Final Report

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Guidance for Identifying Corridor Conditions that Warrant Deploying Transit Signal Priority and Queue Jump

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The opinions, findings, and conclusions expressed in this publication are those of the authors and not necessarily those of the State of Florida Department of Transportation.

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16. Abstract
Transit Signal Priority (TSP) is an operational strategy that facilitates the movement of transit vehicles, either buses or streetcars, through traffic-signal controlled intersections. As transportation demand increases various transportation networks are facing increasing congestion. To mitigate the high-density impact of congestion on transit operations, TSP is a significant solution and has been widely applied to improve transit service quality and increase bus ridership. TSP can be planed and implemented considering many variables to achieve several valuable benefits such as: reducing transit travel times, better schedule adherence, and better transit efficiency. The objective of this research is to develop warrants and performance standards for transit agencies to implement signal priority based on identified decision factors. The research assesses existing guidelines and provides new guidelines for TSP implementation. Furthermore, this research evaluates the effectiveness of TSP in improving the performance of public transportation bus lines. The improvements are assessed by comparing the total travel time and total delay on the same single corridor with and without TSP applied utilizing microscopic analysis. The results show significant improvements in reducing the travel times and delays for the buses as a result of applying the TSP.

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EXECUTIVE SUMMARY

Transportation system congestion is increasing as a result of the large number of cars entering the system due to rise in population. The traffic congestion is greatly influenced by signalized intersection, which is one of the primary causes of the transit schedule reliability. Transportation management measures that maximize the use of existing capacity must be explored to obtain financially viable transportation solutions. Transit supportive strategies that hold the potential to improve transit operation include intersection treatments such as transit signal priority (TSP), queue jump lanes, and managed bus lanes.

To mitigate the high-density impact of congestion on transit operations, TSP is a significant solution and has been widely applied to improve transit service quality and increase bus ridership. TSP can be planed and implemented considering many variables to achieve several valuable benefits such as: reducing transit travel times, better schedule adherence, and better transit efficiency. Transit signal priority strategies may be applied across multiple signalized intersections along a corridor; depending on the level of service and lane configuration characteristics of the intersections. The technique uses readily available information on the signal control, traffic conditions, and transit vehicles. It also takes into consideration the extra delays due to additional queues that are likely to occur on non-priority approaches.

To apply TSP in the most effective way, developing and utilizing the right guidelines is essential. This research project assesses existing TSP guidelines and proposes new guidelines to be applied in the state of Florida. The study's primary purpose is to develop a guidance for the transit agencies in identifying corridor conditions that warrant TSP and queue jump. This study also provides the foundational concepts regarding TSP and the solutions it can offer specific to the context framework of a public transportation system. Furthermore, it discusses previous studies in the state of Florida and around the nation including policy issues and challenges to resolve when considering TSP and Queue jump. The study utilizes simulation modeling to assess the impacts of TSP and alternative associated guidance.

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CHAPTER 1
INTRODUCTION

1.1 Background

Mobility and safety impacts on transit vehicle operations from traffic congestion in most urban areas necessitate new approaches to these issues. Intelligent Transportation Systems (ITS) technologies and transportation system management and operations (TSM&O) strategies have such as transit signal priority (TSP) has been applied to improve transit system performance.

TSP uses technology to detect approaching transit vehicles and alter signal timings to provide priority control to transit vehicles. Transit vehicles typically spend 15% of their trip time waiting at traffic signals. Reducing this delay by an average of 40% would reduce the travel time of a 60-minute round trip to 55 minutes. If this route requires a 5-minute headway, only 11 buses are required with 55-minute travel time, compared to12 buses with 60 minutes trip length. Therefore, secondary benefits include decreasing vehicle and operator costs and improved return on investment (ITSA, 2004). Transportation agencies benefit from TSP strategy implementations that encourage travelers to use public transportation; and thereby improve roadway level of service by reducing vehicular demands. TSP reduces delay and unreliability due to traffic signals. However, the type of TSP that can be implemented in a particular corridor or intersection and the benefits it generates depend on a number of factors including:

- the parallel and crossing roadway and intersection traffic operations (level of service),
- transit service characteristics (the frequency and ridership of the transit service),
- the considered vehicle and roadway TSP technologies, and
- other factors as will be discussed in this document.

Many agencies around the nation are pursuing TSP implementations. Important questions to address as part of TSP and Queue jump effort include:

- What types of transit service will be eligible for TSP and in which period of the day?
- What are some of the minimum operating characteristics and on-time performance indicators that would necessitate TSP along the corridor?
- How often should priority requests be granted?
- What weights should be given to transit ridership versus general vehicle and person movements when granting conditional TSP requests?
- Should the transit operations center be integrated or separated with respect to TSP?
- How should potential signal operations change when combined with other priority treatment options (queue jumps, exclusive guideways, etc.)?

It is vital to point out that implementing and operating TSP within a network by its very nature requires agreements and coordination between operating agencies and across different modes. The purpose of TSP includes improved schedule and transit travel time efficiency, while minimizing the impact to normal traffic operations (USDOT-FTA, 2005). It is essential to keep in mind that while they use many of the same systems and components, TSP is *not* signal preemption. TSP modifies usual signal operations to conditionally accommodate requests for transit vehicle priority. Preemption disrupts signal operations to ensure a green light for emergency and other vehicles that warrant it from safety considerations. The following are the types of TSP strategies:

Passive Priority strategies involve signal timing changes (supporting the transit vehicle), as well as, geometric or infrastructure improvements. Passive priority can include changes to signal timing such as phase splits, cycle length, or coordination to support transit movements. Queue jumps may be also included in these strategies. Passive priority is most utilized for transit routes for which passenger loads, schedule, and or dwell times etc. are known and transit can be operated predictably (Reza, 2012). The advantages of passive priority are ease of application, cost reduction, and the ability to change plans dependent upon changing traffic and transit operating conditions. Passive priority is helpful for applications where the transit service is reasonably too heavy and uniform during the day and overall traffic conditions are light to moderate. Disadvantages to passive priority include: increased side-street traffic delay, extreme green time allocation to priority vehicles, normal signal maintenance or dissatisfaction from the general public. As is generally the case in small-medium size cities, these strategies may bring unnecessary delay to the entire system when buses are not present and the transit headways are significant (Kittelson & Associates, 2008).

Active Priority strategies include dynamic signal timing improvements which are modified signal phases that detect transit vehicles. Active priority strategies are classified into two categories: conditional and unconditional. To get conditional priority, when detected, the bus must meet the specified conditions, such as the number of passengers, route schedule adherence, or the time since last priority is awarded. Unconditional active transit priority is described as a strategy where transit vehicles obtain needed green extensions or red truncations, irrespective of cross street queue lengths or the time since the last priority was granted (Urbanik et al., 2015). Different types of active priority strategies are available including:

- Green extension
- Early green
- Actuated transit phase
- Phase insertion
- Phase rotation

Green extension is extending the green time for the forthcoming TSP-equipped vehicles for situations where the signal is green for the approaching TSP equipped vehicles. Early green shortens the green time for the detected TSP equipped vehicle to ensure early green is the early green strategy. Phase insertion includes inserting a special priority phase within a usual signal sequence only when a transit vehicle is detected and requests priority for this phase. Phase rotation is the order of signal phases that can be rotated to provide TSP. ***Figure 1*** provides the elements for implementing Active Priority (Sabra and Wang, 2013).

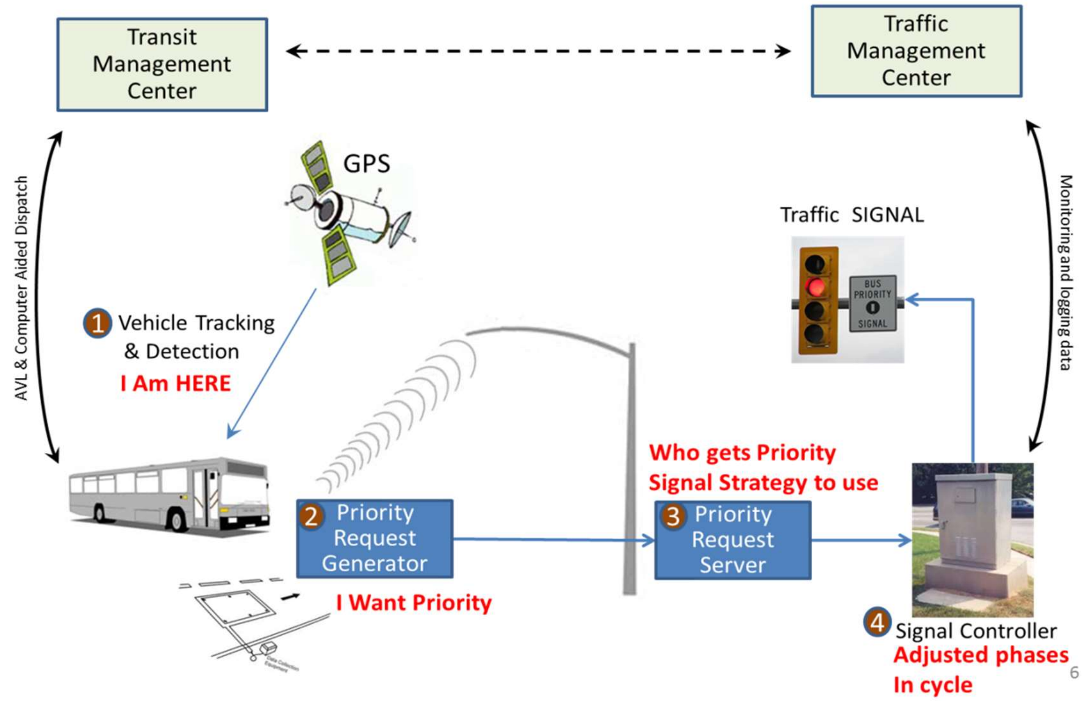


Figure 1. *Representation of Active Transit Signal Priority (Sabra and Wang, 2013)*

The simplest active signal priority system grants a priority request every time an eligible vehicle is detected. Early TSP systems often used this active priority type with mixed benefits because although they provided transit system benefits, they also caused delays. Most modern TSP systems are based on conditional priority using schedule adherence and other criteria. As more factors are desired for conditional strategies (such as passenger loadings), the information and interface needs/requirements and architecture to support them will become more complex. Also, signal controllers differ as to which signal priority strategies and/or conditional compromises they can implement.

TSP has been implemented in many cities around the United States. However, interest for TSP has been affected by concerns that transportation network performance may be compromised when signal timing plans developed to optimize traffic flow are dominated by travel advantage request from transit vehicles. Many studies evaluate TSP effects on local networks, not following the similar ratio of increased traffic demand. There are several factors that can affect the purpose of TSP such as: the frequency of the assigned service on a transportation network, the increased importance of reducing system travel time variability, and ensuring that transit vehicles run on a specific headway.

1.2 Project Objective

The purpose of this project is to develop guidance to transit agencies to identify conditions where TSP is justified to improve transit travel times and transit trip reliability without adverse impacts on the other traffic. While TSP has been successfully implemented across the nation, there are a number of issues that transit agencies face when designing and implementing TSP. This study will use simulation modeling to determine if transit signal prioritization impacts corridors and to develop measurements of effectiveness to assess these impacts to traffic performance. Also evaluated as part of this study are the TSP system benefits for transit operations.

1.3 Project Case Studies

The case studies of this research include transit operations on urban street facilities in Hillsborough, Miami-Dade and Palm Beach counties in the State of Florida. The urban street facilities are Nebraska Avenue in Tampa, Hillsborough County; along State Road 7 in Miami-Dade County and along Okeechobee Boulevard in Palm Beach County. These facilities were selected after various meetings organized with local agencies such as Florida Department of Transportation (FDOT) District 7 Regional Transit/Intermodal Systems Planning agency in Tampa, Palm Tran and Palm Beach Metropolitan Planning Organization in West Palm Beach, and Miami-Dade Department of Transportation & Public Works (DTPW) in Miami. The selected corridors have a larger number of public transit lines operating in congested traffic conditions. As such they present problematic segments to transit operations and thus constitute use cases of interest for detailed assessment of possible enhancements of operations through the implementation of different Intelligent Transportation Systems (ITS) technologies and strategies such as Transit Signal Priority.

1.4 Summary of Project Tasks

In order to achieve research objectives, the following tasks are conducted. Each task is accompanied with a short description on which chapters of this report address each of the tasks.

Task 1: Conduct a literature review of current state of practice and recommend warrants and thresholds

This task intends to review transportation journals, online articles, and transit agencies publications, etc., and identify any TSP warrants or minimum thresholds that have been developed around the nation to assess the feasibility and necessity for implementing TSP and queue jump. Recommended warrants and thresholds were identified based on the literature review. The effectiveness of these recommendations were tested in Task 2. This task also entails the identification of three potential testing locations across Florida for Task 2.

Task 2: Simulation Modeling

This task utilizes simulation modeling of the three selected corridors across Florida, as identified in Task 1, and test and evaluate warrants under normal and incident conditions for urban areas. The micro-simulation model evaluated different signal control priority scenarios and use cases that can be used to assess the guidance for the implementation of TSP in the identified corridors. The purpose of these scenarios is to show where logical decisions can be made and where warrants will be able to prioritize TSP based on different decision factors such as: roadway geometry, traffic volumes, traffic signal systems, pedestrians, adjacent intersection operations, length of queue and acceleration lane etc. The research team develops technical specifications for defining corridor screening criteria and applying the screening criteria (warrants) to identify a priority corridor and intersections for FDOT. The results of the simulation modeling were used to assess the recommended warrants and thresholds in Task 1.

Task 3: Production of Final Report and Quick Guide

This task produced a draft and final report documenting the tasks and results of the activities of this project.

Task 4: Development of Presentations for FDOT

The research team will develop a presentation for the FDOT that provides an overview of the project – its objectives, methodology, findings, and recommendations.

1.5 Document Organization

This final report is comprised of six chapters. The first chapter, introduces the problem and background that led into the need for research as well as specific tasks which were supposed to be accomplished during the course of this study. The second chapter, describes an extensive literature review about various previous works on transit signal priority. The third chapter, is the methodology section which refers to developed guidelines and necessary research steps needed to be taken for conducting research studies for the case studies. Each of the necessary research steps are comprehensively described along with case studies and their scope. The fourth chapter, presents the results and discussion chapter provides overall results obtained through conducted case studies. Results are expressed through several Measures of Effectiveness (MOE) such as travel and delay time. Furthermore, the fifth chapter provides conclusions based on entire project including all three conducted studies. Finally, the sixth chapter provides recommendations for future research work.

CHAPTER 2
LITERATURE REVIEW

This literature review discusses topics related to TSP, queue jump, and their applications throughout the United States. The objectives of this section are to:

- identify completed TSP and queue jump studies,
- which strategies have been applied,
- Features of the transportation system where TSP have been applied, and the outcomes from these studies.
- Previously developed TSP guidance

As specified previously, TSP has been analyzed since the early 1970s (Evans, 1970 and ITSA, 2004), and it is essential to understand previous TSP and queue jump studies by reviewing all the aspects related to it.

A literature review was conducted by reviewing research articles, papers, and technical reports, as documented within this section. Important issues reviewed and researched in this study include: the TSP strategies applied, the characteristics of the transportation system where the TSP was applied, the TSP assessment method, and the results from these studies. It is vital to understand TSP and queue jump by studying all associated aspects. While TSP had been successfully implemented across the nation, there are number of issues that transit agencies face while designing and implementing TSP, as discussed in Section 2.1.

