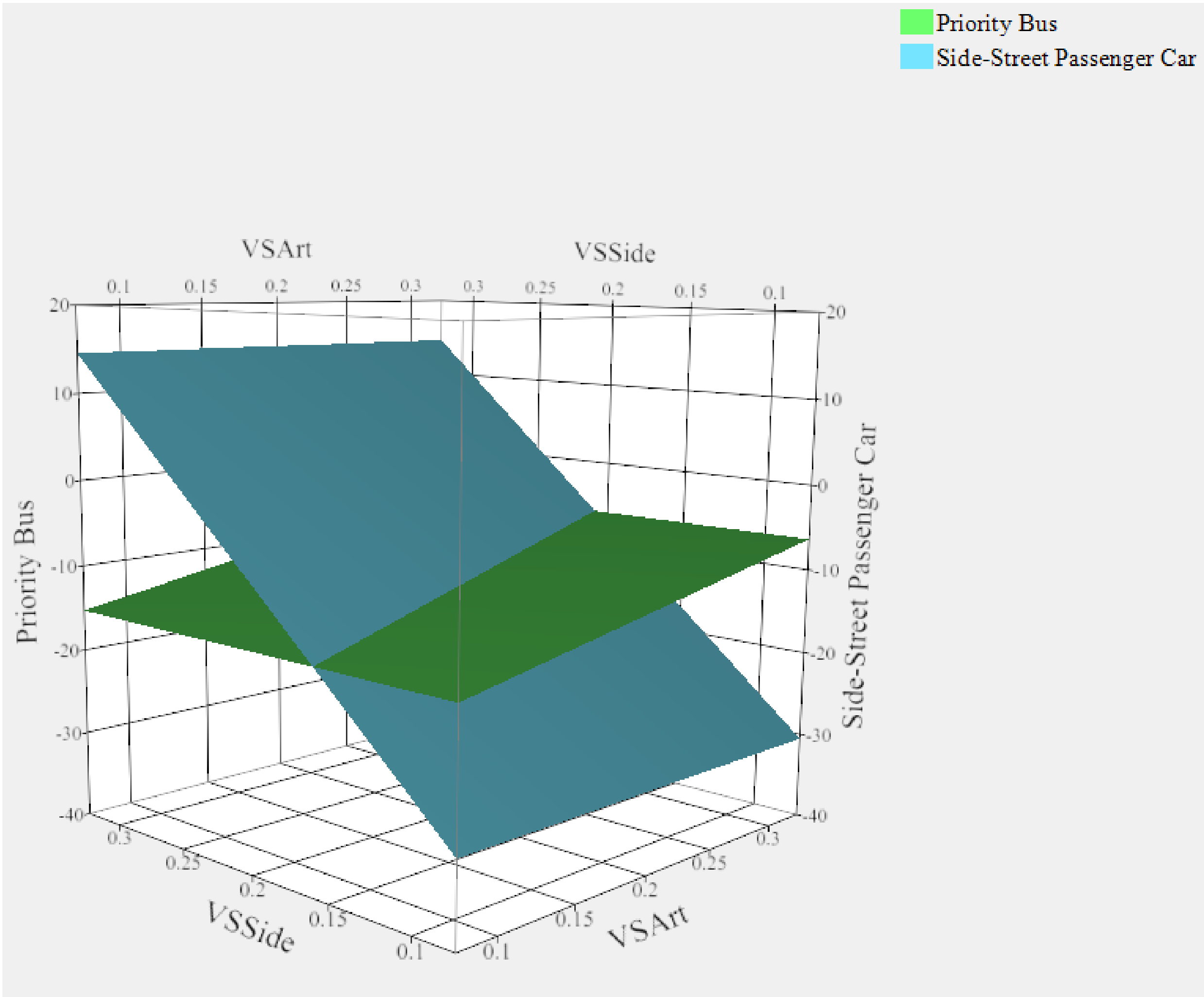

Figure 10: Surface plot of delays against VS-Art and VS-Side

2.6 Conclusion and Future Research

In this study, TSP was implemented on five bus lines travelling on Prices Fork Road arterial and the surrounding side streets in town of Blacksburg, VA. The aim was to investigate how TSP will improve transit performance in a conflicting TSP request network and under various bus frequencies and traffic demands. The parameters of transit signal priority menu of Ring Barrier Controller, embedded in VISSIM simulation software, were examined to study whether or not these parameters significantly influence TSP operation. It was found that among green extension, priority progression, and priority level, green extension and priority level significantly improved the travel time of priority buses. Green extension played an important role in TSP efficiency; not only did its optimal value reduce priority travel time for buses, but it also reduced the delay experienced by side-street passenger cars. Priority level on the other hand, was a significant independent factor for priority bus delay, but not for passenger cars. Since the number of side-street transit lines was higher than the arterial transit lines, setting higher priority to side-street bus lines reduced the priority bus delay even further.

Considering traffic condition, this variable does not have any significant influence on priority bus delay, while side-street passenger car delays increases in higher side-street traffic volumes.

Priority level parameter of RBC controller affects signal timing on the intersection level; while a bus is provided priority on one intersection due to higher priority level assignment, it may be stuck in the downstream intersection because it is requesting priority from a phase that is not assigned high priority level, and therefore the upstream priority provision would become ineffective. Future research can be investigating the effect of Route-based Priority Level on the TSP performance. The other important factor is the location of buses' check-in detectors. While detecting a bus when it is close to an intersection makes the travel time prediction of the bus more reliable, it limits the TSP options on what priority strategy to use. On the contrary, checking-in a bus further from an intersection provides more flexibility for signal controller, while the travel time uncertainty increases and this reduces the efficiency of a priority phase. Therefore, another interesting research area is optimizing the location of transit's check-in detection in a conflicting transit signal priority request environment by using a GPS-based detection method.

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CHAPTER 3: EVALUATION OF THE ADAPTIVE TRANSIT SIGNAL PRIORITY OF THE VISSIM RING BARRIER CONTROLLER

Kianoush Kompany[1]; Montasir Abbas, Ph.D., P.E.[2]

3.1 Abstract

By using the adaptive transit signal priority feature of the VISSIM Ring Barrier Controller; this study aims to identify the traffic conditions in which this adaptive feature can be most useful. In order to activate adaptiveness, Detector Slack, Detector Adjust Threshold, and Adjust Step are the parameters that should be hardcoded in the controller. The network corridor is based on three signalized intersections of Prices Fork Road in Blacksburg, Virginia. A total of five transit lines are assumed to request signal priority, whereas their operating routes are a combination of corridor and side street links. The experiment results suggest that a regression model can map transit lines and passenger car delays to the adaptiveness parameters of the Ring Barrier Controller, bus frequency, and traffic demand levels. This study also revealed that service overlap among the bus routes can enhance or exacerbate each bus performance when transit signal priority is implemented, depending on the scheduled headway of the buses and the frequency of signal priority requests in each intersection.

Keywords: Adaptive Transit signal Priority, Detector Slack, Detector Adjust Threshold, Adjust Step, VISSIM Ring Barrier Controller, Regression Analysis, Coordinated-actuated Arterial

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3.2 Introduction

There are several bus preferential treatment strategies, both in terms of geometric as well as signal control enhancements. Signal controllers can be modified to change the signal plans in favor of transit vehicles either on the middle of the links (pre-signals) or on the intersections (transit signal priority) [1]. Pre-signals stop the traffic flow on the same link a transit vehicle is traversing, in order for the bus to encounter less congestion when it arrives at the intersection [1]. Transit signal priority (TSP), on the other hand, manipulates signal lights on the intersections in favor of the transit vehicles.

The effectiveness of TSP highly depends on the traffic condition [2]; therefore, TSP algorithms that account for bus travel time and traffic condition randomness are superior to passive TSP methods in terms of reducing bus delay as well as the negative impacts on passenger car delay. This type of TSP is called Adaptive Transit Signal Priority (Adaptive TSP), a term initially introduced by Ling and Shalaby [3].

The Ring Barrier Controller (RBC) of the VISSIM traffic simulation package allows for using an adaptive TSP algorithm by introducing three parameters: Detector Slack, Detector Adjust Threshold, and Adjust Step [4]. Detector slack is defined as a time by which a bus can arrive earlier or later than the controller's estimated travel time. If the transit vehicle passes the check-out detector earlier or later than the allowed estimated travel time and detector slack, the detector would gap or max out, respectively. If the consecutive number of gap or max out events reaches detector adjust threshold, the detector will update the travel time estimation by "Adjust Step" seconds (with an upper bound limit of 10 seconds) [4]. While detector slack and detector adjust threshold can accept only one common value for all the phases of a signal controller, adjust step can be configured independently for each phase.