TSP is an operational method that facilitates the movement of transit vehicles through traffic-signal controlled intersections. The underlying purpose of TSP applications are to improve schedule adherence and transit travel time efficiency, as well as, minimize any impacts to normal traffic operations. Transit priority at signalized intersections has been reviewed in the United States since the 1970s (ITSA, 2004). In recent years, TSP has been increasingly applied by transportation agencies in North America and these growing deployments of TSP across the nation require evaluation studies to assess their historical impact. A large number of studies had been conducted to assess TSP using either empirical, analytical or simulation tools.

Various TSP projects have been conducted for the last 30 years, mainly in large metropolitan areas. For example, signal priority for light rail transit (LRT) vehicles had been used in various California cities, including Sacramento, San Jose, Los Angeles/Long Beach and San Diego. The algorithms used in conjunction with the Los Angeles/Long Beach LRT line was described by Li (2008), while an algorithm which gives trolleys signal progression in downtown San Diego was described by Celniker (1992). Further research on the use of signal progression for light rail vehicles in Baltimore was performed by Kuah (1992). A report by Jacobson (1993) indicates that signal priority using radio-frequency priority system had been in use along express bus routes in Charlotte, North Carolina since 1985. Additional research was also conducted on the use of this system in the Seattle area.

2.1 Transit Signal Priority Deployment Issues

Many factors impact the planning and deployment of TSP. These issues can be divided in two primary categories: traffic related factors and transit related factors. The implementation and deployment of a TSP system involves a careful process considering the many design and operation issues associated with both transit and traffic. Some factors related to the traffic in TSP system are listed below.

Traffic signal agency capability maturity is important to determine if the agency has the resources and workforce required to plan, deploy, operate, manage, and maintain TSP.

Performance measures need to be identified to allow assessing the performance of the system with and without TSP. Person-delay reduction and enhancing transit schedule reliability are discussed as the two main goals of developing TSP within the work completed by (Li et al., 2008). In order to reach these goals, the performance of TSP is measured by both vehicle delay and person delay and then compared to transit travel times. The decrease in transit vehicle travel time is related to a reduction in person delay. A balance must be maintained between transit vehicle delay and other traffic delay to develop a TSP system that is viewed as a success by all stakeholders. Person delay is one of the best methods to measure this balance; however, intersection approach vehicular data should be evaluated as well.

Traffic volumes change regularly in any area with the peak hours seem to be the most candidate time intervals to apply TSP (Li et al., 2008). Asmussen et al. (1997) pointed out that TSP can result in a cost reduction to agencies; achieved by reducing transit delay, allowing the removal of one or more vehicles from operation and still keeping the same schedule. Research also found that the effects of TSP on regular traffic conditions are mainly dependent on the volume of the traffic traveling in the same direction as the transit route, as well as the volumes of approaches conflicting with the transit route.

Roadway geometry is an important issue for the operation of any TSP system because it directly dictates the transportation system capacity and types of possible operations. Roadway geometry is impacted by the topography and land development, which dictate the number and location of intersections and the transit stops. Therefore, roadway geometry is usually the most constraining factor for TSP implementation (MCPD, 2013).

Pedestrian traffic has a significant influence on TSP management at signalized intersections (Zegeer and Seiderman, 2003). Typically, the time needed for a pedestrian to cross the street safely in a signalized intersection limits the time needed to provide TSP. Significantly, pedestrians are always transit customers and they require service at the same time as transit vehicles. This is a significant factor related to the extent to which the transit signal priority system can accomplish the desired results (Jarrett, 2011).

Signal hardware and software are needed to deploy intended priority strategies. If the TSP functional objectives are not possible with the existing setup, a new signal controller hardware and firmware and possibly central software will need to be deployed.

Adjacent intersection operations are very important when implementing TSP. This is particularly essential in the case of narrowly spaced intersections. The decision regarding which adjacent corridor or intersection to consider is based upon field conditions and the characteristics of the traffic system operation.

Traffic agency signal operation policies and practices should be examined in advance of deploying TSP. These processes demonstrate one of the most significant factors in defining the type and method of TSP that is ultimately employed. The most important factors related to the transit system are: the type of transit system, transit stop location, transit pull outs, existing transit agency hardware and software, and transit agency operating policies and practices (Hounsell and Leod, 1998 and Hounsell et al., 2000)

2.2 Evaluations of Cases of Study of Transit Signal Priority around the United States

Sunkari et al. (1995) developed a model for evaluating a bus priority strategy for a signalized intersection in a coordinated signal system in College Station, Texas. The model used the 1985 Highway Capacity Manual delay equation for signalized intersections and adapted the equation to calculate person-delay for cases with and without priority strategies. Priority is provided by early green and green extensions of the priority phase at regular intervals, coordinating with the estimated bus arrival interval. Five cases were identified:

1- No priority
2- Priority phases receive a minimum extension
3- Priority phases receive a maximum extension
4- Priority phases provide a minimum early start
5- Priority phases provide maximum early start

Priority strategy remunerations were established by measuring the delay for vehicles and buses on a cycle by cycle basis. A site was chosen in College Station, TX, and the controller altered to accept manual inputs to simulate a bus approach.

Research completed by Ludwick in 1975 is amongst the first TSP studies in the United States (Ova and Smadi, 2001). This work assessed the initial Urban Traffic Control System - Bus Priority System (UTCS-BPS) in Washington, D.C, District of Columbia; using a microscopic simulation model, UTCS-1. The UTCS-1 model simulated a network with unconditional preemption for transit buses, applying early green and extended green logic; building the initial assessment. This assessed different scenarios by varying the headways of one transit route from 30 seconds to 4 minutes, therefore, moving the bus stops to represent far side or near side stops. The model used bus detection zones 210 feet upstream from the instrumented intersection to within 5 feet of the intersection (Ludwick, 1975). The key findings from this report are summarized as follows:

- the mean bus travel times decreased by 22 percent to 32 percent,
- the crossing street traffic travel time increased by 6 percent to 30 percent for far-side stops,
- crossing street traffic travel time increased by 9 percent to 66 percent for near-side stops and,

- the mean bus travel time was within 15 percent of the theoretical minimum travel time of the transit vehicle.

In San Diego, CA the high rate of trolleys brought extensive delays with the deployment of a passive priority system. In order to improve the situation, an active priority system was planned to produce a better progression to the next station in the transportation network with savings in operating travel time throughout the center city by as much as 2-3 minutes (Celniker et al., 1992). In 1992, Kuah investigated signal progression for light rail transit (LRT) located in downtown Baltimore, MD. The evaluated corridor was 2.4 miles long corridor along Howard Street. Based on TRANSYT-7F simulation, the study reconfirmed that priority LRT operations could be designed without significantly affecting cross street progression (Kuah, 1992). In Chicago, IL, TSP resulted in approximately 2-3 minutes saved on the travel time by a bus run, and the impact to traffic was minimal (Collura et al., 2000). The system examination also showed that the priority was provided to only 30% buses as 70% of the buses arriving during the normal green time. In addition, Chang et al. (2003) research report mentioned that the modern technology facilitated the design, testing, and deployment of TSP strategies for transit buses. This research tries to assist in the evaluation of such strategies through presentation of an evaluation framework and plan that provides a systematic method to assess potential impacts.

Another research study related to TSP was conducted by Ova and Smadi in 2001, for the St. Cloud Metropolitan Transit Commission in Minnesota. The study corridor is approximately 15.7 miles in length and crosses 11 signalized intersections in the Southwest/Crosstown bus route. This study provided a theoretical evaluation of TSP strategies in a small-medium size urban area. Several scenarios were evaluated, involving two TSP strategies; existing and reduced bus headways; and two traffic peak periods. The results from the comparison show a 43 percent savings in the overall average bus delay caused by signalized intersections for all periods (Westwood Professional Services, 2000, Ova and Smadi, 2001). The average bus running speed for the route was also observed. The drop-in intersection delay permitted the drivers to keep schedules without the need to speed up by increasing travel speeds. Comparison between the increase in person delay for non-transit and decrease in person delay for transit resulted in average bus occupancy of 24 required to balance the delay (Westwood Professional Services, 2000).

In the City of Portland, Oregon, the Oregon Department of Transportation (ODOT) conducted a summary and evaluation of the development of Portland TSP system in 2002. This summary outlines the data collection and evaluation of Portland's TSP system for a signal priority project. The travel time, travel time variability, and on time performance based on automatic vehicle location (AVL) data were the factors where bus performance was evaluated. During eight-week period, ODOT collected the data and divided it into two cases. ODOT dedicated four weeks to collect data before the TSP and completed another four weeks to collect data with the TSP activated (TEA-21, 2003). Examples of TSP studies conducted as part of the ODOT evaluation are as follows:

- On Tualatin Valley Highway, Portland, active priority strategy: green extension, and early green was implemented for 13 signalized intersections. The research concluded that the bus travel time savings was 1.7 to 14.2% per trip, 2 to 13 seconds reduction in per intersection delay 19 (Lewis, V. 1996).

• On Powell Blvd. in Portland, for four signalized intersections active priority strategy: early green, green extension was provided. 5-8% reduction of bus travel time as well as reduction in bus person delay was reported Kloos et al. (1994).

• At Rainer Avenue in Seattle, active priority strategy: green extension and red truncation was provided for 20 intersections. The research concluded that there was 5-8% reduction in travel times, 25-34% reduction in average intersection bus delay, and $40,000 passenger benefit per intersection. (Atherley, 2000).

• In Tacoma, Washington, the combination of TSP and signal optimization reduced transit signal delay by about 40% in two corridors and signal coordination alone brought $4.5 million economic benefit according to the Valley Transportation Authority.

In California, 34 key study intersections in the Russel Boulevard corridor, California was used as a TSP case study. The study, based in transit passenger delay, identified key intersections and corridors that degrade transit on-time performance due to high vehicle passenger delays. Using Bus AVL technology, researchers evaluated the detailed ranking of 34 study intersections and selected them for detailed VISSIM analysis (see Table 1). They utilized a combination of signal coordination, TSP, and operational improvement strategies to fully analyze these intersections using the VISSIM multi modal microsimulation analysis software for weekday AM and PM peak hour conditions. Table 1 shows the result of the total transit vehicle delay analysis at the 34 key study intersections. The total delay was calculated by multiplying the number of transit vehicles passing through each intersection by the average delay at each intersection based on the detailed VISSIM microsimulation analysis results. It was determined that improving signal operations and coordination will benefit overall traffic flow and reduce stop and go conditions, therefore, the overall impact of transit signal priority on general traffic would be negligible. Also, the vehicle emissions would be reduced and the average travel speeds maintained with the implementation of "green extension" for approaching transit vehicles.

The need of TSP was studied and implemented by the IBI group and applied to recent TSP projects in New York. TSP implementation guidelines were developed based on TSP system capabilities and TSP strategies for different intersection characteristics. The guidelines take a two level approach: overall governing guidelines, which include general rules that should be adhered to during TSP operations, and intersection specific guidelines, which deal with intersection specific TSP parameters. These guidelines are then used to establish parameters for groups of signalized intersections (Stewart, 2006). In each case, the IBI group devised an analysis process to effectively categorize and group the signalized intersections according to intersection characteristics and intersection operations. A database tool compiled and organized the information logically. Subsequently, the appropriate TSP parameters and strategies were identified to match the key intersections characteristics. In summary, the TSP implementation guidelines were successful in developing the initial TSP parameters.

Table 1. *Summary of Transit Delays at 34 Signalized Intersections*

Intersection	Total Transit Vehicle Delay		Total Passenger Delay		Total Average Delay	
	Sum of All Peak Hours (sec.)	Rank	Sum of All Peak Hours (min.)	Rank	Sum of All Peak Hours (sec.)	Rank
1 Russell/Howard	3758.9	1	4,195.1	2	94.0	17
2 Russell/Anderson	3428.0	2	6,356.3	1	107.1	8
3 Anderson/Covell	2327.8	3	2,936.0	7	101.0	10
4 Russell/B St.	2151.1	4	2,749.5	8	107.6	7
5 Russell/Sycamore	1558.5	5	2,611.4	11	111.3	5
6 Anderson/Villanova	1513.1	6	2,215.6	12	72.2	31
7 Anderson/8th	1447.3	7	2,702.0	9	83.5	25
8 5th/F St.	1408.6	8	1,617.2	17	111.9	4
9 Cowell/Research Park West	1305.0	9	3,299.3	5	110.1	6
10 5th/Pole Line	1284.1	10	1,694.1	16	99.6	12
11 Cowell/Pole Line	1271.8	11	853.0	21	75.3	30
12 5th/L St.	1266.8	12	1,701.2	15	97.6	16
13 Richards/Olive	1238.0	13	3,574.3	3	103.0	9
14 Russell/Arthur	1206.0	14	1,788.3	13	75.4	29
15 Cowell/Drew	1202.4	15	2,645.6	10	98.1	15
16 Anderson/Rutgers	1183.5	16	1,705.9	14	76.8	27
17 Richards/1st	1120.8	17	3,145.7	6	99.4	14
18 5th/G St.	1106.4	18	1,209.8	19	138.3	1
19 Cowell/Valdora	1062.0	19	1,584.2	18	88.0	24
20 1st/D St.	1012.1	20	3,509.6	4	92.0	20
21 Covell/Pole Line	963.3	21	581.9	22	111.9	3
22 Mace/2nd	898.9	22	518.5	23	112.7	2
23 Mace/Chiles	847.4	23	420.3	24	99.5	13
24 8th/F St.	775.9	24	992.7	20	93.2	18
25 Covell/F St.	605.1	25	300.0	29	100.8	11
26 Mace/Cowell	600.2	26	375.6	25	91.9	21
27 Pole Line/Loyola	553.4	27	331.5	26	92.2	19
28 F St./14th	450.1	28	286.4	30	76.6	28
29 Mace/Alhambra	428.7	29	146.2	32	47.5	33
30 Covell/Sycamore	385.4	30	323.5	27	91.2	23
31 Covell/Shasta	327.4	31	310.9	28	91.4	22
32 Covell/John Jones	298.5	32	162.2	31	82.6	26
33 Covell/J St.	277.0	33	128.8	33	50.3	32
34 Covell/Alhambra	188.0	34	68.8	34	38.7	34

Notes:
Candidate Corridor #1: Russell Boulevard - Sycamore Lane to Howard Way
Candidate Corridor #2: Richards Boulevard/Cowell Boulevard - First Street to Pole Line Road
Total transit delay calculated by multiplying the number of transit vehicles passing through each intersection by the average delay at each intersection.
Total passenger delay calculated by multiplying the number of passengers by the average delay at each intersection.

Researchers looked at how TSP is impacted by varying traffic volumes, transit headways, intersection spacing and two or three lane directional roadways (Hunter et al., 2000). The objective was to determine guidelines and planning strategies to implement TSP control in traffic operations on arterials. The focus was on determining the change in measures of effectiveness (MOEs) under varying traffic volumes, bus volumes, intersection spacing, and number of lanes (Hunter et al., 2000). Two different areas in Burlington, Vermont were studies using the microsimulation model, VISSIM. With the generated guidelines the objective was to assist state DOTs and highway and transit agencies in the design and implementation of signal priority strategies for transit buses with other preferential signal treatments, such as those currently in place and being planned for emergency response, including fire and rescue services. The results of the simulation analyses suggest that transit priority may aid in improving overall bus travel time along of the sceneries evaluated. The guideline envelopment divided findings into two sections, planning and deployment. Local jurisdictions, transportation agencies, and public safety agencies should utilize these guidelines in the planning and design of transit priority along signalized arterials (Vlahou, 2010).