3.2.1 Objective

Previous research studies are filled with various algorithms for adaptive TSP; however, there is a gap in the literature for investigating the impact of VISSIM ring barrier controller's adaptive TSP algorithm. This study aims to evaluate and quantify the impact of this adaptive TSP algorithm on a coordinated-actuated arterial consisting of three signalized intersections and five priority transit routes. Three levels of volume to saturation flow rate and three frequency levels of transit operation are considered in order to assess the sensitivity of VISSIM RBC adaptive TSP to the network variations. The network is based on Virginia State Route 412, a major corridor in Blacksburg, home of the Virginia Tech University. Figure 1 depicts the intersections in the modeled network. Rest of the paper is organized as follows: 1) Literature Synthesis; 2) Methodology; 3) Results; 4) Conclusions.

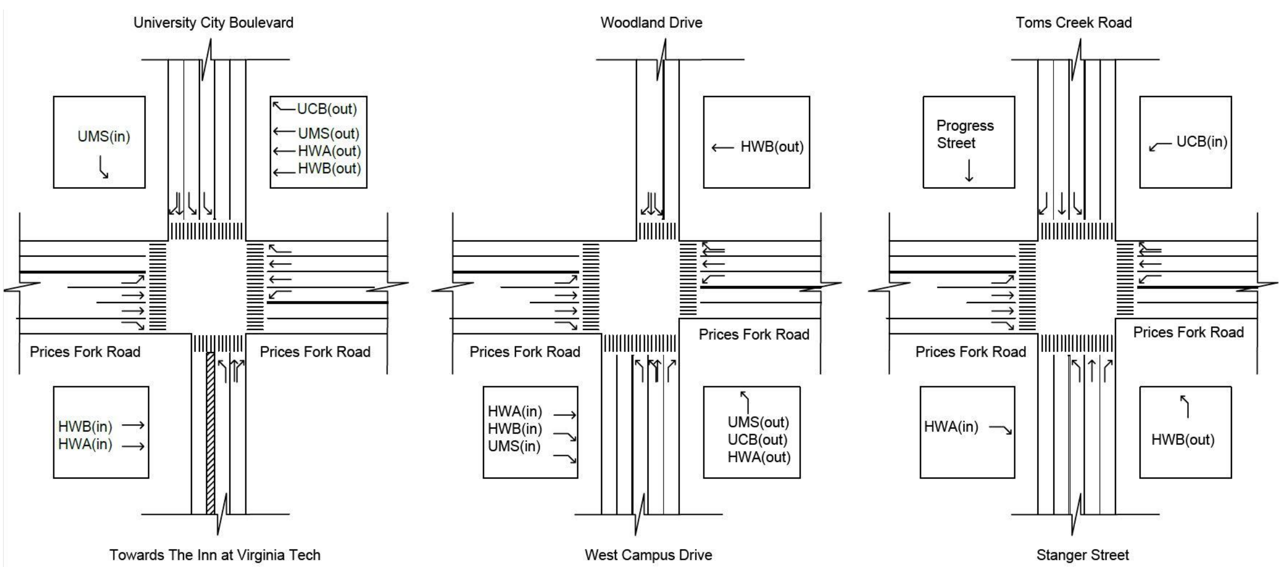

Figure 1: Layout of the intersections

3.3 Literature Synthesis

Transit signal priority is a preferential treatment strategy for ameliorating bus delays. Intelligent transportation systems have allowed for applying adaptive transit signal priority (Adaptive TSP), which uses detector actuation and considers network traffic conditions and bus travel time variability to accomplish the goal of reducing transit delay [3]. The issues that the literature deals with in developing adaptive TSP strategies are described below.

Accurate prediction of bus arrival time to the intersection is probably the most important factor for a successful adaptive TSP implementation. Bus travel time depends on driving behavior, bus passengers' activities, bus dwell time at bus stops, and the interaction of transit vehicles with the normal traffic [5]. For this purpose, Ekeila, Sayed [6] proposed a dynamic transit signal priority (DTSP) model that assumes an upper and lower bound for the travel time prediction and it delays implementation of the TSP plan in order to avoid substantial delay on the side-street traffic. Travel time was defined as the dependent variable on the arrival prediction model, and it was mapped to bus distance and dwell time. By continuously observing the location of the transit vehicles (Automated Vehicle Location technic) on each segment, the most suitable priority plan was activated at such a moment that the negative effect on the normal traffic was minimal. Implementing DTSP on an LRT line operating in a corridor of seventeen intersections revealed that this TSP method outperformed conventional active TSP by reducing bus delay at thirteen intersections [6].

The impact of providing buses with signal priority on the other modes of travel should be taken into account during the development of adaptive TSP algorithms. Ding, Yang [7] applied an ARIMA-SVM hybrid model that predicts transit travel time and finds optimal signal splits by a multi-criteria objective function. The goal was to minimize average delay per person, maximal queue lengths on the intersection, and all exhaust emissions. The proposed method decreased the negative impact of applying TSP on person delay, queue length, and emissions, compared to the conventional TSP [7].

Traditional practice for dealing with conflicting priority calls is to serve the requests on a first-come first-served basis. This logic would not be optimum in a situation when a conflicting late call would benefit more from the signal priority, compared to an already prioritized transit vehicle [8]. Christofa and Skabardonis [9] suggested a traffic responsive scheme that addresses the problem of conflicting bus calls in real-time and minimizes the negative impacts on passenger cars. The novelty of this work was introducing a person-based objective function that reduces the delay for each road user regardless of the type of vehicle they are in [9]. The implementation of this method on a congested intersection used by four bus lines in Athens, Greece, brought about 9.5% delay decrease of all passengers and 35.5% delay decrease of transit users [9]. This method was later developed by using a pairwise optimization model to make it applicable to arterials. This model was implemented through a case study on an arterial in Berkeley, CA, which includes four intersections and three bus lines. The results showed that the average speed of all the vehicles in the network increased, compared to the TRANSYT-7F traffic signal optimization software [10].

The current study was conducted on a corridor consisting of overlapping bus routes, in such a way that four bus lines travel on three link segments. Presumably, this would negatively affect adaptive TSP efficiency of VISSIM RBC emulator, as Diab, Bertini [11] found that overlapping bus routes were responsible for 3.8 seconds of increase in bus headway delay in Portland, Oregon, USA., where all the buses are equipped with TSP technology [11].

TSP benefits vary based on different traffic demands and bus operation levels. For running sensitivity analysis on a signalized intersection, Zhang and Rakha [2] designed an experiment using nine variables including: departure time of transit vehicle, signal phasing method, traffic demand, demand distribution among the approaches, signal cycle length, signal phase splits, bus dwell time at the bus stops, bus frequency, and the link on which the transit vehicle arrived. The analysis revealed that TSP is most useful for reducing bus delay in higher traffic demands, while the delay difference of passenger cars remained marginal, proving to be insensitive to travel demand. This study also reported that passenger car delays were insensitive to bus frequency [2].

To overcome the burden of implementing a fully adaptive transit signal priority on the current infrastructure (which needs huge investment), Li, Yin [12] formulated an adaptive TSP that can be integrated with actuated systems. This adaptive TSP minimizes the weighted sum of bus and other vehicle delays by optimizing the phase splits of three consecutive cycles. This method revealed a reduction of thirty-six percent, considering both buses and auto vehicles [12].

Some of the suggested TSP algorithms are coded using Vehicle Actuated Programming logic (VAP) of VISSIM. However, more clarifications are needed to make sure whether or not these methods comply with the controller operations and provide rational transition from the TSP implemented cycles to the normal operation [13], [14]. On the other hand, the methods that do not consider stochasticity of the network cannot assure real-world benefits; therefore, this study quantifies an embedded TSP algorithm in VISSIM RBC emulator by considering the variabilities in the traffic condition and transit level of operation.

3.4 Methodology

3.4.1 Design of Experiment

The variables used in this study are based on the findings of previous research studies. The most important parameters that can influence the performance of TSP are either related to traffic condition or signal controller. In terms of traffic condition, this study included traffic demand, bus frequency, and bus dwell time at the bus stops. In order to relax the dwell time effect, bus check-in detectors were placed after the bus stops. This reduces travel time variability as the dwell time follows a normal probability distribution and increases uncertainty. In terms of the controller, the parameters included in this study were detector slack, detector adjust threshold, and adjust step. The independent variables and their values are illustrated in Table 1.