In March 2013, the Montgomery County Department of Transportation (McDOT) commissioned Rapid Transit System (RTS) Concept Study, in order to assist in determining how TSP and its operations integrate and operate within the overall RTS system. The researchers' primary goals were to "define the appropriate metrics for the implementation of TSP systems on each RTS corridor, building on what was developed for TSP for local bus operations" (Sabra &Wang, 2013). The developed framework is shown in Figure 2.

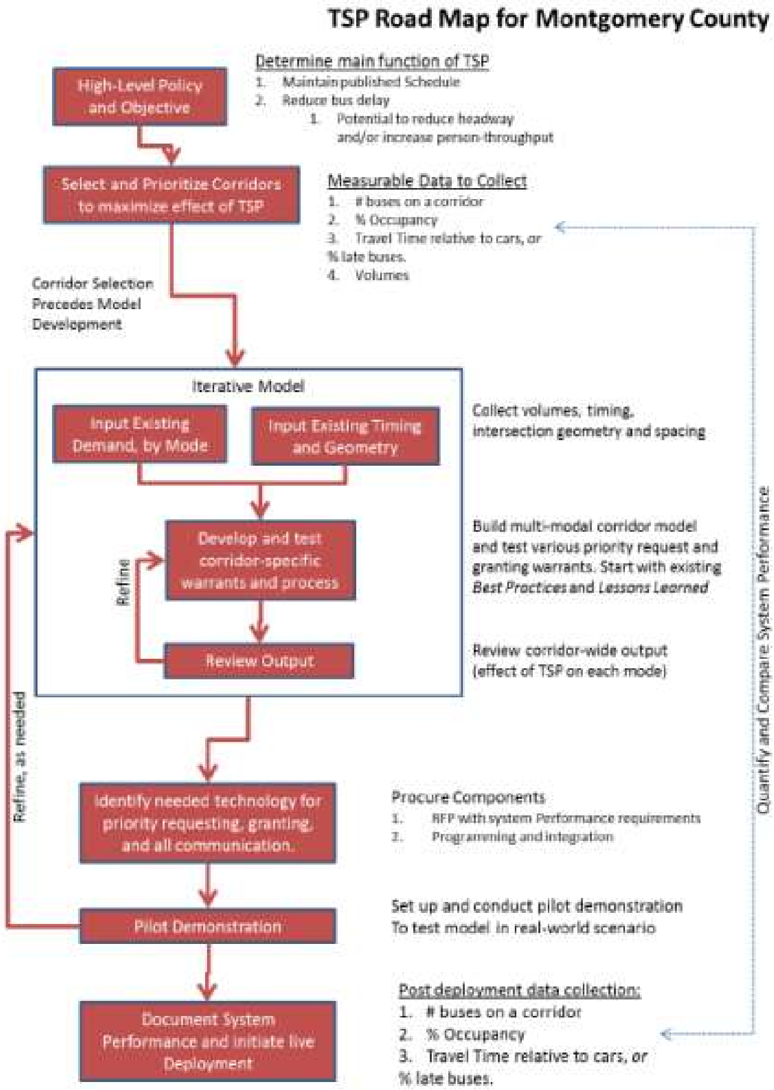


Figure 2. *Transit Signal Priority Map for Montgomery County, Maryland (Sabra &Wang, 2013)*

In addition, the District of Columbia DOT led the TSP design and implementation effort for over 100 signalized intersections along four corridors (Urbanik et al., 2015).

2.3 Sample of Cases of Study of Transit Signal Priority in Florida

In Tampa, Florida Kittleson and Associates led a project to assess the TSP along portions of three selected corridors: Fletcher Ave, N 56th St, and Nebraska Ave. The results of the research delivered critical input into the completed design of initial implementation of the BRT system in Tampa (known as Metro Rapid) along the Fletcher Ave and Nebraska Ave corridors. As a result of the stakeholder input, the TSP technology chosen was a GPS/Radio based system that could be integrated with the previously existing Automatic Vehicle Location (AVL) system installed on buses to provide conditional priority. The project included the demonstration of emergency vehicle preemption using the same TSP technology and participating emergency reaction agencies include Hillsborough County and the City of Temple Terrace, Florida (Kittleson & Associates, 2006).

In addition, another TSP project was implemented along Atlantic Boulevard in Jacksonville, Florida with six Naztec controlled signalized intersections. The project included reviewing alternate TSP strategies and technologies as well as conducting "before" and "after" evaluations of bus and auto performance measures, and the Opticom GPS system was selected as the bus detection system for the implementation. An interface amid the bus detection system and the bus Automatic Vehicle Location (AVL) system was developed to test "conditional priority" along the corridor. The project identified an implementation strategy to expand TSP implementation to other portions of the Jacksonville region (Kittleson &Associates, 2006).

Three (3) projects in the State of Florida highlighted the implementation of TSP systems. The first project included the installation of a TSP systems on fifty (50) intersections on Pines/Hollywood and Broward Boulevards in Broward County. The evaluation of this project, showed a reduction in travel times and increased schedule adherence during the AM peak hours; however, the PM peak hours had no recognizable impacts as a result of the TSP systems (NBRTI, 2011). A TSP system was to be installed on 32 intersections in Duval County connecting Downtown Jacksonville to Jacksonville Beach. Six of those intersections also included the queue-jumping feature. This project is known as the First Coast Flyer East Corridor BRT Project and there are four other extensions of this project. The North Corridor was completed in December of 2015 and is comprised of the latest TSP technology and has dedicated bus lanes (jtafla.com, 2016). The remainder of the project was to be completed soon after (JTA, 2015). The last project is in Central Florida which connects a five-county area. It is comprised of 39 intersections throughout the Downtown Orlando area that have TSP systems (FDOT, 2014).

In July 2014, the Florida Department of Transportation (FDOT) identified key factors for the successful application and implementation of TSP systems in metropolitan arenas. The core skeleton of the guidelines is consequent from the USDOT's 2005 *TSP: A Planning and Implementation Handbook*. The research involved a complete overview of TSP systems planning, installation, operation, and evaluation. The information provided in the FDOT report, however, was based on the input provided by numerous municipalities with successful TSP systems. This four-phase process is critical for the application, guidance, and strategy required of all stakeholders involved. The most important key point that heavily impacts the success of a TSP system is to involve and coordinate with all affected agencies. According to (Tindale, 2014) there are seven key factors for choosing the primary stakeholders of TSP systems project. The seven key factors are the following:

- Geography – interagency communication
- Jurisdictional Responsibility – maintenance
- Type of Transit Agency – public or private ownership, interagency relationships
- Funding – state, federal, or private and guidelines
- Technology – personnel training and involvement
- Extent of project – scope of work
- Extent of Institutional Knowledge – prior knowledge equals less stakeholders

Stakeholders for most projects include individuals involved in the following categories: planning, scheduling, technology, and finance. In all TSP system projects the core stakeholders should comprise at least two primary points of contact, i.e., Project Manager and Traffic Operations Engineer. With the proper stakeholders involved project goals, approach, and timeline are more easily achieved. For example, signal operators training is very important to the operational efficiency of the TSP system. Guidelines and expected outcomes should be used as a foundation in the early planning phase of every TSP system project. Application of these principals has been shown to pay dividends throughout project and at completion. Tables 2 to 4 offer example of the key elements found during the survey and research process for the FDOT study (Tindale, 2014).

Table 2. *TSP Implementation Guidelines Key Elements - Part I, (Tindale, 2014)*

IMPLEMENTATION GUIDELINE (Applicable Phase of TSP System Development)	KEY FINDINGS	"LESSONS LEARNED" OR RECOMMENDATIONS FROM OTHER AGENCIES
Leverage Existing Relationships (establish during planning phase; continuously strengthen and develop throughout all project phases)	• **The benefit of existing relationships was cited as the most important element to successful communication** between the transit agency and traffic operations personnel.	• Consider the strength of existing working relationships as a key asset when identifying key stakeholders and core project team. • Hold in-person meetings to continue/strengthen relationships of TSP project team. • Ensure that the transit agency project manager has a good working relationship with the traffic engineer(s).
Identify Core Stakeholders/ Project Team (establish during planning phase)	• While the involvement of various stakeholders will fluctuate throughout the TSP system process, **a core project team should remain constant through planning, implementation, and operation phases.**	• Identify core project team members, organizational structure, and roles/responsibilities early in the planning process. • Include a primary contact/project lead from both the transit agency and traffic agency/operations department(s). • When possible, include a transit agency staff person with an engineering background on the core project team who can "speak the same language" as traffic operations personnel.
Identify and Leverage TSP "Champions" (establish during planning phase)	• As with most projects, **leveraging the enthusiasm and support of one or more project champions is critical to the successful outcome** of TSP system.	• Identify and engage TSP champions early on who are well-respected by both the transit agency and traffic operations personnel.

Table 3. *TSP Implementation Guidelines Key Elements - Part II, (Tindale, 2014)*

IMPLEMENTATION GUIDELINE (Applicable Phase of TSP System Development)	KEY FINDINGS	"LESSONS LEARNED" OR RECOMMENDATIONS FROM OTHER AGENCIES
Balance Existing and Future Stakeholders in the Education and Planning Process (establish during planning phase; carry-on throughout project)	• **Consider the extent to which potential TSP stakeholders (those likely to become active stakeholders upon system expansion) should be involved in the early education and planning processes**, especially if expansion plans are more near term.	• In addition to current stakeholders, identify potential stakeholders based on future TSP expansion plans. Evaluate the appropriateness of their involvement in the process, especially during the early discussions of TSP and educational components to provide general agreement and knowledge about the approach and identify compatibility issues up front. This will more easily allow the system to be expanded when the time is right, as the goal is to avoid having "pockets" of separate systems.
Educate from All Perspectives (establish during planning phase)	• **Touting only the benefits of TSP is unrealistic.** Ensure that the education does not *feel* one-sided (i.e., discusses only the benefits to transit).	• Include both transit agency and traffic operations professionals as part of the educational process to give a realistic expectation of what to expect from both viewpoints.
Leverage Peer Experiences and Exchanges of Information (establish during planning phase; carry-on throughout project)	• One of the most successful educational tools cited by case study agencies was **leveraging the prior experiences of peer agencies through a peer exchange of information.**	• Conduct on-site visits or tours of peer agency systems. • Hold conference calls with peer agencies when in-person visits are not possible. • Attend peer exchange working groups where TSP is discussed. • Include funding for peer agency visits as part of the TSP budget. Lane Transit District used FTA funds to fund a scanning tour where transit agency and city traffic engineers went to see first-hand how Chicago's TSP system was developed and functioned.

Table 4. *TSP Implementation Guidelines Key Elements - Part III, (Tindale, 2014)*

IMPLEMENTATION GUIDELINE (Applicable Phase of TSP System Development)	KEY FINDINGS	"LESSONS LEARNED" OR RECOMMENDATIONS FROM OTHER AGENCIES
Identify Appropriate Professional Resources (identify during planning phase; carry-on throughout project)	• **Considerably underestimating the required time commitment by the core project team, especially the Project Manager(s) in the planning and implementation of the TSP system, was cited as a barrier** to the overall project process. • **The use of consultants/outside experts was cited as a frequent resource in the educational process** during initial implementation of new TSP programs.	• Universities and research centers can be a good source of information concerning TSP and often at less cost than a private consultant. A university/research center also may provide a more neutral perspective on technology than a consultant who is invested in a particular type of technology.

CHAPTER 3
METHODOLOGY

This chapter provides comprehensive information regarding the developed methodology, research steps and conducted case studies. The overall objective of this methodology is to assess potential impacts of implementing TSP strategies which are created based on developed guidelines. It provides an understanding of the effectiveness of the developed guidelines when applied to the particular case study. The TSP guidelines assessment was conducted through several case studies. Each conducted study involves the design of a microsimulation model based on the available data from the field and implementation of the TSP scenarios following the guidelines. The methodology research steps are presented in the Figure 3 below:

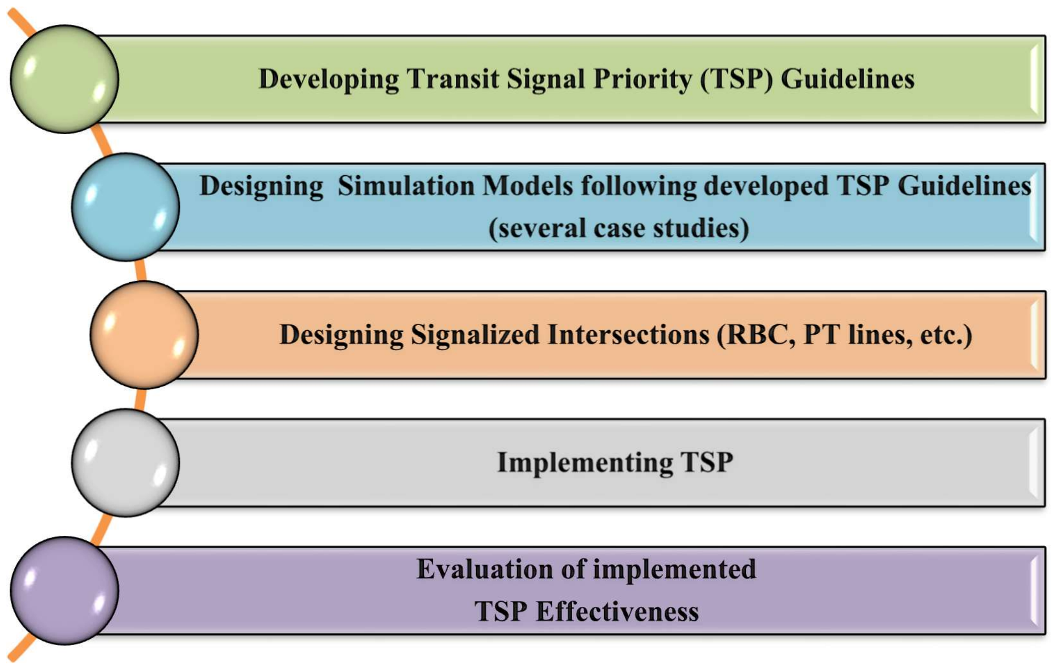


Figure 3. *Methodology - research steps*

The methodology of this research consists of the two main parts: (i) development of the guidelines for identifying corridors that warrant deploying Transit Signal Priority (TSP) and (ii) evaluation of effectiveness of the implemented TSP guidelines in case studies.

3.1 Development of Transit Signal Priority (TSP) Guidelines

The developed guidelines include the following: (I) the set of mandatory feasibility traffic operations criteria and (II) if the conditions from (I) are fulfilled intersections are "qualified" to be assessed through secondary set of 7 weighting factors based on geometric features and transit operations. The set of mandatory feasibility traffic operations criteria were established based on the work produced by Sabra-Wang with combination of the work originated by our research team. ***Volume-to-capacity ratio (V/C)*****:** Capacity is the maximum hourly rate at which vehicles can reasonably be expected to proceed through an intersection under prevailing roadway, traffic, and control conditions. A V/C ratio at or above 0.95 indicate that an intersection operates close to or beyond its capacity. The V/C ratio is an indicator of where mobility might be an issue due to roadways having traffic volumes that exceed their capacity. For the purposes of TSP, an ideal V/C ratio would be between 0.60 and 0.95. At greater than 0.95 V/C ratio, the intersection is approaching capacity and the opportunities to grant TSP requests may be limited. At less than 0.60, the intersection would likely be operating with minimal delay and the effectiveness of TSP may be marginal.