Table 1: Discription of the Independent Variables

Variable	Variable description	Input Values	Unit
BF	Bus Frequency	2.0, 4.0, 6.0	vehicles/hr.
V/S	Volume to Saturation Flow Rate	0.1, 0.2, 0.3	-
Slack	Detector Slack	2.0, 4.0, 5.0, 6.0, 8.0, 10.0, 12.0, 14.0, 16.0	seconds
Threshold	Detector Adjust Threshold	2.0, 3.0, 4.0, 5.0	-
Step	Adjust Step	4.0, 6.0, 8.0, 10.0	seconds

Independent variables were input to JMP Statistical Software to obtain the necessary scenarios that can lead to statistically significant inferences from the results [15]. A total of twenty-four scenarios were offered by JMP.

Since the delay imposed on each transit line depends on the direction (heading to the campus or away from the campus), the authors decomposed the results of the bus lines based on the directions to analyze the delays separately for each direction and intersection. Table 2 explains the abbreviated intersection names and the dependent variables related to directional transit operation, total priority bus and passenger car delay.

Table 2: Description of the Dependent Variables

Variable	Variable description	Traversing Intersection(s)
UCB	Prices Fork Road at University City Boulevard	
WCD	Prices Fork Road at West Campus Drive	
TOM	Prices Fork Road at Toms Creek Road	
HWA(in)	Delay difference* of Hethwood A bus line inbound to campus	UCB, WCD
HWA(out)	Delay difference of Hethwood A bus line outbound from campus	UCB, WCD
HWB(in)	Delay difference of Hethwood B bus line inbound to campus	UCB

HWB(out)	Delay difference of Hethwood B bus line outbound from campus	TOM, WCD, UCB
Progress	Delay difference of Progress Street bus line (only inbound to campus)	TOM
UCB(in)	Delay difference of UCB bus line inbound to campus	TOM
UCB(out)	Delay difference of UCB bus line outbound from campus	WCD
UMS(in)	Delay difference of UMS bus line inbound to campus	UCB
UMS(out)	Delay difference of UMS bus line outbound from campus	WCD, UCB
PB	Average delay difference of all the priority bus vehicles	TOM, WCD, UCB
PC	Average delay difference of all the passenger cars	TOM, WCD, UCB

Note: Unit of delay difference is sec/vehicle and is the comparison between adaptive TSP and Base scenarios.

3.4.2 Signal Plan Development

Traffic volumes of each scenario were input into VISTRO signal optimization software and phase splits, cycle lengths, and offsets were optimized assuming a coordinated-actuated operation, due to the close distances between the intersections [16]. The objective was to minimize the total vehicle delays. Genetic algorithm option in VISTRO was used to reach near optimal phase splits and cycle lengths to address this minimization problem [17]. Although VISTRO signal optimization method suggests satisfactory and near optimal signal plans, it does not account for driving behavior and randomness of traffic condition. To consider network stochasticity, Dabiri and Abbas [18] integrated VISSIM and MATLAB using COM interface and obtained delay results after each iteration of the simulation, results were used to generate new signal plans for the next iteration. The heuristic algorithm used was Particle Swarm Optimization, which led to modified signal timing plans capable of reducing the average vehicle delays by seven percent more than the near optimal plans of VISTRO [18].

Signal phasing was modeled based on the real-world configuration of the intersections. Phasing operation on UCB intersection is protected. Once the green indication of left turn signal heads changes to red, left turners are prohibited to turn. Nevertheless, left turners on the intersections of WCD and TOM are allowed to turn during the green phase of their adjacent through movements, given that there are enough gaps between the through moving vehicles of the opposite direction. Figure 2 and 3 show the intersections signal phasing.

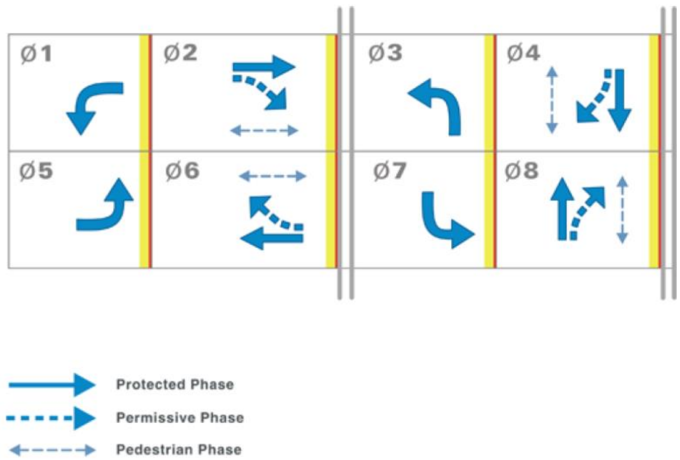

Figure 2: Signal phasing at UCB intersection [19].

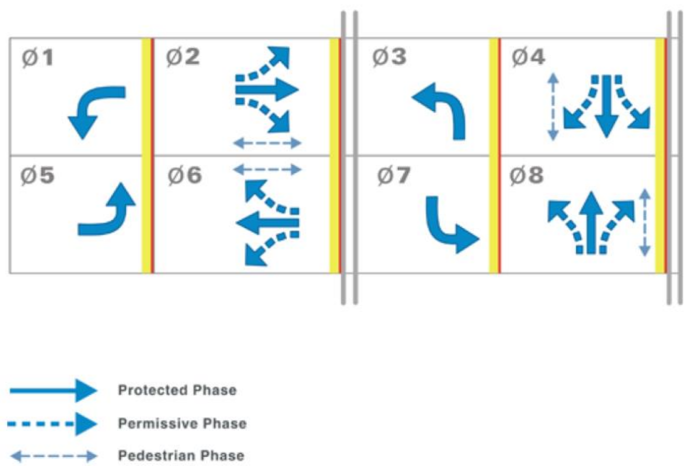

Figure 3: Signal phasing at WCD and TOM intersections [19].

3.4.3 Detectors Layout

The fact that the speed limits on the network links are equal to or less than 55 km/hr. made the use of stop line loop detectors legitimate. These presence detectors were placed on actuated approaches, with a length of 12 meters for through movements and 6 meters for left-turn movements. Memory of the signal controllers was set to non-locking mode, so that the permissive movements do not induce a phase change.

For the detection of transit vehicles, check-in detectors were placed right after each bus-stop (if there is any bus-stops on the link), upstream of the intersection that a bus may call for signal priority; therefore, considering dwell time variations of transit vehicles at the bus-stops was not required. Check-out detectors were placed right before the stop-lines. If the check-out detectors be placed after the stop line, signal state becomes an influential factor of the travel time, which makes implementation of adaptive TSP methods futile. Figure 4 shows the layout of the detectors for a typical intersection of the network.

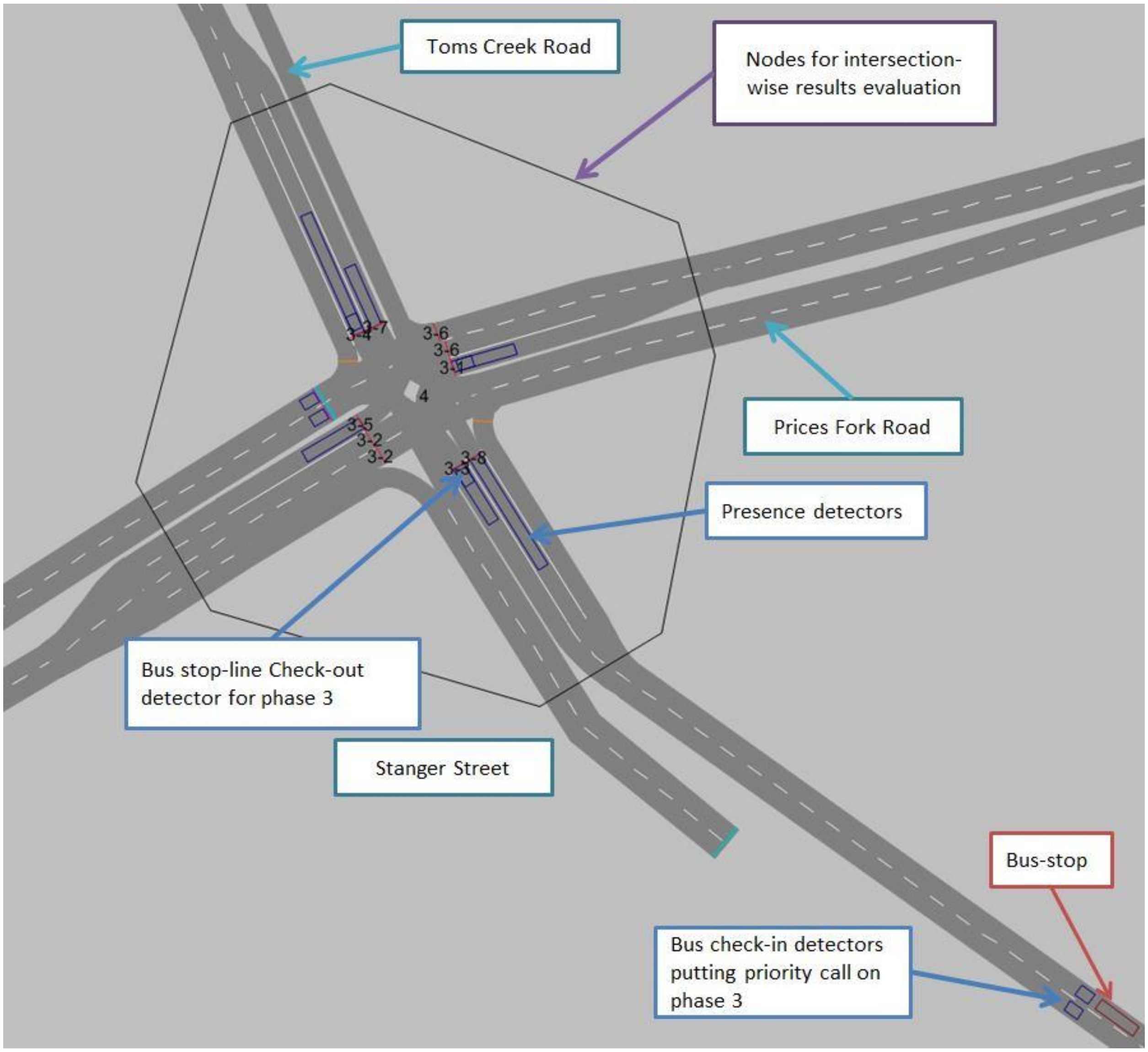

Figure 4: Layout of the detectors

3.4.4 Bus Entrance Time to the Network

The time it takes for the transit vehicles to enter the modeled network was input to the simulation by estimating the travel time between the time-check bus station (outside the model) and the network, and a dwell time of 20 seconds was considered if there were any bus stations in between. Equation 1 represents the formula used for the estimation of transit vehicle entrance time to the network:

$$ET_i = \frac{D_i}{v_{mean}} + DT_{mean} \times N_i \qquad (1)$$

Where,

ET_i = entrance time of bus i to the network

D_i = closest distance between the time-check bus station (outside the network) of bus i and the modeled network

v_{mean} = bus average speed (assumed to be 50 km/hour)

DT_{mean} = average dwell time of transit vehicles at bus stops (assumed to be 20 seconds)

N_i = number of bus stops that transit vehicle i stops at before entering the network

The scenarios were modeled in VISSIM traffic simulation package and iterated 10 times using 10 random seeds. Base scenarios with the same configuration of adaptive TSP scenarios were also modeled, except for the fact that they TSP feature was inactive for them. Simulation time was 120 minutes, in which the first 30 minutes were used for the network warm-up; hence, the networks were analyzed for 90 minutes.

3.5 Results and Discussion

Priority bus delay, passenger car delays, and the directional delay of each bus line were analyzed for each intersection. The results of delay on UCB intersection is firstly presented and discussed, followed by the representation and discussions for WCD and TOM intersection results.

3.5.1 UCB Intersection

Analysis of variance (ANOVA) on the regression model of each bus shows that PC, HWB(in), HWB(out), HWA(in), are the delay difference variables that are significantly affected by adaptive TSP. P-values of the t-test on the independent variables are presented in table 3.

Table 3: T-test for Significantly Predicted Dependent Variables (UCB Intersection)

UCB Intersection	PC	HWA (in)	HWB(in)	HWB (out)
Term	Prob.>|t|	Prob.>|t|	Prob.>|t|	Prob.>|t|
Intercept	0.1964	0.6568	0.687	0.3361
Slack(2,16)	0.1413	0.837	0.4244	0.8033
Slack*Slack	0.6658	0.1707	0.8815	0.3533
V/S(0.1,0.3)	**0.0008**	**<.0001**	0.251	0.0674
V/S*V/S	0.7007	**0.0224**	0.2337	0.4856
Threshold(2,5)	0.3646	0.0686	0.1613	**0.0373**
Threshold*Threshold	0.7705	0.6826	**0.0126**	**0.0178**
Step(4,10)	0.1977	0.8782	0.0823	0.0535
Step*Step	0.7381	0.6363	**0.0474**	0.3674
TotalBus	0.0853	**0.0171**	**0.0043**	0.9748
(TotalBus-34.5)*(TotalBus-34.5)	0.4015	**0.0263**	**0.0059**	**0.0119**

Note: Bold numbers indicate significant variables in 95% confidence interval.

Significance analysis for each dependent variable shows that PC increases with the increase of traffic demand (Figure 5). As the volume increases, side-street vehicles request for higher duration of green. This allocates more green time to the side-street phases and imposes higher delay on the coordinate approaches.

TotalBus is the average number of buses that arrived to the intersection. This variable defines the relationship of scheduled headway of the bus lines and the delay differences. As the number of buses increases in the intersection, delay of HWA (in) increases. The reason is that serving the priority requests received from other bus lines disturbs HWA (in) movement and makes this line hit the red light more often. However, HWB (in) and HWB (out) gain benefit from increasing number of buses to a certain point, and after the minimum delay is achieved, higher frequency of buses increase the delay again.

HWB (in) was served effectively by the adaptive TSP and a detector threshold of five and step of eight seconds minimized the delay difference for this direction of HWB bus line. The close headway among the transit lines that travel westbound on the link between UCB and WCD intersection helps HWB (out) to join the platoon of prioritized buses. This direction of HWB line prefers the least variations on the travel time estimation, as a threshold of 5 and step of 10 favors this line the most.

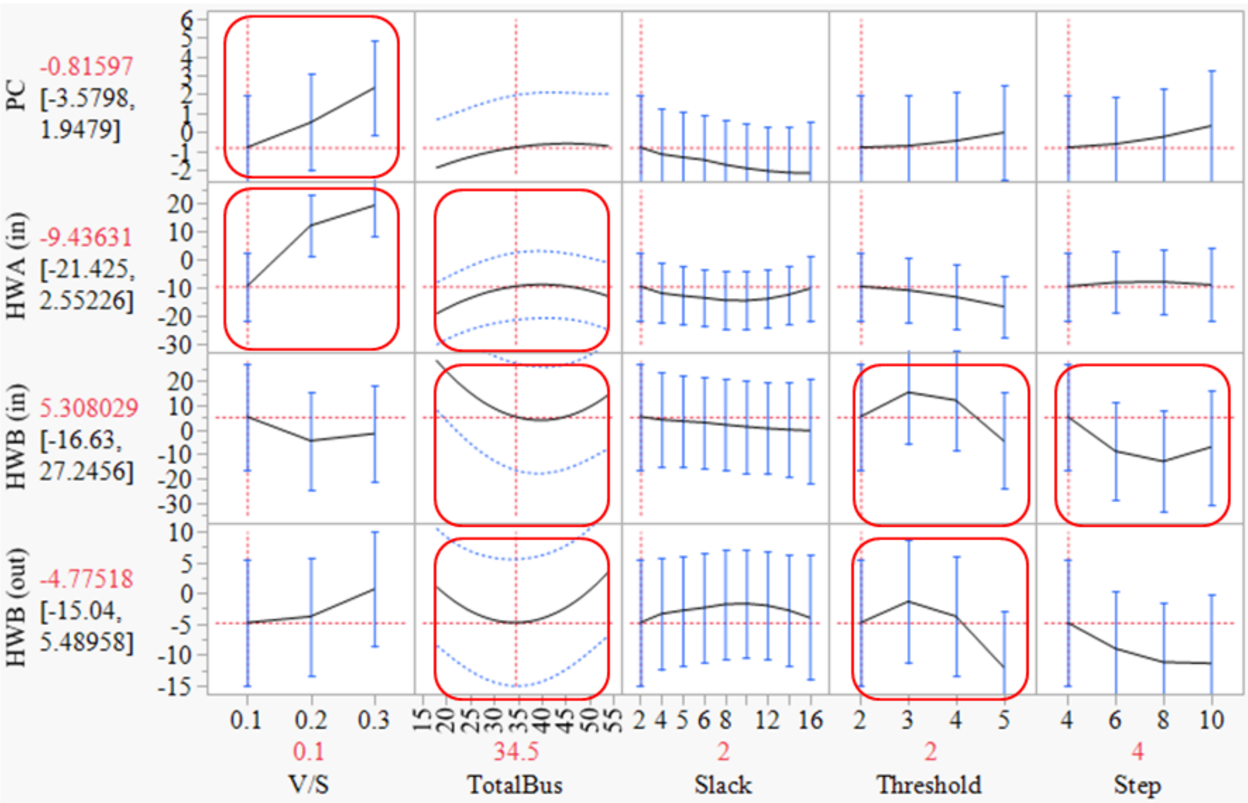

Figure 5: Sensitivity analysis of delay (sec/vehicle) vs. independent variables (UCB intersection)

Although the results indicate that the priority bus delay has significantly reduced compared to the base scenarios (Figure 6), the regression analysis was not able to capture the difference. The main reason is the operational differences of the bus lines, which made taking the average among all the bus lines not explanatory. Moreover, the impact of adaptive TSP depends on the congestion, priority phase request, and the conflicting signal priority requests.