Slack Time**:** Minimum split times for a phase may include required clearances minimum vehicle green, yellow and all-red vehicle clearances, pedestrian walk and flashing don't walk clearances. If slack exists, this time can be reallocated from one phase to another phase, for example to provide TSP by extending the mainline green time and shortening the side street green. Slack time for TSP can typically be taken from the conflicting phases. The minimum slack time needed in a signal cycle during any weekday peak hour to satisfy this mandatory criterion is at least 5 seconds, provided that minimum pedestrian clearances for the conflicting phases, and minimum splits for the left-turn (5 seconds of green + yellow + all-red) are all met. The secondary set of the seven weighting factors based on geometric features and transit operation are used to prioritize intersections for priority and are listed below:

Overall Corridor Ranking**:** The overall corridor ranking is a qualitative assessment of the relative benefit to transit operations that TSP may provide versus the likely impact to overall traffic operations. The influencing metrics include the average bus speeds, average bus productivity (passengers per revenue mile), number of failing intersections and vehicle speeds. Corridors with high bus frequency and ridership, but low bus speed and a low number of failing intersections would be considered more attractive for prioritizing TSP deployment.

Cross-Street Facility Type and Transit Service**:** This factor considers whether the intersecting roadway at a signalized intersection is a primary facility (e.g. major highway or principal arterial). If the intersecting facility is not a principal arterial it is more likely that TSP will be beneficial as side street traffic operations can be disrupted temporarily and the side street is not carrying other bus routes. Also, as part of this criterion, it was noted if the cross street had bus transit service.

Bus Stop Location**:** This factor considers whether the bus stop location is a near-side (before the stop line) or far-side (after the stop line). For TSP-only applications (e.g. not combined with any other priority treatments) a far-side stop is preferable due to dwell time variability and to avoid false calls for TSP.

Presence of Other Priority Treatments**:** This factor considers the presence of other priority treatments for transit vehicles such as a queue jump or dedicated lane. The combination of TSP with these other investments can significantly improve travel time reliability and reduce signal related delay for buses over the provision of TSP alone.

Average PM Peak Hour Bus Speed on Approach: Based on AVL data, the average bus speed on each link approach can be used as a good indicator of current transit operations. Although influences other than signal delay such as dwell time and stop locations may also reduce bus speeds, when compared to average vehicle speeds a larger speed differential can indicate a greater benefit of TSP in improving bus travel time reliability. A maximum 10 mph average bus speed threshold was set for satisfying this weighting factor.

Peak Hour Bus Passengers**:** Based on ridership data, the average bus passengers on each link approach can be used as an indicator of TSP's ability to improve person-throughput along a corridor. A combined link ridership of 100 passengers per peak hour per direction was set for satisfying this weighing factor.

Bus Frequency**:** The route density and headways on each link approach can be used as a possible indicator of the frequency of TSP requests. A minimum 5 buses per hour was set for satisfying this weighting factor.

The flow chart for TSP Intersection Selection Process is presented in Figure 4. The assessment of each intersections starts with determination of the TSP feasibility at the intersection. Intersection needs to satisfy the criteria where the V/C) ratio is between 0.60 and 0.95. If this condition is fulfilled, the next assessment is related to the slack time. It is required that slack time be grated than 5 seconds. After determining the feasibility of TSP at each intersection using the above two mandatory criteria, the intersections are ranked based on the seven weighting factors to show the relative likelihood that they will provide significant TSP benefits to transit without significant negative impacts to traffic operations. The intersections that meet the most thresholds are likely to produce more benefits than those that meet the fewest (1 or 0). Likewise, the more intersection along a corridor that meets a high number of weighting factor thresholds the more likely that coordinated TSP implementation within the corridor will produce benefits.

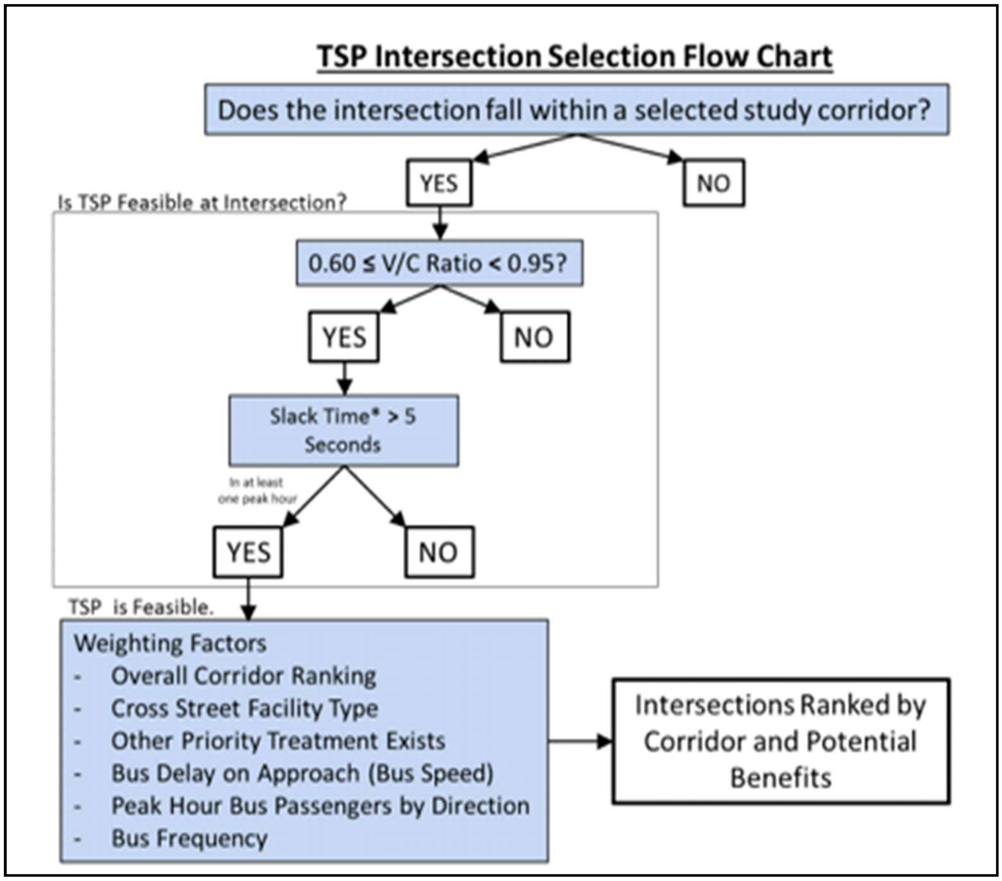


Figure 4. *Flow Chart for TSP Intersection Selection Process (Wang, 2013)*

3.2 Design of Simulation Models following developed TSP Guidelines

Microsimulation models are capable of assessing the TSP performance under different scenarios and setups. Building microsimulation model in order to evaluate the effects of transit signal priority and queue jump was a critical component of this research. Three case studies in Florida have been identified by the research team for the assessment of the proposed method. After various meetings with different state and local traffic agencies, two locations in Southeast Florida and one location in Tampa were selected as case studies. During the project period, the team had several meetings with different local agencies such as Palm Tran in West Palm Beach, Palm Beach Metropolitan Planning Organization in West Palm Beach, and Miami-Dade County in Miami. The selected corridor for the study based on the interviews are Okeechobee Blvd in West Palm Beach, Nebraska Avenue in Tampa and Florida State Road 7 in Miami-Dade County. For the third case study, is in Florida State Road 7 in Miami Dade County and besides developing the model and testing TSP guidance, as is done in the other two case studies, the case study includes an advanced sensitivity analysis.

The impacts of TSP are assessed by comparing the results of total travel time and total delay on the same single corridor with and without TSP applied based on the simulation results. To reach these objectives, the PTV Vissim simulation platform was used, along with the TSP modeling option that exists in this software package, to create the simulation models used in the assessment. The studies included two public transportation lines (one line in both directions) along the corridor.

3.2.1 Case Study # 1: Okeechobee Boulevard, West Palm Beach, Florida

In this case study, the research study area is in Okeechobee Blvd, West Palm Beach, Florida which extends from Haverhill Rd (West border) to Church St (East border) with 9 signalized intersections. Okeechobee Blvd is a major and highly congested corridor which has few industries in the region and it connects the west part with the east and is a 16-mile corridor. The 9-signalized intersection was selected as per the recommendations given by the Traffic Division of the Palm Beach County at West Palm Beach. The research study area is comprised of total 3.1 miles. The list of intersections of the selected corridor for the simulation model is in Figure 5.

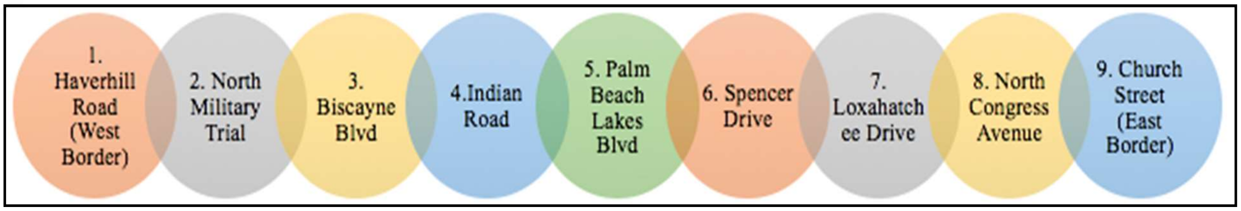


Figure 5. *List of Intersections of the Study Area in Okeechobee Blvd, West Palm Beach, Florida*

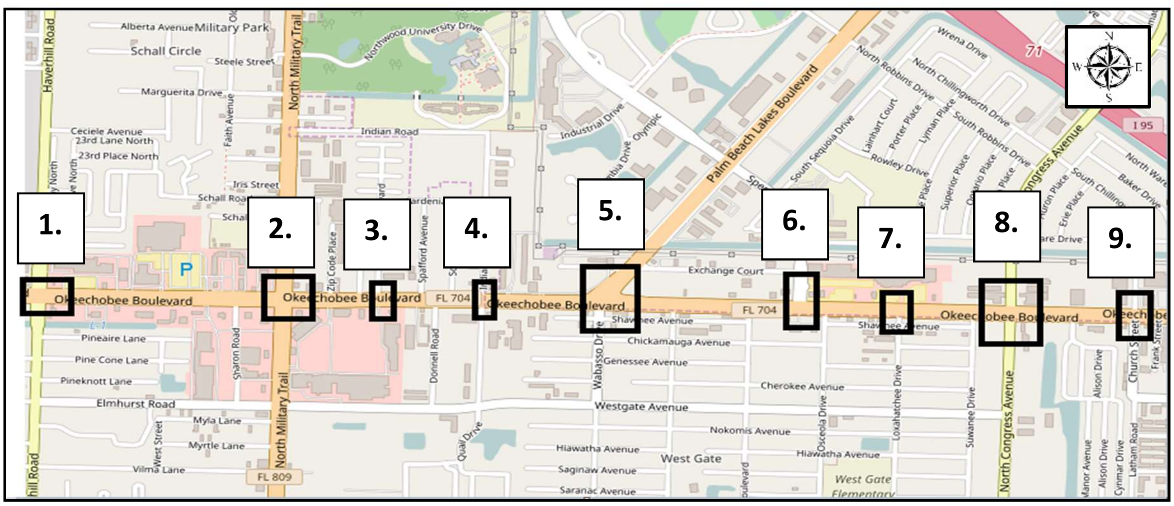


Figure 6. *Map of Okeechobee Blvd with Black Boxes Representing Signalized Intersection*

Figure 6 displays the area of research study in Okeechobee Blvd, West Palm Beach. The black boxes show all the 9-signalized intersection in the length of 3.1 miles. The corridor is positioned in the east-west direction. The furthermost left box represent intersection at Haverhill Road and Okeechobee Blvd, next is North Military Trial and Okeechobee Blvd, followed by Biscayne Blvd and Okeechobee Blvd, Indian Road and Okeechobee Blvd, Palm Beach Lakes Blvd and Okeechobee Blvd, Spencer Dr. and Okeechobee Blvd, Loxahatchee Drive and Okeechobee Blvd, North Congress Ave and Okeechobee Blvd, and Church Street and Okeechobee Blvd. Figure 7, shows the complete network modeled in the micro simulation platform starting from the intersection of Okeechobee Blvd. and Haverhill Road at the left side until the intersection of Okeechobee Blvd. and Church Street on the right side.

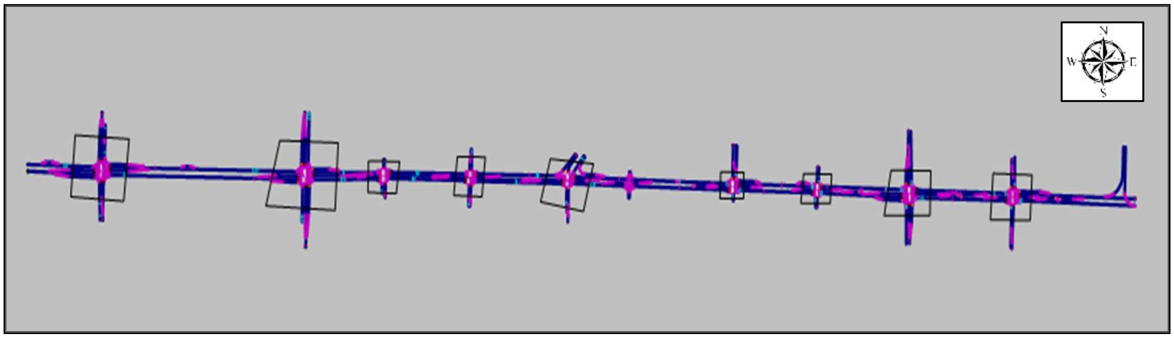


Figure 7. *Microsimulation Model Designed - Okeechobee Blvd., WPB,FL*

3.2.2 Case Study # 2: Nebraska Avenue, Tampa, Florida

Nebraska Avenue is a key arterial that connects the north area of Tampa to Downtown. On average, there are 48,750 vehicles that travel along the corridor each day. Table 5 shows the Annual Average Daily Traffic (AADT) recorded by the Florida Department of Transportation (FDOT) for 2006 – 2015 at four count stations along Busch Boulevard to Marion Transit Center. Traffic volumes peaked around 2008/2009, then declined, and have remained relatively steady for the past four years. The traffic of Nebraska Avenue is nearly 20 percent less today than 2008.

Table 5. *Existing and Historical AADT (Florida Traffic Online, 2012)*

Count Location	AADT									
	2015	2014	2013	2012	2011	2010	2009	2008	2007	2006
Nebraska Ave & Busch Bvld	48,500	48,500	47,000	50,000	48,000	48,500	57,800	50,000	47,000	48,500
Nebraska Ave & Hillborough Ave	49,500	49,500	49,500	48,000	55,500	54,000	54,500	60,500	55,000	53,500
Nebraska Ave & M.L.K Blvd	53,500	49,500	51,500	51,500	-	-	-	54,000	52,000	51,000
Nebraska Ave & Kennedy Blvd	45,500	43,500	47,000	45,000	48,500	43,000	54,500	49,500	49,000	50,500
						I-4 Reconstruction				

To understand how traffic fluctuates throughout the day and by direction of travel, hourly directional volumes are presented in Figure 8 below.