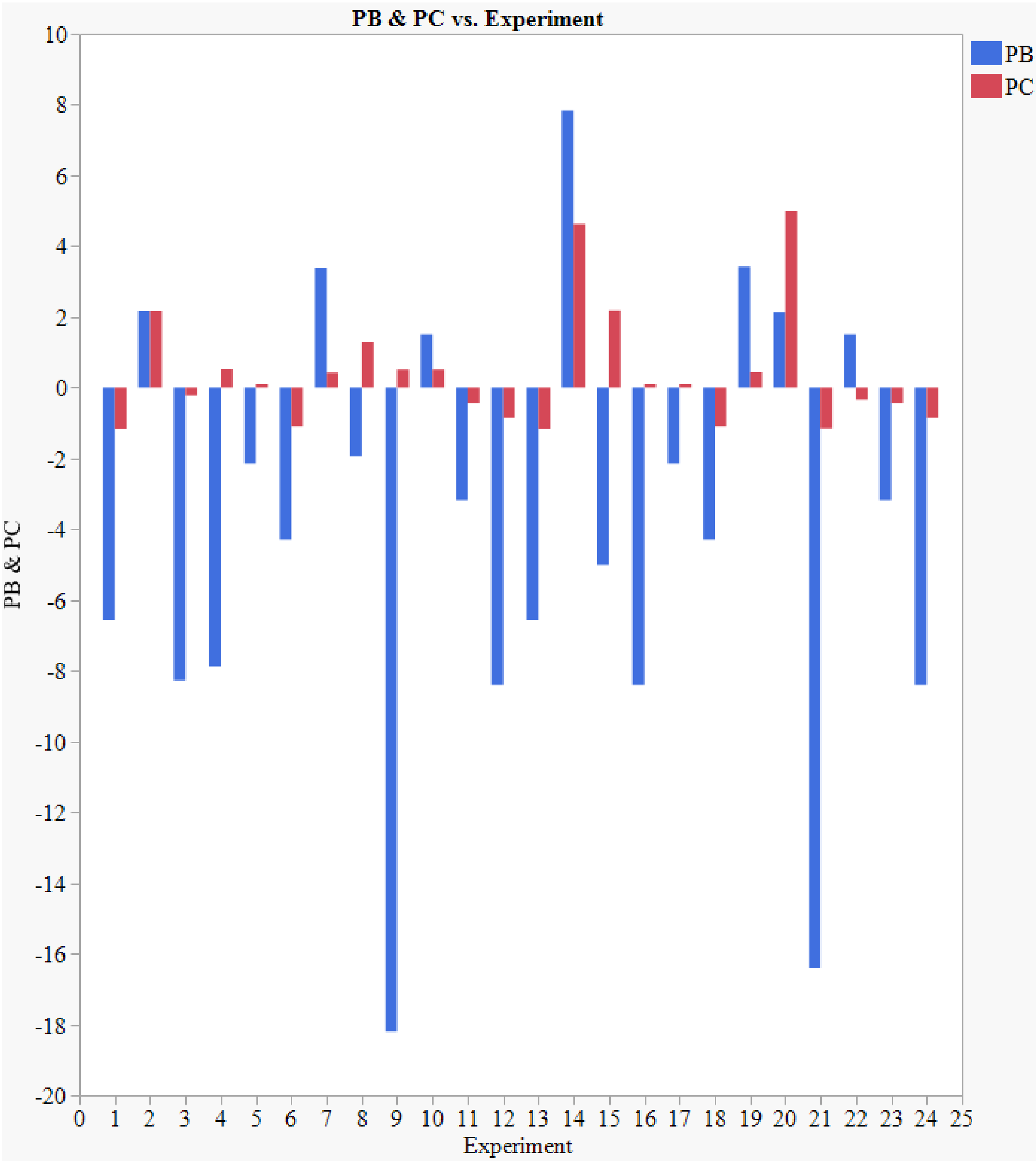

Figure 6: PB and PC delay difference (sec/vehicle) against each experiment for UCB intersection

When UMS (out) and HWA (out) call for signal priority, the close proximity between the check-in and check-out detectors results in very little fluctuations for their travel time, thus the adaptiveness feature does not work for these lines. In other words, UMS (out) and HWA (out) used to get benefit from the implementation of TSP, and not the adaptive TSP (Figure 7).

The delay results in Figure 7 explain the reason for insignificant regression model for UMS (in). UMS (in) requests priority on phase 7 (southbound left turn); because the traffic demand of this approach does not vary among the experiment for this approach (it is 10 % of the total traffic of the approach), there was no queue on the stop line before each bus arrival event at the intersection. The fact that the check-out detectors are placed before the stop lines, signals the controller that the travel time estimation has been accurate and that the travel time has not exceeded the time frame defined by detector slack. Hence, the benefit was obtained from implementation of TSP, and not the adaptiveness feature.

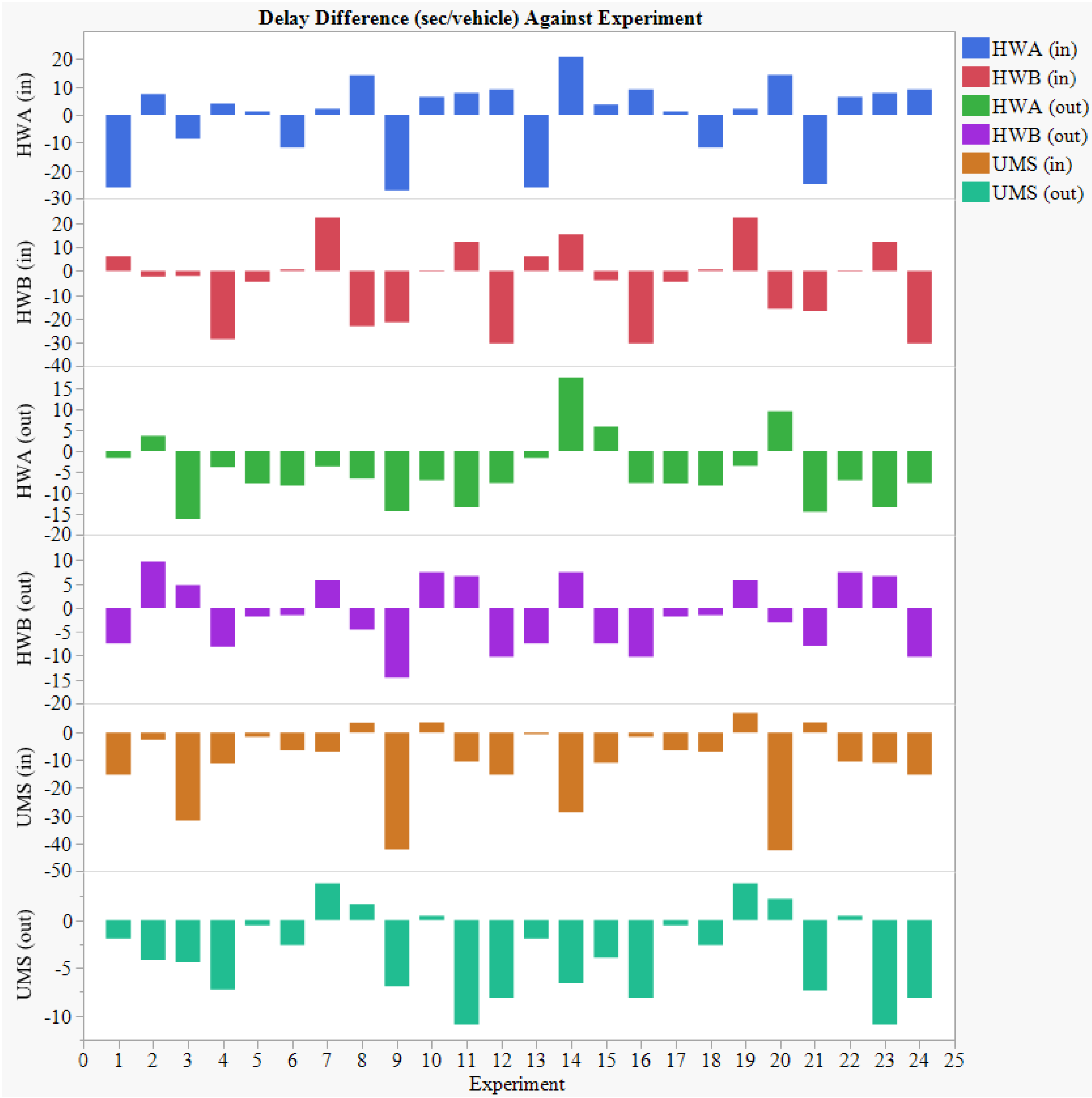

Figure 7: Effect of conflicting calls on delay difference (UCB intersection)

3.5.2 WCD Intersection

The model significantly captured the delay differences of UMS (out), HWA (out), PB, PC. Results of the t-test are shown in Table 4. As can be observed from table, slack was a significant predictor of all the dependent variables. Figure 8 reveals that the higher the slack was, the lower the delay differences would become. This means that in the intersection of WCD, updating travel time estimation rapidly, when the variability of travel time falls beyond the time frame defined by detector slack, would be the best practice.

Table 4: T-test for Significantly Predicted Dependent Variables (WCD Intersection)

WCD Intersection	PB	PC	HWA(out)	UMS(out)
Term	Prob.>|t|	Prob.>|t|	Prob.>|t|	Prob.>|t|
Intercept	**0.0227**	0.2343	**0.0029**	0.995
Slack(2,16)	**0.0076**	**0.0153**	**0.0046**	**0.0042**
Slack*Slack	0.1096	0.8509	0.0906	0.2486
V/S(0.1,0.3)	**0.0374**	**0.0002**	**0.0352**	0.3681
V/S*V/S	0.6795	**0.0002**	0.5664	0.8034
Threshold(2,5)	0.0902	0.211	**0.0297**	**0.0123**
Threshold*Threshold	0.9246	0.6618	0.8596	0.9384
Step(4,10)	0.8016	0.4196	0.246	0.5038
Step*Step	0.6847	**0.0157**	0.4415	0.4646
TotalBus	0.2523	0.7097	0.9126	**0.0016**
(TotalBus-34.5)*(TotalBus-34.5)	0.7818	0.1376	0.7995	0.6153

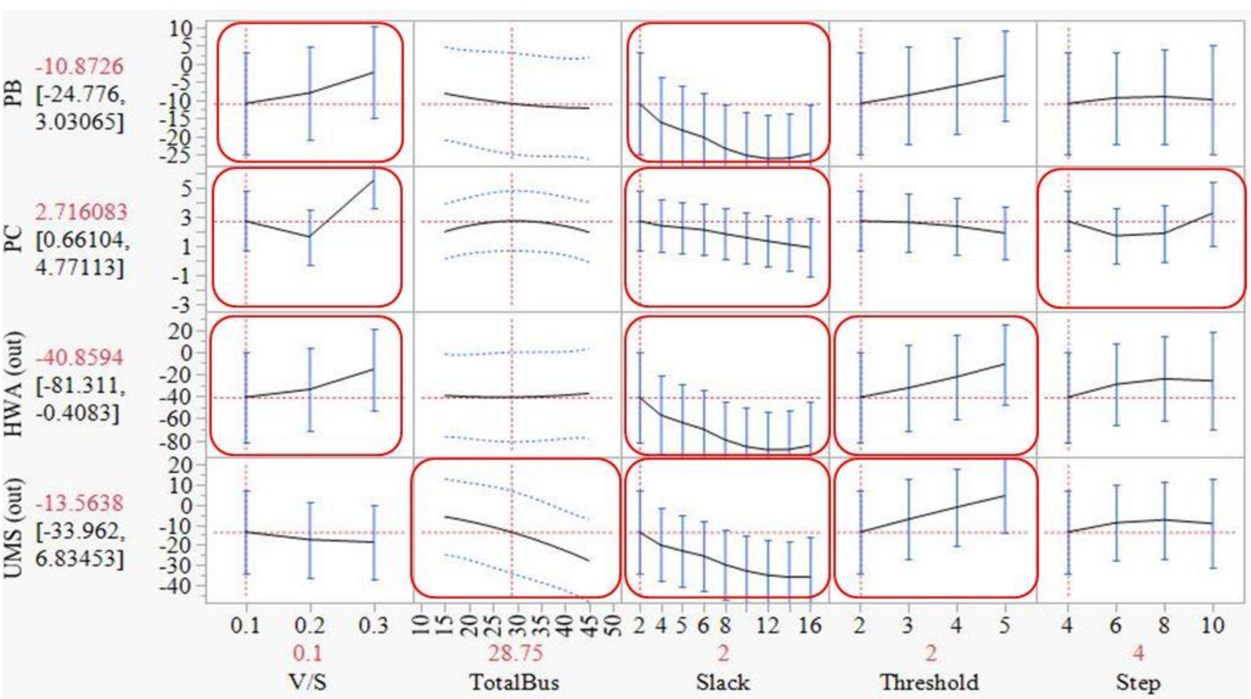

Figure 8: Sensitivity analysis of delay (sec/vehicle) vs. independent variables (WCD intersection)

The variables cannot predict changes of HWB (in), HWB (out), and UCB (out). However, Figure 9 shows that delay reduction was significant; so the inference is that the travel time was not highly variable for HWB (in), HWB (out), and UCB (out), and this is the main reason why the adaptiveness feature is not activated for these directions of the bus lines.

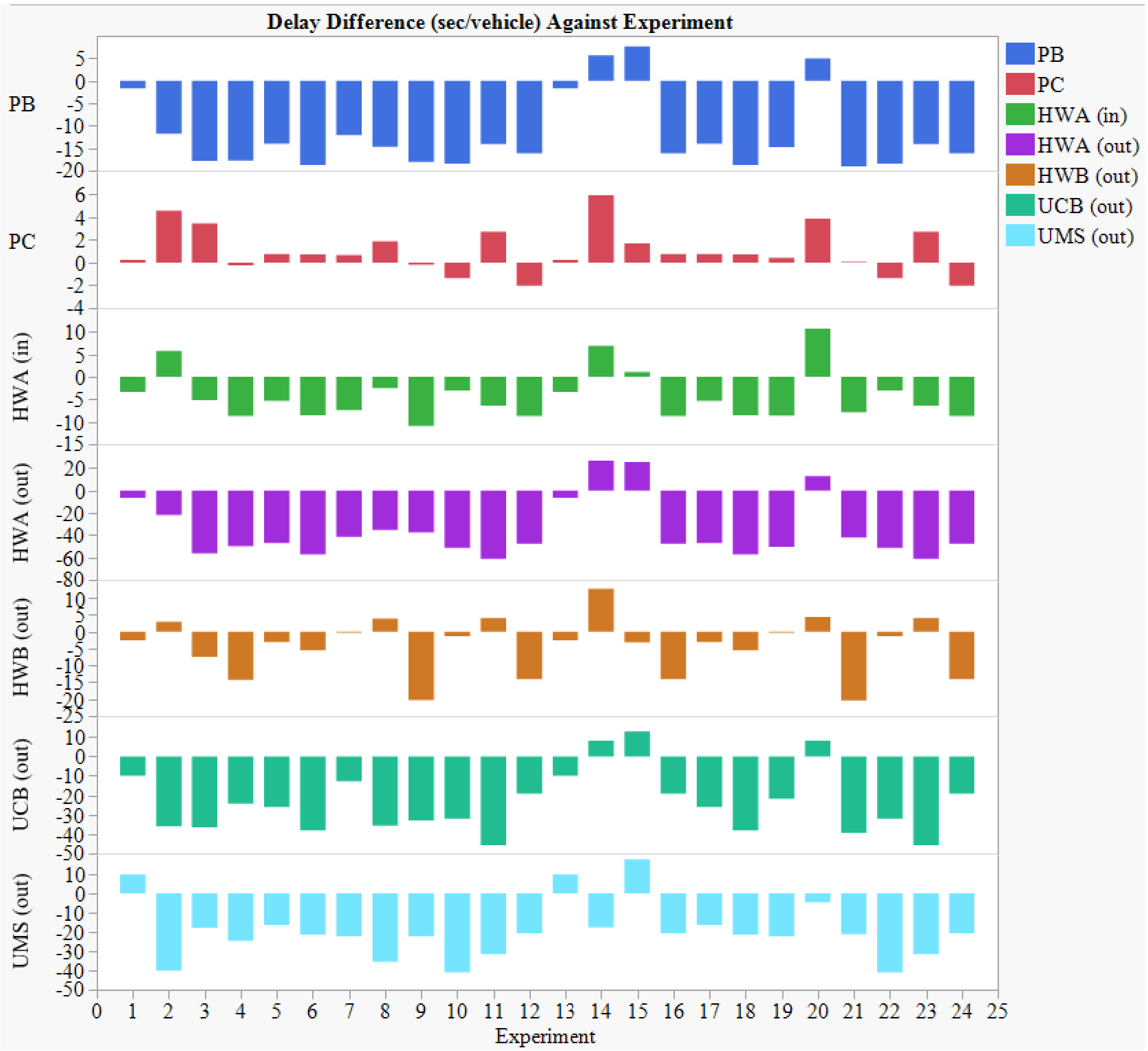

Figure 9: Delay Difference (sec/vehicle) against each experiment for WCD intersection

3.5.3 TOM Intersection

Regressions models can predict all the dependent variables including: PB, PC, Progress, UCB (in), HWB (out). This declares the fact that an intersection with fewer number of priority buses, provides more room for adaptive TSP implementation, since the intersection signal controller does not get confused by the overlapping bus lines that ask for the priority of similar phases. Specifically, Progress St. transit line gained the most benefits, as its delay was mostly decreased when the parameters of adaptiveness were set to the lowest values (Figure 10 and 11). Table 5 represents P-values of the t-test.