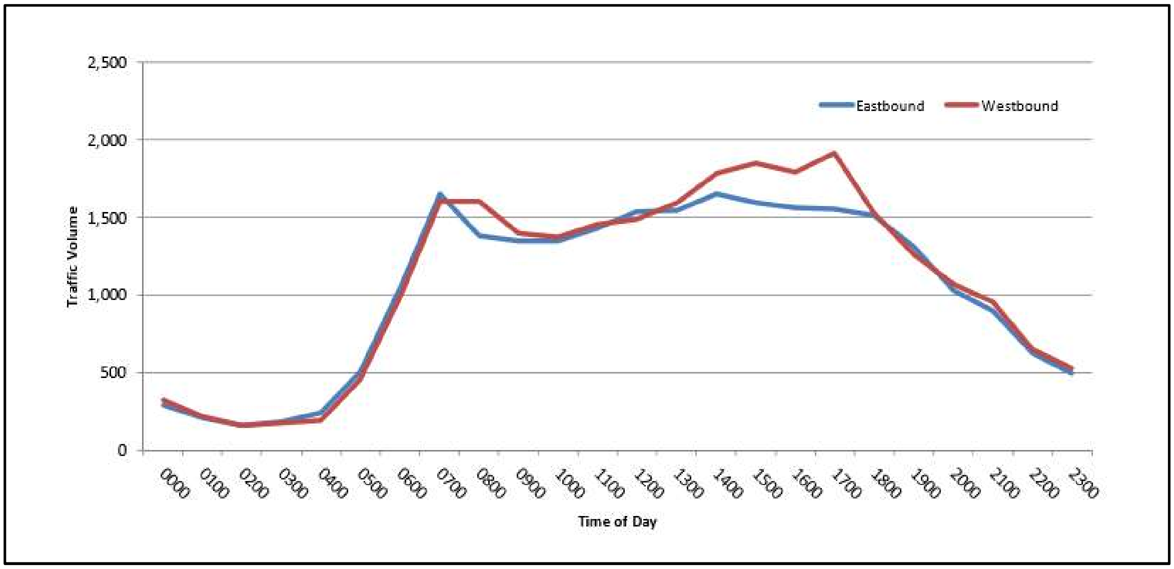


Figure 8. *2014 Hourly Directional Volume – Nebraska Avenue & Busch Blvd*

Hillsborough Area Regional Transit (HART) Authority is the regional transportation authority charged with planning, financing, constructing, and operating public transit facilities and service within Hillsborough County, Florida. HART provides fixed route local and express bus services to most of Hillsborough County.

The North, South Bus Rapid Transit (BRT) corridor begins at the Marion Transit Center (MTC), travels south along the Marion streets transit parkway (MSTP), then turns east along the one-way pair of Kennedy Avenue and Jackson Avenue, then turns north on Nebraska Avenue and terminates near the Busch Avenue. The BRT route will operate mixed traffic, except for the MSTP, and several existing HART routes will either share the proposed stations or will have stops near a proposed station to facilitate transfers. The case study area is presented in the Figure 9 below.

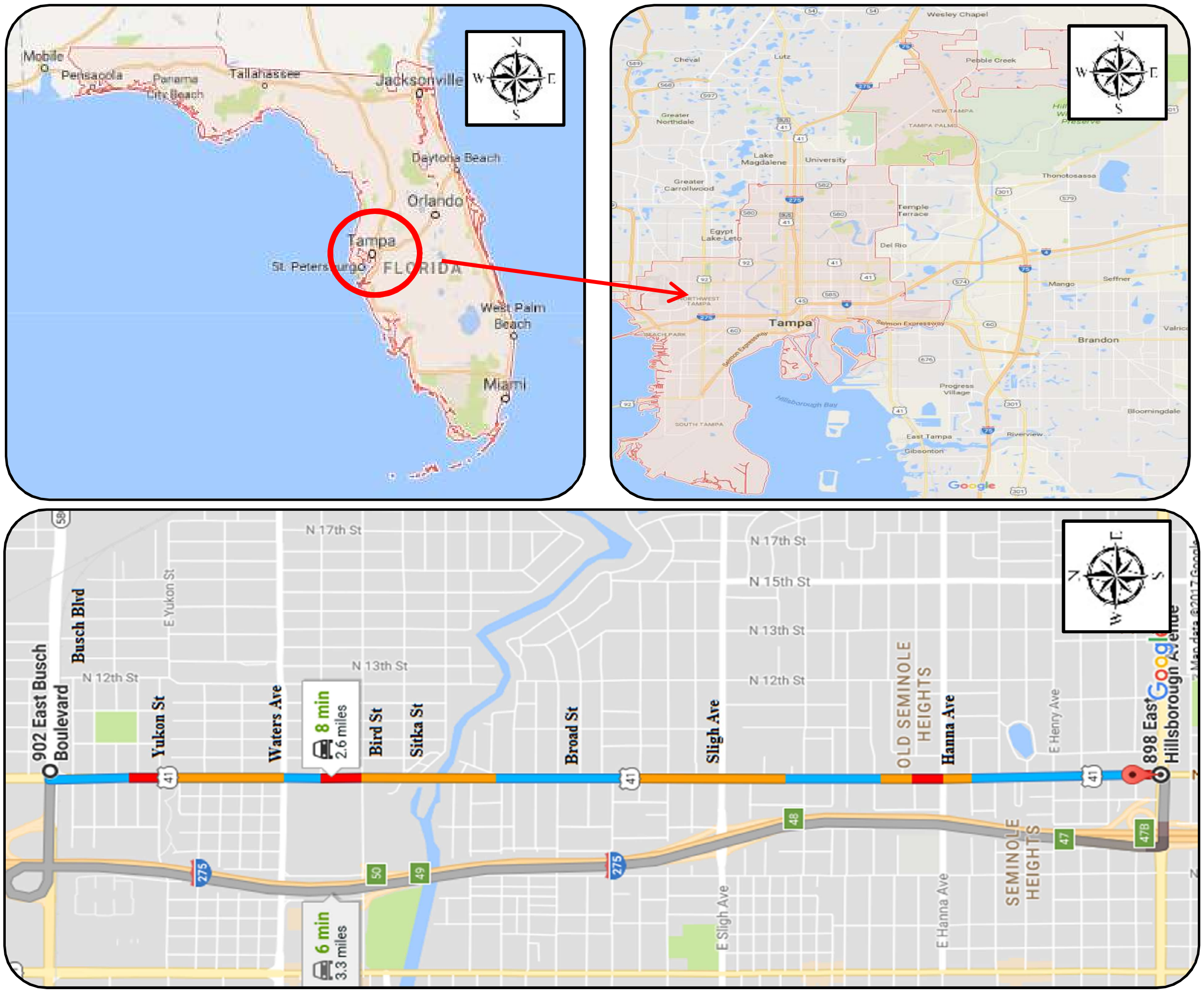


Figure 9. Nebraska Avenue Corridor location, Tampa, FL

The corridor consists of 37 signalized intersections, but due to the lack of data collection only 10 intersections were simulated using PTV VISSIM from Busch Blvd to Hillsborough Blvd with 2.55 miles length (Figure 10).

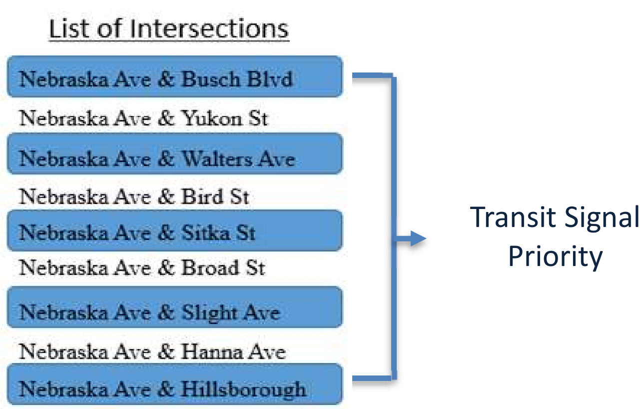


Figure 10. List of Intersections of Study Area at Nebraska Avenue, Tampa, Florida

The Nebraska Avenue case study includes modeling of the queue jumpers and possible implementation of the same. Federal Transit Administration (FTA) defines queue jump lane as a short stretch of bus lane combined with traffic signal priority. It enables buses to by-pass waiting queues of traffic and to cut out in front by getting an early green signal. A special queue jumper phase may be required.

Queue jump lanes are designed to facilitate straight-ahead movements through intersections or turning movements (left or right). Bus Rapid Transit Service Design Guideline mentioned five typical configurations of queue jumpers:

1) Right-turn only lane with transit exemption
2) Queue jump lane adjacent to right turn only lane
3) Queue jump lane with advanced stop bar
4) Curbside bus-only lane with transit exemption
5) Curbside bus-only lane with "pork chop" island

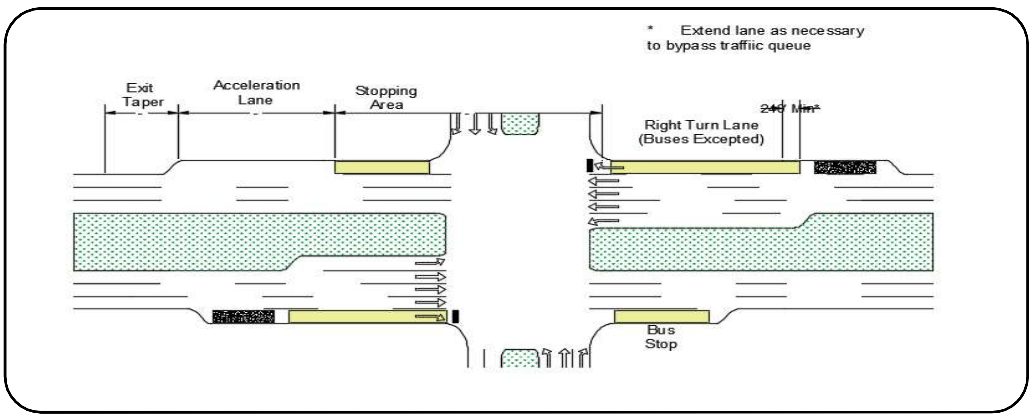


***Figure 11**. Queue jumper bus bay configuration*

The Figure 11 above shows that the queue jumper bus bay consists of three parts: stopping area, acceleration lane, and exit taper and near-side right-turn only lane should be of minimum 240 ft. In the existing network, no change was made for the entrance or exit queue jumper lane. The length of the stopping area is 50 feet for each standard 40-foot bus and 70 feet for each 60-feet articulated bus. 70-foot-long stopping area was used as 60-foot BRT used the queue jumper. The length of acceleration lane and exit taper varies with respect to through speed (mph) and entering speed (mph). Speed of the transit varies from 36.0 to 42.3 mph so the queue jumper lanes needed to be designed for 40 mph through speed and 30 mph entering speed. However, due to space constraint queue jumper lanes were designed for 35 mph through speed and 25mph entering speed.

An example of queue jumper bus bay is shown in Figure 12 for Nebraska Ave & Hillsborough Blvd intersection. Far side bus bay is highlighted by purple color. This intersection has one near side bus stop in westbound direction and one far side bus stop in eastbound direction. Therefore, considering 35 mph through speed and 25 mph entering speed the length of the far side bus bay should be 70 ft (stopping area length for articulated bus stop) + 250 ft (length of acceleration lane) + 170 ft (length of exit taper) = 490ft.

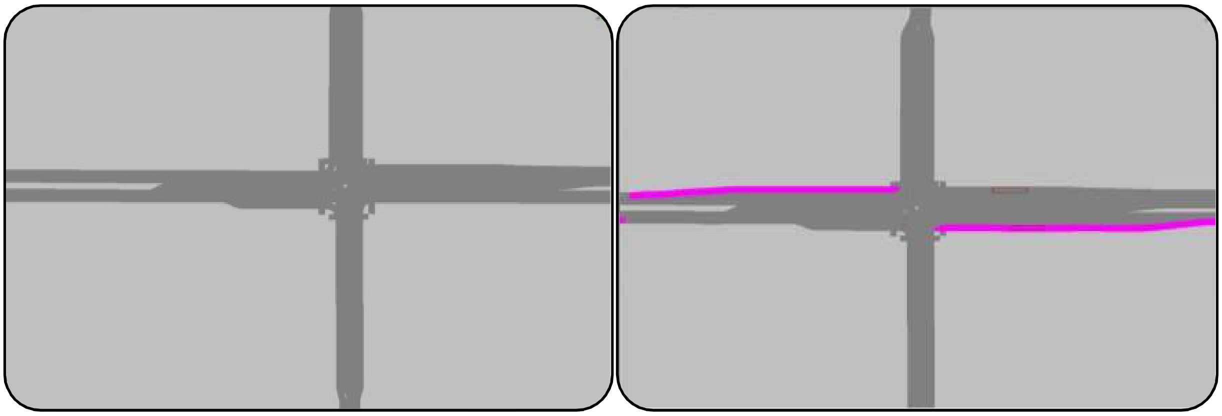


Figure 12. *Intersection with & without queue jumpers*

In order to succeed with the proposed guidelines, the research team developed a set of calculations of volume to capacity ratio of each signalized intersection to prove that the intersections are inside of the parameters proposed for the implementation of transit signal priority. These calculations were performed based on V/C ratio where V is the total number of vehicles passing a point in one hour, and C for the maximum number of cars that can pass a certain point at the reasonable traffic condition.

The highway capacity manual procedures were used in order to analyze the segment and obtain the V/C ratio. For a transit signal priority, an ideal volume to capacity ratio is be between 0.50 to 0.85 and for satisfactory mandatory criteria the slack time must be at least 5 seconds. The **Error! Reference source not found.**below table shows the maximum V/C according to the signalized intersections simulated through the PTV VISSIM platform.

Table 6. *Nebraska Avenue, Tampa - Calculation of Volume to Capacity Ratio*

Signalized Intersections	Density (pc/mi/ln)	Speed (mph)	Maximum V/C
Nebraska Ave & Busch Blvd	31,81	30 - 40	0,84
Nebraska Ave & Yukon ST	22,47	30 - 40	0,70
Nebraska Ave & Walters Ave	27,55	30 - 40	0,70
Nebraska Ave & Bird St	28,07	30 - 40	0,70
Nebraska Ave & Sitka St	27,55	30 - 40	0,70
Nebraska Ave & Broad St	13,46	30 - 40	0,50
Nebraska Ave & Slight Ave	28,28	30 - 40	0,70
Nebraska Ave & Hanna Ave	27,45	30 - 40	0,50
Nebraska Ave & Hillsborough	24,71	30 - 40	0,70

This case study considers two possible scenarios:

- Scenario #1: No TSP with no queue jumpers' operations in mixed traffic lane. It does not consider either queue jumpers or TSP.
- Scenario #2: TSP with queue jumpers, introduces queue jumpers along with special queue jumper phase and simultaneously with TSP. Table 7 below shows the sources used to get the required inputs to the model.

Table 7. *Nebraska Ave, Tampa- Data Resources for VISSIM modeling*

Data Element	Source
Traffic Signal Control	FDOT
Traffic Characteristics	FDOT
Transit Information	FDOT & HART TAMPA
Geometric Characteristics	FDOT & HART TAMPA

Developed simulation model is presented in the Figure 13 below.

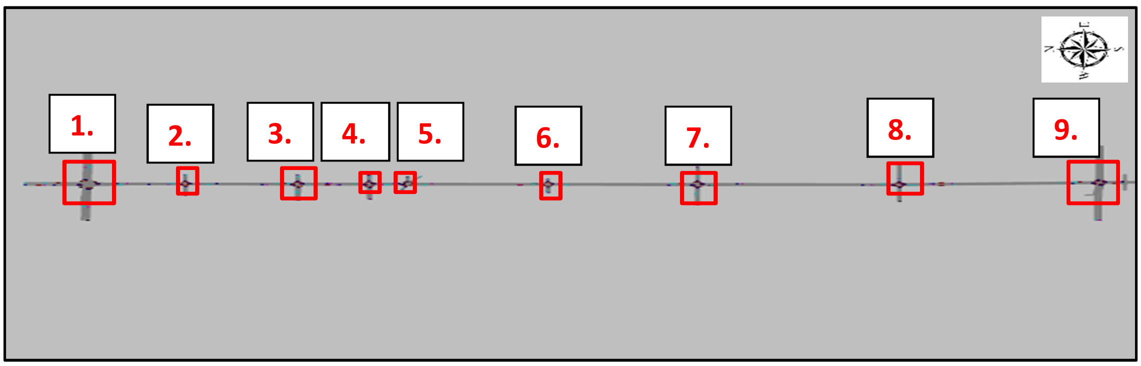


Figure 13. *Simulation Network Model Designed - Nebraska Ave., Tampa, FL*

3.2.3 Case Study # 3: State Road 7, Miami, Florida

The SR 7 (US 441) between SW 8th St. and Golden Glades Interchange in Miami, FL was used as a case study corridor. As shown in Figure 14, SR 7 is parallel to the I-95 limited access facility in Miami, FL, a major north-south corridor in Miami, FL. The study time period is the PM peak period in this case study. Considering the existence of major north-south bus routes along this study corridor, the implementation of the TSP strategy focuses on the 25 signalized intersections between NW 6th St. and NW 159th St in a length of 9.5 miles.

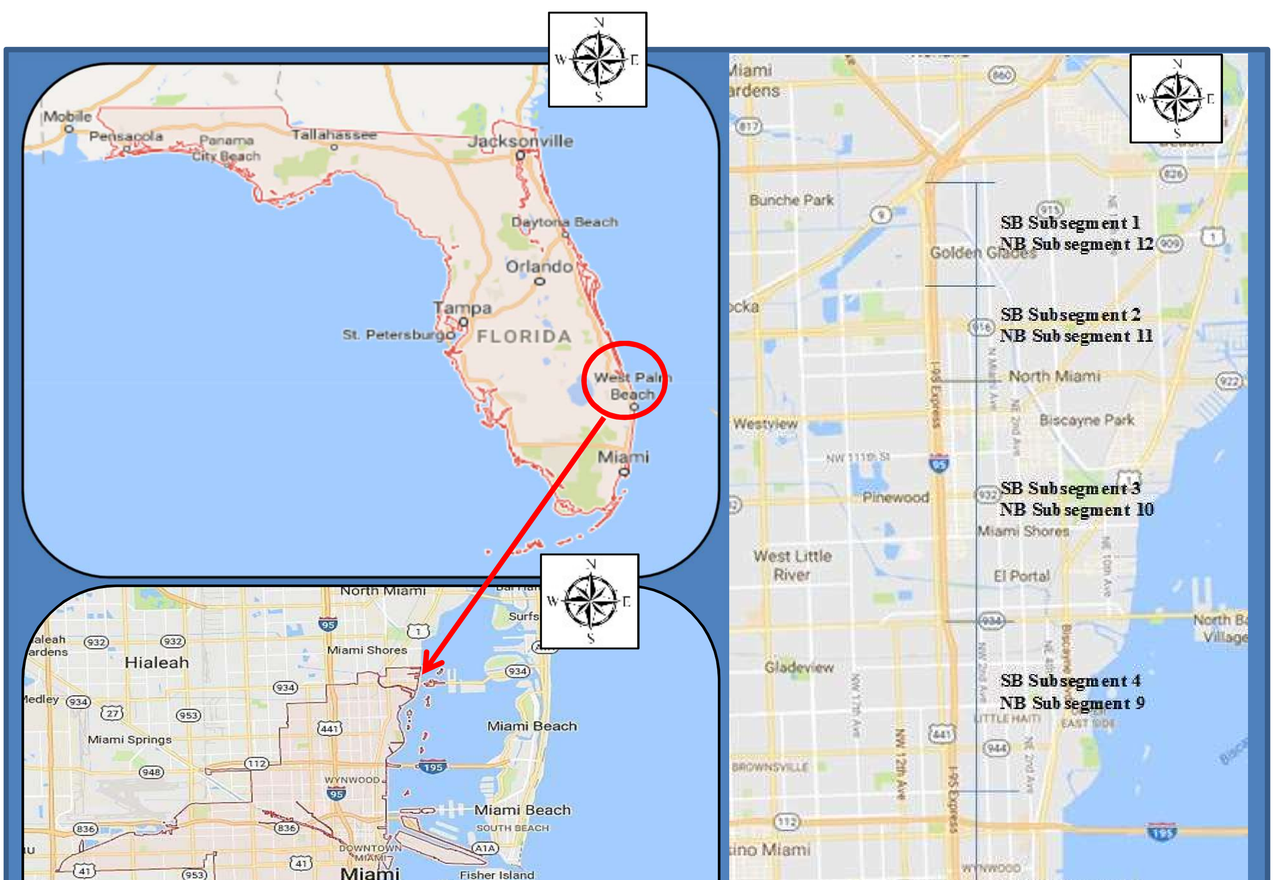


Figure 14. *State Road 7 Corridor Location, Miami-Dade County, FL*

Figure 15. *State Road 7 Corridor Location, Miami-Dade County, FL*

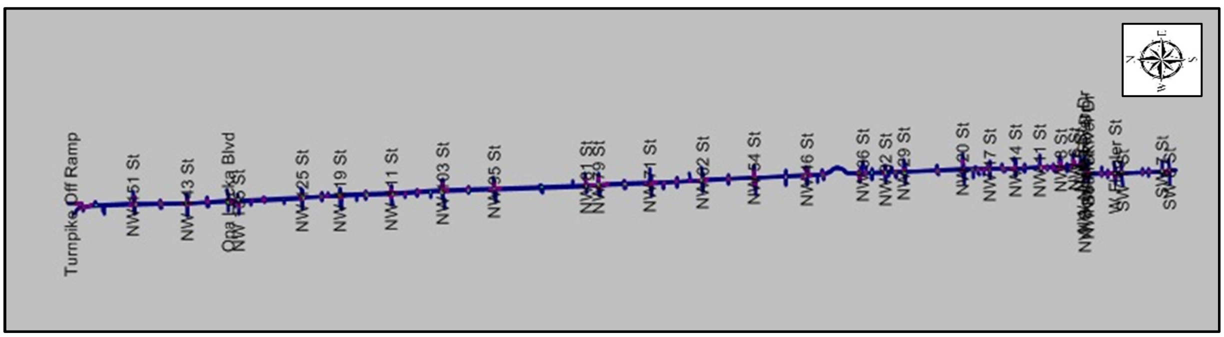


Figure 16. *Simulation Network Model Designed – State Road 7, Miami, FL*

List of the intersection analyzed in the Miami case study is presented in the Table 8.

Table 8. *List of Intersections of Study Area at State Road 7, Miami, Florida*

	Intersections Considered at State Road 7 Corridor
1	*NW 6th St.*
2	*NW 8th St.*
3	*NW 11th St.*
4	*NW 14th St.*
5	*NW 17th St.*
6	*NW 20th St.*
7	*NW 29th St.*
8	*NW 32nd St.*
9	*NW 36th St.*
10	*NW 46th St.*
11	*NW 54th St.*
12	*NW 62nd St.*
13	*NW 71st St.*

14	*NW 79th St.*
15	*NW 81st St.*
16	*NW 95th St.*
17	*NW 103rd St.*
18	*NW 111th St.*
19	*NW 119th St.*
20	*NW 125th St.*
21	*NW 135th St.*
22	*Opa Locka Blvd.*
23	*NW 143rd St.*
24	*NW 151st St.*
25	*NW 159th St.*

The first step of defined guidelines was to identify the feasibility of TSP at the intersection level. This includes checking, if the volume-to-capacity (v/c) ratio is between 0.6 and 0.95 and if slack time is greater than 5 seconds. In this study, a Synchro model as well as a microscopic VISSIM simulation model for SR 7 study corridor was obtained from a previous work conducted by a consultant company. The signal timings in both files are not consistent as they reflect different scenarios. Updates were made to the Synchro file based on the input of VISSIM file to make it represent the existing traffic conditions. The v/c ratio for each movement was estimated using the updated Synchro model and the slack time was calculated based on the signal timing plan coded in the VISSIM model. However, it is not clear which v/c ratio the guideline refers to as it only mentions that capacity is the maximum hourly rate at which vehicles can proceed through an intersection under prevailing conditions. Therefore, three v/c ratios were tested in this study, including the critical v/c ratio based on the main street through traffic, critical v/c ratio based on all movements at the intersection, and the average v/c ratio of all movements at intersection. Table 9 lists the intersections that meet the v/c ratio and slack time criteria. Note that the value of 1 in this table indicates that intersection satisfies the criterion. As shown in this table, seven intersections meet the v/c ratio criterion when using the main street critical v/c ratio as a measure. This number becomes 17 and 4 when using the intersection critical v/c ratio and the intersection average v/c ratio, respectively. It can also be seen from this table that all the intersections satisfy the criterion of slack time.

Table 9. *Intersections Meeting Mandatory Criteria*

Nbr.	*Intersection*	*Main Street Critical V/C Ratio-Based Criteria*	*Intersection Critical V/C Ratio-Based Criteria*	*Intersection Average V/C Ratio-Based Criteria*	*Slack Time Criteria*
1	*NW 6th St.*	0	1	0	1
2	*NW 8th St.*	0	1	0	1
3	*NW 11th St.*	0	0	0	1
4	*NW 14th St.*	0	0	0	1
5	*NW 17th St.*	0	1	0	1
6	*NW 20th St.*	0	0	1	1
7	*NW 29th St.*	1	1	0	1
8	*NW 32nd St.*	0	0	0	1
9	*NW 36th St.*	1	1	0	1
10	*NW 46th St.*	0	1	0	1
11	*NW 54th St.*	1	1	0	1
12	*NW 62nd St.*	1	0	1	1
13	*NW 71st St.*	0	1	0	1
14	*NW 79th St.*	0	1	0	1
15	*NW 81st St.*	0	1	0	1
16	*NW 95th St.*	0	0	1	1
17	*NW 103rd St.*	1	1	1	1
18	*NW 111th St.*	0	1	0	1
19	*NW 119th St.*	0	1	0	1
20	*NW 125th St.*	1	0	0	1
21	*NW 135th St.*	1	1	0	1
22	*Opa Locka Blvd.*	0	1	0	1
23	*NW 143rd St.*	0	1	0	1
24	*NW 151st St.*	0	1	0	1
25	*NW 159th St.*	1	1	0	1
Total		**7**	**17**	**4**	**24**

In addition to the above two mandatory criteria, a set of seven weighting factors based on geometric and transit operations are listed in the guideline to allow the prioritization of TSP implementations. These weighting factors include overall corridor ranking, cross-street facility type and associated transit service, bus stop location(s), presence of other priority treatments, average PM peak hour bus speed on the approach, peak hour bus passengers, and bus frequency. Each study intersection was assessed against these weighting factors except the factor of the overall corridor ranking, which is not applicable to this case study. Note that an intersection is considered to meet a weighting factor threshold, if either of the main street approaches (the NB approach or SB approach) satisfies the threshold.

Table 10. *Intersections Meeting Weighting Factor Thresholds*

Nbr.	*Intersection*	*Cross-St. Facility Type and Transit Service*	*Bus Stop Location*	*Presence of Other Priority Treatments*	*Peak Hour Bus Passenger*	*Average Peak Hour Bus Speed on Approach*	*Bus Frequency*	*Total Number of Thresholds Satisfied*
1	*NW 6th St.*	0	1	0	1	0	1	3
2	*NW 8th St.*	1	1	0	1	1	1	5
3	*NW 11th St.*	0	1	0	1	1	1	4
4	*NW 14th St.*	0	1	0	1	1	1	4
5	*NW 17th St.*	0	1	0	1	1	1	4
6	*NW 20th St.*	0	1	0	1	1	1	4
7	*NW 29th St.*	0	0	0	1	1	1	3
8	*NW 32nd St.*	0	1	0	1	0	1	3
9	*NW 36th St.*	1	1	0	1	1	1	5
10	*NW 46th St.*	0	1	0	1	0	1	3
11	*NW 54th St.*	1	1	0	1	1	1	5
12	*NW 62nd St.*	1	1	0	1	1	1	5
13	*NW 71st St.*	1	1	0	1	1	1	5
14	*NW 79th St.*	1	1	0	1	1	1	5
15	*NW 81st St.*	1	1	0	1	1	1	5
16	*NW 95th St.*	0	1	0	1	1	1	4
17	*NW 103rd St.*	1	1	0	1	1	1	5
18	*NW 111th St.*	0	1	0	1	1	1	4
19	*NW 119th St.*	0	1	0	1	1	1	4
20	*NW 125th St.*	1	1	0	1	1	1	5
21	*NW 135th St.*	1	1	0	1	1	1	5
22	*Opa Locka Blvd*	0	1	0	1	1	0	3

23	*NW 143rd St.*	0	1	0	1	1	0	3
24	*NW 151st St.*	0	1	0	1	1	0	3
25	*NW 159th St.*	0	1	0	1	0	0	2

In this case study, the intersections passing the mandatory criteria and with a score of weighting factors greater than 3 is selected as potential intersections for TSP implementation. However, it is also noticed that even when an intersection (the intersection at NW 29th St.) satisfies the above requirement, the TSP cannot be deployed at this intersection because the near-side bus stops for both NB and SB approach are too close to the stop line, resulting in a travel time of less than 1 second from the TSP check-in detectors to the stop line.

Table 11 lists the remaining intersections that meet the requirements and are identified as candidates to have TSP implementation based on the guideline for Montgomery County. As shown in this table, 4 out of 25 signalized intersections are candidates to be implemented with TSP when the average v/c ratio is used. This number increases to 6 when the main street critical v/c ratio is considered and it further reaches 16 when the critical v/c ratio is estimated based on all the movements at the intersection. Table 11 also shows that the NW 29th St. is not identified as a candidate due to the presence of near-side bus stops on both the NB and SB approaches, as explained above. It should be pointed out that even though some of intersections are listed as the candidates for TSP implementation in Table 11, the TSP may only be applicable to one of the NB or SB approaches due to the existence of near-side bus stops at one of these two approaches.