Table 5: T-test for Significantly Predicted Dependent Variables (TOM Intersection)

TOM Intersection	PB	PC	Progress St.	UCB(in)	HWB(out)
Term	Prob.>|t|	Prob.>|t|	Prob.>|t|	Prob.>|t|	Prob.>|t|
Intercept	**0.0127**	0.1101	**<.0001**	0.8903	0.2761
Slack(2,16)	0.5824	**0.038**	0.1826	0.3613	0.1337
Slack*Slack	0.7631	0.6857	0.9901	0.4783	0.0996
V/S(0.1,0.3)	0.5288	0.5232	**0.0301**	0.355	**0.0006**
V/S*V/S	0.29	**0.0024**	**<.0001**	0.2047	0.182
Threshold(2,5)	0.6546	0.6211	**<.0001**	**0.0082**	0.7173
Threshold*Threshold	0.3674	0.3954	**0.0111**	0.6055	0.9283
Step(4,10)	0.9211	0.1176	**<.0001**	**0.0003**	0.1526
Step*Step	0.2989	**0.0205**	**0.0002**	**0.0357**	**0.0423**
TotalBus	**<.0001**	0.2437	**0.018**	**0.0242**	**0.0013**
(TotalBus-34.5)*(TotalBus-34.5)	**<.0001**	0.0671	0.2625	0.6716	**0.0002**

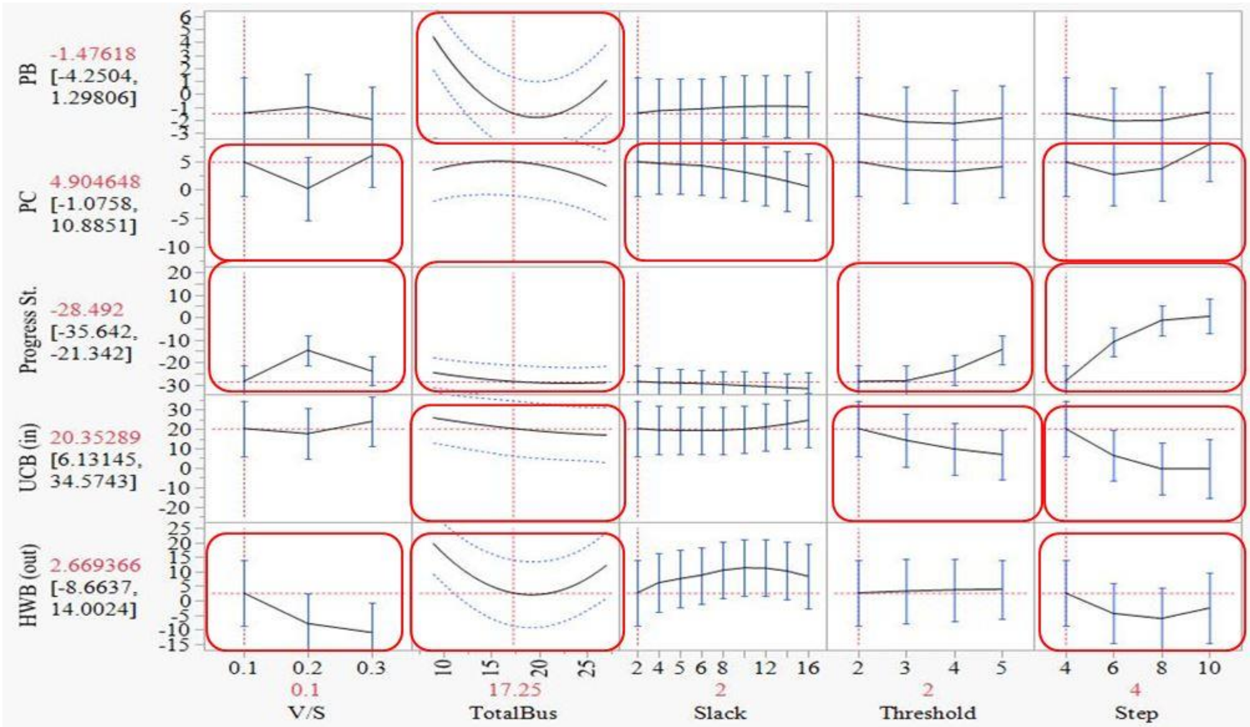

Figure 10: Sensitivity analysis of delay (sec/vehicle) vs. independent variables (TOM intersection)

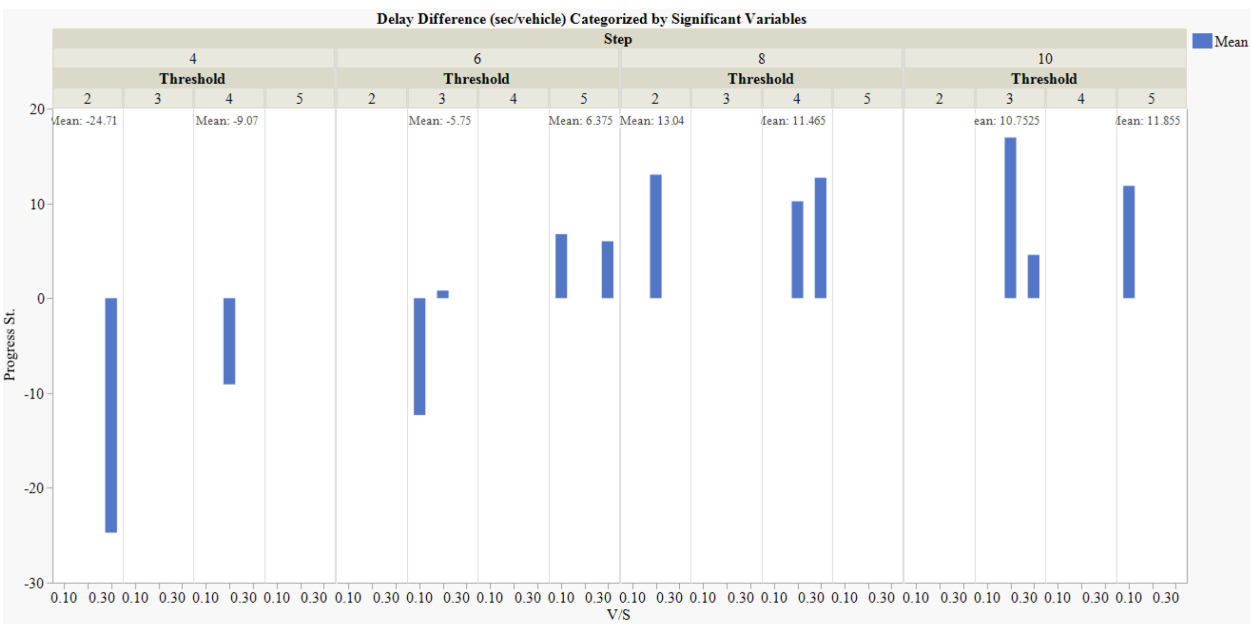

Figure 11: Delay difference of Progress St. categorized by the significant variables

Priority bus delay was quadratically sensitive to the TotalBus variable. This proves the importance of scheduling and headway relationship among the bus lines. As figure 10 suggests, when the total transit volume was 20 (vehicles/hour), the conflicting calls on TOM intersection became minimum.

UCB (in) was the only bus that used to ask for an arterial left turn phase. It was insensitive to traffic demand level (V/S) because the rate of left turn was low (ten percent of total volume of the approach); however, updating the controller's travel time estimation after five consecutive gap or max outs by eight seconds will drastically reduce the delay of this line at the intersection of TOM.