Table 11. *Summary of Intersections that can be Implemented with TSP*

Nbr.	***Intersection***	***Main Street Critical V/C Ratio-Based Criteria***	***Intersection Critical V/C Ratio-Based Criteria***	***Intersection Average V/C Ratio-Based Criteria***	***Candidate Intersections for TSP***
1	NW 6th St.	0	1	0	1
2	NW 8th St.	0	1	0	1
3	NW 11th St.	0	0	0	1
4	NW 14th St.	0	0	0	1
5	NW 17th St.	0	1	0	1
6	NW 20th St.	0	0	1	1
7	NW 29th St.	1	1	0	0
8	NW 32nd St.	0	0	0	1
9	NW 36th St.	1	1	0	1
10	NW 46th St.	0	1	0	1
11	NW 54th St.	1	1	0	1
12	NW 62nd St.	1	0	1	1
13	NW 71st St.	0	1	0	1
14	NW 79th St.	0	1	0	1
15	NW 81st St.	0	1	0	1
16	NW 95th St.	0	0	1	1
17	NW 103rd St.	1	1	1	1
18	NW 111th St.	0	1	0	1
19	NW 119th St.	0	1	0	1
20	NW 125th St.	1	0	0	1
21	NW 135th St.	1	1	0	1
22	Opa Locka Blvd	0	1	0	1
23	NW 143rd St.	0	1	0	1
24	NW 151st St.	0	1	0	1
25	NW 159th St.	0	0	0	1
Total		**6**	**16**	**4**	**24**

3.2.3.1 Miami Dade Case Study Sensitivity Analysis

As discussed in the previous section, there are limitations with the existing TSP implementation guidelines, including unclear definition of the v/c ratio and lack of consideration of TSP implementation feasibility in terms of geometry. To overcome these limitations, a sensitivity analysis was first conducted over a simplified network with three intersections to identify the influential factors that impact the performance of TSP implementation. The considered factors include the main street v/c ratio, minor street v/c ratio, signal coordination, bus headway, and upstream implementation of TSP. The sensitivity analysis showed that bus headway is the most important influential factor.

Based on the review of existing TSP guidelines and the sensitivity analysis results, a new model was derived in this study to guide the implementation of TSP. Figure 1-13 shows the flowchart of the model. The first step of the proposed model is to check if buses experience severe delay at the study intersection. Without delays at the intersection, the TSP cannot be beneficial in terms of reduction in the bus travel time. In the proposed model, three criteria are used to check the potential benefits to bus operations. The first criterion is the average bus speed approaching the intersection. A threshold of maximum 10 mph average bus speed was set in the Montgomery County guideline as a weighting factor for implementing the TSP at intersection level. However, such an absolute value of bus speed threshold does not take the variation of speed limit into account. To account for that, this study proposes to use the ratio of the average bus speed to the speed limit as the measure for this criterion. If this ratio is less than 0.25, the bus is considered to experience a significant delay at intersection that requires the consideration of bus priority. For example, if the speed limit is 40 mph, this criterion requires an average bus speed of less than 10 mph when approaching the intersection to be considered for TSP implementation. The other two criteria related to bus operations are bus frequency and ridership. These two criteria ensure the consideration of total person-delay savings. For these two criteria, the thresholds used in the Montgomery County guidelines for TSP implementation are adopted. The thresholds are a frequency of at least 10 buses per hour per direction and at least 100 passengers per hour per direction. Note that an intersection is considered to meet the criteria, if one of the directional movements along the main street satisfies the above criteria.

Even though the checking of the above three criteria may identify that there is a need for implementing TSP at a study intersection to reduce bus delays, it may not be possible to implement TSP due to intersection geometry or traffic constraints. Therefore, the second set of criteria is developed to check the feasibility of implementing TSP. This set of criteria starts with the examination of bus stop locations. The variation of the dwell time at a near-side bus stop causes unpredictable arrival time at intersection stop line, making the implementation of effective and efficient travel time difficult. According to the TSP guideline proposed in the Transit Signal Priority Planning and Implementation Handbook (Smith, et al., 2005), it is recommended to relocate a near-side bus stop to the far-side before considering it for TSP implementation. The next criteria within this set examines the slack time, to see if there is enough time for relocating green time between phases. Note that the slack time is calculated as cycle length minus the sum of the minimum split times for all the phases at the intersection, including the pedestrian phases, if any. A threshold of 5 seconds, as proposed in the Montgomery County guideline, is used in this study.

The third set of criteria examines the impacts of TSP on other movements. It is expected that the implementation of TSP will improves the thru traffic along the main approaches. However, it may also cause delays for the main street left turn and cross street movements. An optimal solution for the TSP implementation is to balance these two. With this concept, this study proposed to check the congestion level of the cross-street movements and the main street left turn movements as a third set of criteria. If these movements are already congested, for example, with a v/c ratio greater than 0.85, it is not recommended to implement TSP as this will make these movements even worse. Rodegerdts et al., (2004) stated in the informational guide for signalized intersection that a v/c ratio less than 0.85 generally indicates adequate capacity and thus traffic is not expected to experience significant delays. To minimize the impacts of TSP on cross street bus services, the cross-street bus frequency and bus ridership are also checked. The corresponding thresholds for the bus frequency and bus ridership are selected as the same as those used in the first set of criteria that is applied to main street buses.

In the Montgomery County TSP guideline, the feasibility of TSP implementation is only checked based on the v/c ratio and slack time. Other criteria, such as the average bus speed, bus stop location, ridership, and so on, are used as weighting factors for prioritization. On the other hand, the proposed guideline includes these influential factors in the warrants themselves and requires a detailed examination of whether a signalized intersection satisfies these criteria in terms of the existence of bus delay, geometric and traffic feasibility, and the impacts of other movements.

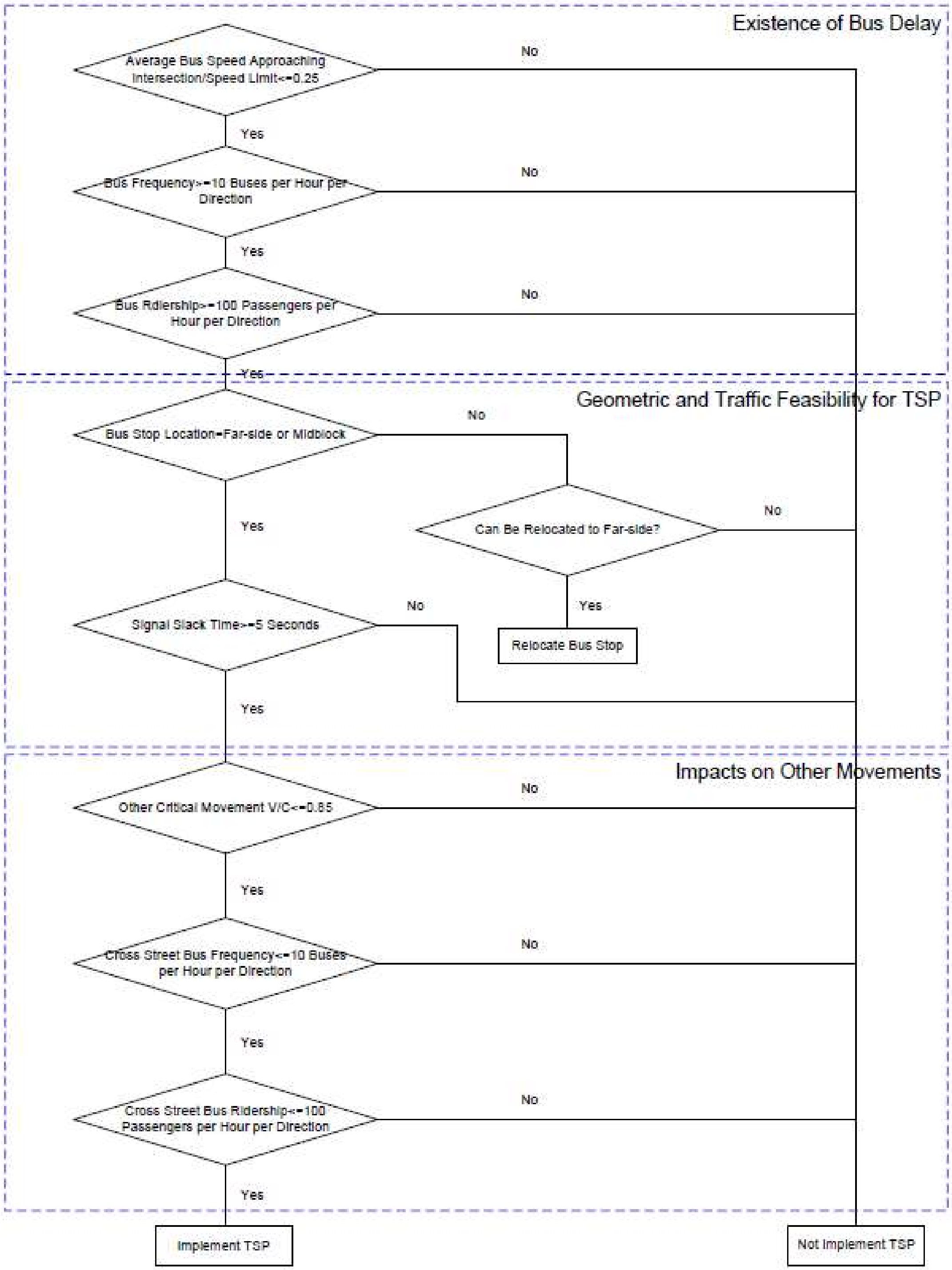


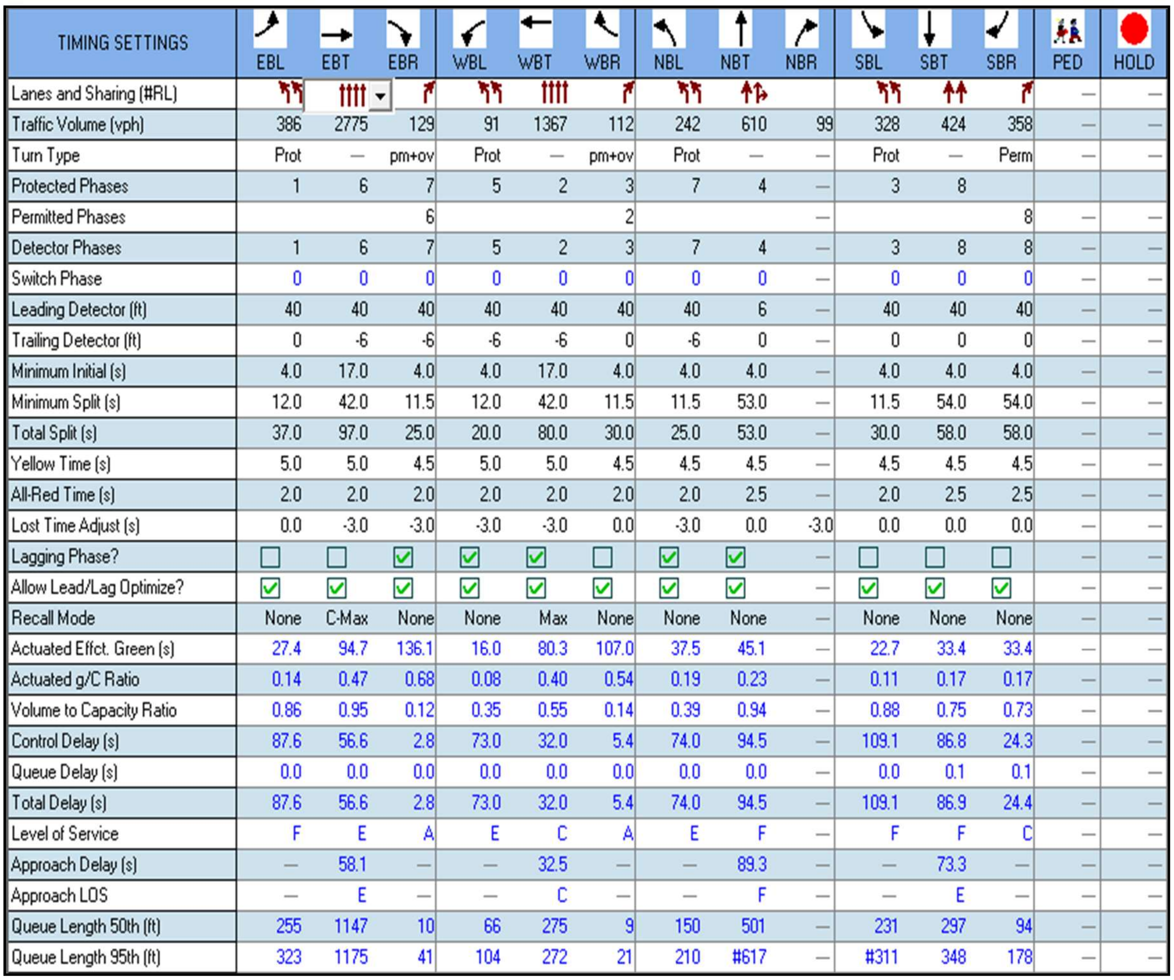
Figure 17. *Guidelines for Miami Dade Case Study Sensitivity Analysis*

3.3 Signalize Intersection Modeling

To model the signalized intersections, the research team obtained various field data for building the microsimulation model such as:

- Geometric data: length of lanes, number of lanes, lane location, and lane assignment.
- Signal timing plan: number of phases, cycle lengths, duration of phases for different time of the day.
- Transit vehicle- travel times, delay time, dwell times and distribution of dwell times.

After collecting, these data were then analyzed and used to produce inputs to the microsimulation platform. Samples of collected data for Haverhill Road from case study #1 (Okeechobee Blvd., WPD, FL) are shown in Figure 17 and Figure 18.



TIMING SETTINGS	EBL	EBT	EBR	WBL	WBT	WBR	NBL	NBT	NBR	SBL	SBT	SBR	PED	HOLD
Lanes and Sharing (#RL)													—	—
Traffic Volume (vph)	386	2775	129	91	1367	112	242	610	99	328	424	358	—	—
Turn Type	Prot	—	pm+ov	Prot	—	pm+ov	Prot	—	—	Prot	—	Perm	—	—
Protected Phases	1	6	7	5	2	3	7	4	—	3	8			
Permitted Phases			6			2			—			8	—	—
Detector Phases	1	6	7	5	2	3	7	4	—	3	8	8	—	—
Switch Phase	0	0	0	0	0	0	0	0	—	0	0	0	—	—
Leading Detector (ft)	40	40	40	40	40	40	40	6	—	40	40	40	—	—
Trailing Detector (ft)	0	-6	-6	-6	-6	0	-6	0	—	0	0	0	—	—
Minimum Initial (s)	4.0	17.0	4.0	4.0	17.0	4.0	4.0	4.0	—	4.0	4.0	4.0	—	—
Minimum Split (s)	12.0	42.0	11.5	12.0	42.0	11.5	11.5	53.0	—	11.5	54.0	54.0	—	—
Total Split (s)	37.0	97.0	25.0	20.0	80.0	30.0	25.0	53.0	—	30.0	58.0	58.0	—	—
Yellow Time (s)	5.0	5.0	4.5	5.0	5.0	4.5	4.5	4.5	—	4.5	4.5	4.5	—	—
All-Red Time (s)	2.0	2.0	2.0	2.0	2.0	2.0	2.0	2.5	—	2.0	2.5	2.5	—	—
Lost Time Adjust (s)	0.0	-3.0	-3.0	-3.0	-3.0	0.0	-3.0	0.0	-3.0	0.0	0.0	0.0	—	—
Lagging Phase?	☐	☐	☑	☑	☑	☐	☑	☑	—	☐	☐	☐	—	—
Allow Lead/Lag Optimize?	☑	☑	☑	☑	☑	☑	☑	☑	—	☑	☑	☑	—	—
Recall Mode	None	C-Max	None	None	Max	None	None	None	—	None	None	None	—	—
Actuated Effct. Green (s)	27.4	94.7	136.1	16.0	80.3	107.0	37.5	45.1	—	22.7	33.4	33.4	—	—
Actuated g/C Ratio	0.14	0.47	0.68	0.08	0.40	0.54	0.19	0.23	—	0.11	0.17	0.17	—	—
Volume to Capacity Ratio	0.86	0.95	0.12	0.35	0.55	0.14	0.39	0.94	—	0.88	0.75	0.73	—	—
Control Delay (s)	87.6	56.6	2.8	73.0	32.0	5.4	74.0	94.5	—	109.1	86.8	24.3	—	—
Queue Delay (s)	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	—	0.0	0.1	0.1	—	—
Total Delay (s)	87.6	56.6	2.8	73.0	32.0	5.4	74.0	94.5	—	109.1	86.9	24.4	—	—
Level of Service	F	E	A	E	C	A	E	F	—	F	F	C	—	—
Approach Delay (s)	—	58.1	—	—	32.5	—	—	89.3	—	—	73.3	—	—	—
Approach LOS	—	E	—	—	C	—	—	F	—	—	E	—	—	—
Queue Length 50th (ft)	255	1147	10	66	275	9	150	501	—	231	297	94	—	—
Queue Length 95th (ft)	323	1175	41	104	272	21	210	#617	—	#311	348	178	—	—