Figure 12 shows the average delay difference (Base scenarios compared to adaptive TSP scenarios) of buses and passenger cars passing TOM intersection. Interestingly, the increase of passenger car delays in seven experiments was not significant, while it has remarkably decreased in four experiments. Allocating more green time to the side streets as a result of TSP requests was the main reason for this observation.

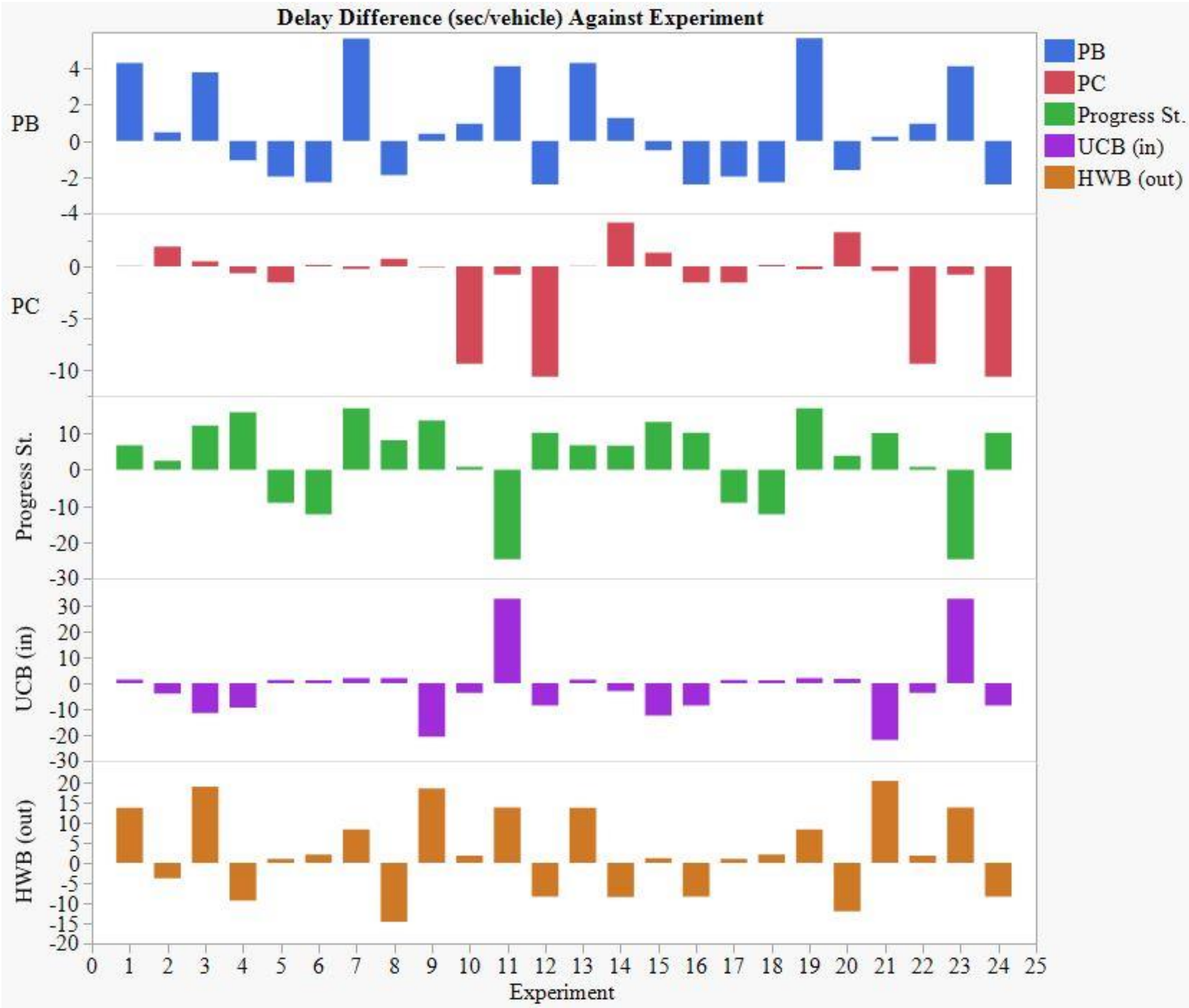

Figure 12: Delay Difference (sec/vehicle) against each experiment for TOM intersection

3.6 Conclusion and Future Research

The effectiveness of internal adaptive TSP logic of VISSIM Ring Barrier Controller was studied in this effort. The logic was applied to an arterial, consisting of three signalized intersections and five bus lines. Layout of the intersections was based on Virginia State Highway 412, known as Prices Fork Road. Required scenarios were obtained from JMP statistical software and the average delay of priority buses, passenger cars, and the directional delay of each bus line were compared to the Base scenarios on which no type of TSP were implemented. Main conclusions from this research are:

- Implementation of adaptive TSP algorithm of VISSIM RBC on the under-saturated approaches does not provide extra benefit compared to normal TSP mechanism.
- Transit lines that were not overlapping gained the most benefit from adaptive TSP. As an example, Progress St. bus line operation improved when the Threshold and Adjust Step were set to small values.
- Overlap among the bus lines has a mixed effect on delay difference. When the scheduled headway of the buses that overlap are temporally close, they form a platoon that can pass through one intersection together (as was the case in WCD intersection northbound left-turn approach); however, on the west bound link of Prices Fork Road between WCD and UCB intersection, HWA (out) was served earlier than other bus lines, HWB (out) and UMS (out), in a manner that these bus lines were used to reach the intersection after the termination of the favorable green phase. This highlights the importance of scheduling during the planning phase for transit service.

Future work in this topic can be investigating whether or not the travel time of the transit lines between the check-in and check-out detector follows any form of probabilistic distribution and whether there is any relationship between the travel time and the adaptive TSP parameters of the VISSIM ring barrier controller. As the importance of headway is revealed by this research, configuring the scheduled headway of transit lines to comply the most with the adaptive logic under discussion would be another interesting area to explore. In this case, it is of utmost importance to account for the transfer activities of passengers and the associated delays, between the transit lines in the bus stations.

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CHAPTER 4: CONCLUSIONS

In this research, transit signal priority feature of the VISSIM ring barrier controller (RBC) was used for an arterial incorporating three signalized intersections and five bus lines that were assumed to be eligible to request signal priority. The aim was to evaluate the performance of the active and adaptive TSP algorithms of RBC on a coordinated-actuated arterial. Evaluating the active TSP (which is not adaptive) revealed that green extension is the controller's feature that can significantly reduce transit vehicle and side-street passenger car delays. Priority level, however, was only a significant variable for transit vehicle delay. Assigning higher priority value to side-street operating transit lines reduced the total delay of transit vehicles, mainly because of high frequency of side-street buses. Adaptive TSP feature of RBC was assessed by designing an experiment in which the adaptiveness parameters: Detector Slack, Detector Adjust Threshold, and Adjust Step were the variables, along with bus frequency and traffic demand. Comparing the results of implementing adaptive TSP option of VISSIM RBC with Base scenarios showed that it was not useful to implement adaptive TSP in under-saturated approaches, for the travel time distribution of each bus, between buses' check-in check-out detectors, was not significantly deviating from the simulation software estimated values. Another observation was that transit lines that were not overlapped on their path by other bus lines gained the most benefit from the adaptive TSP. However, on the segments of the roads where the bus routes were overlapping, depending on the headway, the overlap could help the buses to form a platoon and pass through an intersection together, or one bus might be stuck before an intersection because of an already served bus.

4.1 Future Research

A transit vehicle that travels in a corridor needs to be provided green on all the intersections it passes, otherwise being served by green phase on the upstream intersection may not help this bus with reducing the delay. As the current vehicle to infrastructure (V2I) and infrastructure to infrastructure (I2I) technologies allow for widespread communication between the transit vehicles and signal controllers, future research can be applying a route-based transit signal priority that can serve the priority calls based on the importance of each transit line.

The research also revealed that the check-in detectors that are closer to an intersection, used to put priority calls later than a far-placed check-in detector of a conflicting approach. Automatic vehicle location (AVL) allows for the continuous observation of transit vehicle locations. By using AVL technology and applying a cooperative game theory phenomenon on the intersections exposed to conflicting signal priority calls, the best serving sequence can be obtained. For the adaptive TSP feature of VISSIM RBC, it would be interesting to study whether travel time pattern between transit check-in check-out detectors can provide any rationale for configuring Detector Slack, Detector Threshold, and Adjust Step.

In this dissertation, the performance measure was the delay of the buses and auto vehicles per vehicle. However, since the ridership on the transit vehicles is higher than passenger cars, analyzing the benefits would be better achieved by considering the ridership data.