Figure 18. *Timing Sheet of Haverhill Road and Okeechobee Blvd Intersection*

PHASING SETTINGS	1-EBL	2-WBT	3-SBL	4-NBT	5-WBL	6-EBT	7-NBL	8-SBT
Minimum Initial (s)	4.0	17.0	4.0	4.0	4.0	17.0	4.0	4.0
Minimum Split (s)	12.0	42.0	11.5	53.0	12.0	42.0	11.5	54.0
Maximum Split (s)	37.0	80.0	30.0	53.0	20.0	97.0	25.0	58.0
Yellow Time (s)	5.0	5.0	4.5	4.5	5.0	5.0	4.5	4.5
All-Red Time (s)	2.0	2.0	2.0	2.5	2.0	2.0	2.0	2.5
Lagging Phase?	☐	☑	☐	☑	☑	☐	☑	☐
Allow Lead/Lag Optimize?	☑	☑	☑	☑	☑	☑	☑	☑
Vehicle Extension (s)	3.0	2.0	3.0	4.0	2.0	2.0	2.0	4.0
Minimum Gap (s)	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0
Time Before Reduce (s)	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Time To Reduce (s)	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Recall Mode	None	Max	None	None	None	C-Max	None	None
Pedestrian Phase	☐	☑	☐	☑	☐	☑	☐	☑
Walk Time (s)	—	7.0	—	5.0	—	7.0	—	5.0
Flash Dont Walk (s)	—	27.0	—	41.0	—	27.0	—	42.0
Pedestrian Calls (#/hr)	—	0	—	0	—	0	—	0
Dual Entry?	☐	☑	☐	☑	☐	☑	☐	☑
Inhibit Max?	☑	☑	☑	☑	☑	☑	☑	☑
90th %ile Green Time (s)	30 mx	73 cd	24 mx	46 mx	13 mx	90 cd	29 hd	41 gp
70th %ile Green Time (s)	30 mx	73 cd	24 mx	46 mx	13 hd	90 cd	33 hd	37 gp
50th %ile Green Time (s)	29 gp	74 cd	24 mx	46 mx	13 hd	90 cd	36 hd	33 gp
30th %ile Green Time (s)	26 gp	77 cd	23 gp	46 mx	13 hd	90 cd	39 hd	30 gp
10th %ile Green Time (s)	22 gp	89 cd	20 gp	41 gp	13 hd	98 cd	35 hd	26 gp

Figure 19. *Phase Settings Data of Haverhill Road and Okeechobee Blvd Intersection*

3.4 Implementation of Transit Signal Priority in Developed Models

The strategies adopted for implementing TSP are early green and extended green traffic operations by the assistance of bus detectors. Bus schedules and bus lines were also introduced in the model with the goal of representing the actual field situation. For every intersection ring barrier controller was presented along with positioning of the detectors. All necessary steps were taken in order for TSP system to work in the model. For each intersection in order for the system to work, check in and check out detectors were placed. “Check in” detectors are used to detect the bus before arriving to the intersection so the signals can be adjusted to the green light. This can be done by extending the green light that is already on or by setting it up to change to green before it supposed to be. “Check out” detectors are used to report to the controller that BUS passed the lights and that if it is necessary it can change the light to red. After setting everything for the simulation models, simulations with/ without TSP implemented were played for a period of 2h and 15 min (AM peak of 2 hours from 7 am to 9 am and 15 min warm up period). The illustration of the “Check in” and “Check out” detectors and their position in the microsimulation model is presented in the Figure 19.

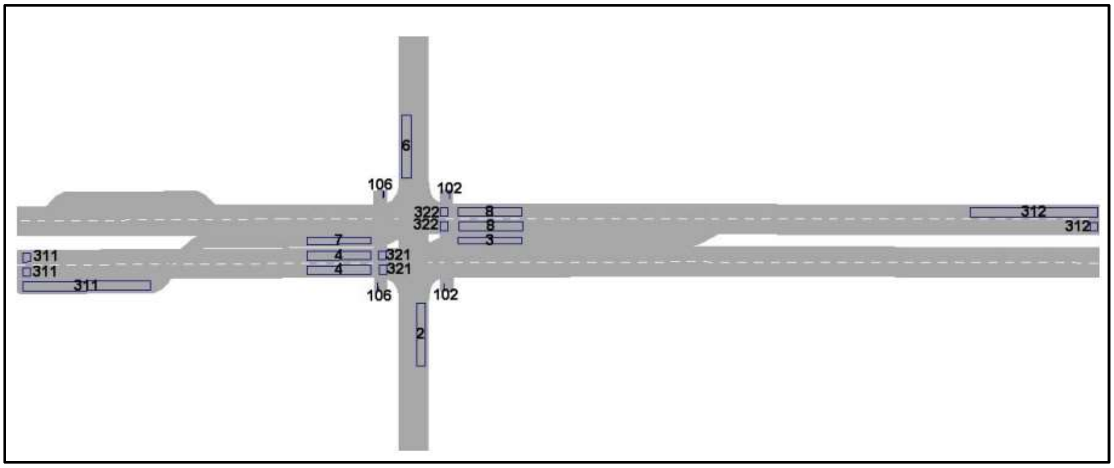


__Figure 20.__ Detectors (including "check in" and "check out") placement for signalized intersection

The queue jump lane is a short stretch of bus lane combined with traffic signal priority. It enables buses to by-pass waiting queues of traffic and cut out in front by getting an early green signal. Queue jump lanes are designed to facilitate straight-ahead movements through intersections or turning movements (left or right). Bus Rapid Transit Service Design Guidelines mentioned five typical configurations of queue jumpers: Right-turn only lane with transit exemption, Queue jump lane adjacent to right turn only lane, Queue jump lane with advanced stop bar, Curbside bus-only lane with transit exemption, and Curbside bus-only lane with “pork chop” island.

Example of the Ring Barrier Controller (RBC) set up for TSP implementation is presented in Figure 20. The setup of “Base Timing” and actuation detectors at the intersections in the RBC present first necessary step in introducing TSP rules in the model. Positioning of the “Check in” and “Check out” detectors at the modeled intersection and setting them up in the RBC is the next necessary step. Positioning of the “Check out” is of the utmost importance. If these detectors are positioned too close to the intersections, the controller will not have sufficient time to recalculate times and assigned green time to approaching bus at right moment. This will cause unwanted delay for the bus and the obtained simulation results would not be accurate enough.

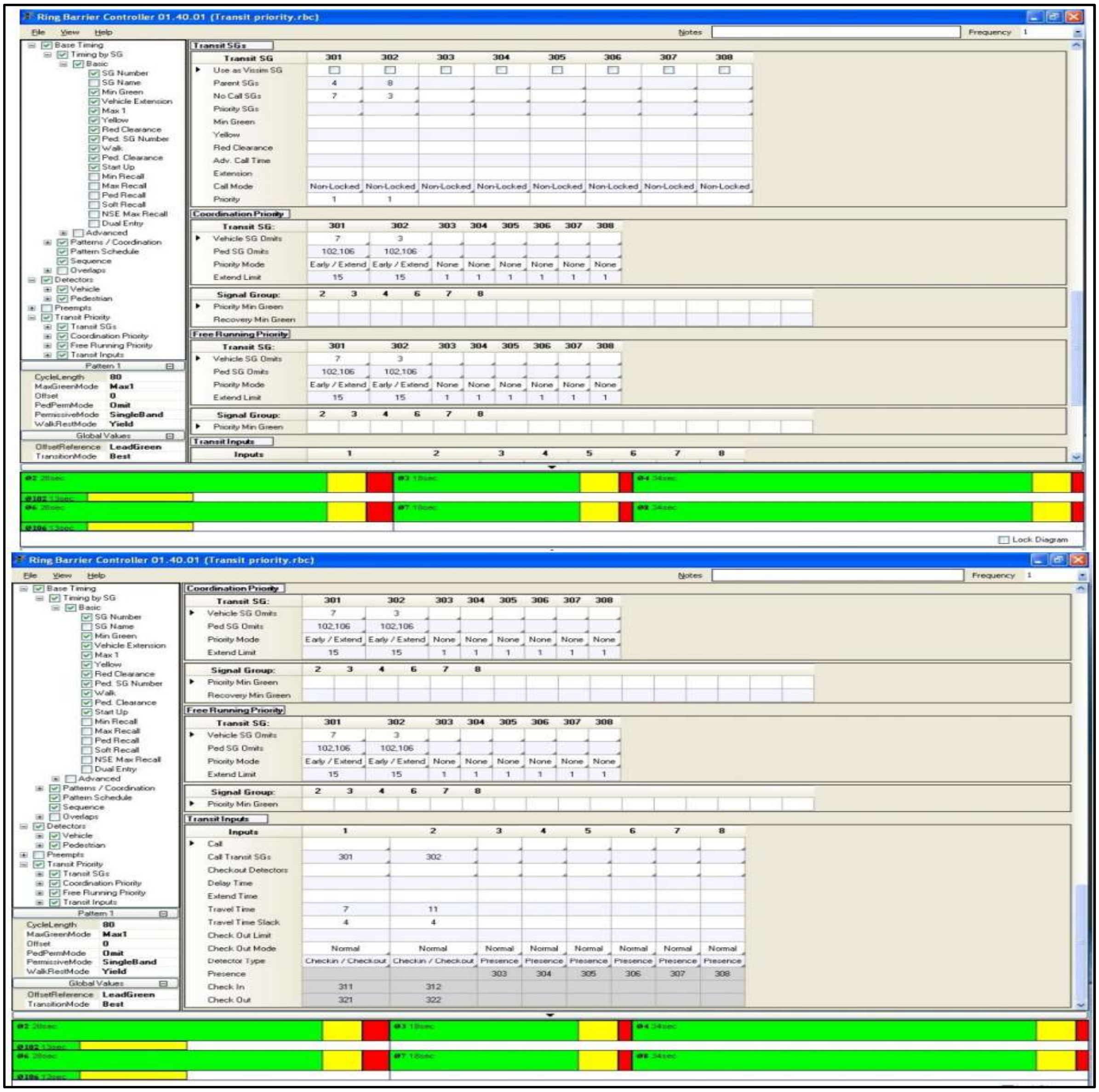


Figure 21. *Example of Transit Signal Priority set up in Vissim 9.0 Ring Barrier Controller*

Early Green Operations: This strategy is used to shorten the conflicting phases whenever a bus arrives at a red light in order to return to the bus's phase sooner. The conflicting phases are not ended immediately but are shortened by a predetermined amount. Early green benefits a large portion of buses (any bus that arrives at a red light), but, provides a relatively modest benefit to those buses. Early green can be combined with green extension at the same intersection to increase the average benefits for transit. There are two unique guidelines which handle main street and side street early green calls. An early green call for the main street movement can be recognized within one cycle length; whereas an early green call for the side street movement is recognized during the transition to a new cycle. Figure 21 illustrates the time segments during which an early green call can be recognized for main street and side street priority movements.

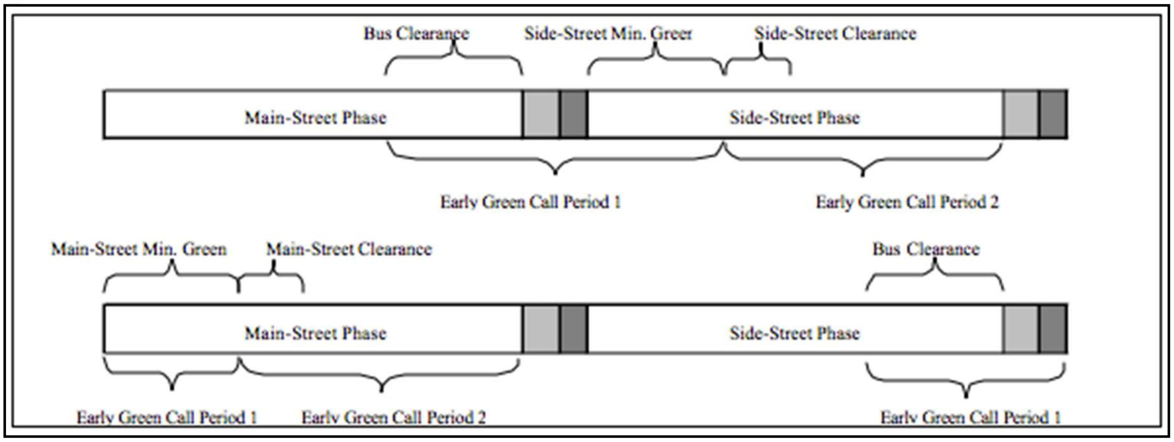


Figure 22. *Illustration of Early Green Logic Concept*

Early green call period 1, illustrated in Figure 21 is the period of time which a call from a bus can be recognized, thus causing an early return to the priority movements. Calls received during early green call period 1 will cause the signal control to recognize a force off at the end of the minimum green time or minimum pedestrian clearance time for the opposite phase, whichever is greater. Similarly, calls received during early green call period 2 will cause the signal control to recognize a force off at the time of the bus actuation. This method provides for maximum priority for the transit vehicle by servicing the clearance interval for the opposing movement and providing a startup time for any queues which may have developed within the bus clearance interval. Both of these rules accept the transit vehicle actuation and apply the new force offs within the current time step. Also, once green is given to the priority phase, the phase will remain green until the original force off is reached. The next section will build upon this discussion for extended green strategy.

Extended Green Operations: This strategy is used to extend the green interval by up to a preset maximum value if a transit vehicle is approaching. Detectors are located so that any transit vehicle that would just fail to catch the green light ("just" meaning by no more than the specified maximum green extension time) extends the green and is able to clear the intersection rather than waiting through an entire red interval. Green Extension provides a benefit to a relatively small percentage of buses (only buses that arrive during a short window each cycle benefit), but the reduction in delay for those buses that do benefit is large (an entire red interval). The extended green strategy is similar to the early green strategy in the use of bus clearance intervals and truncation of green times of opposing phases by adjusting the force offs of the priority phases. Similarly, the extended green logic for the main-street phases are handled within one cycle length, whereas the side-street phases are handled during a transition to a new cycle. The main difference is the amount of time available within the cycle length for the acceptance of an extended green call. This time is equivalent to the clearance time for the transit vehicle (bus clearance interval). Multiple actuations can be recognized, however, resulting in greater benefits for buses arriving in platoons. Figure 22 illustrates the appropriate extended green call periods and extension periods for main-street phases and side-street phases.

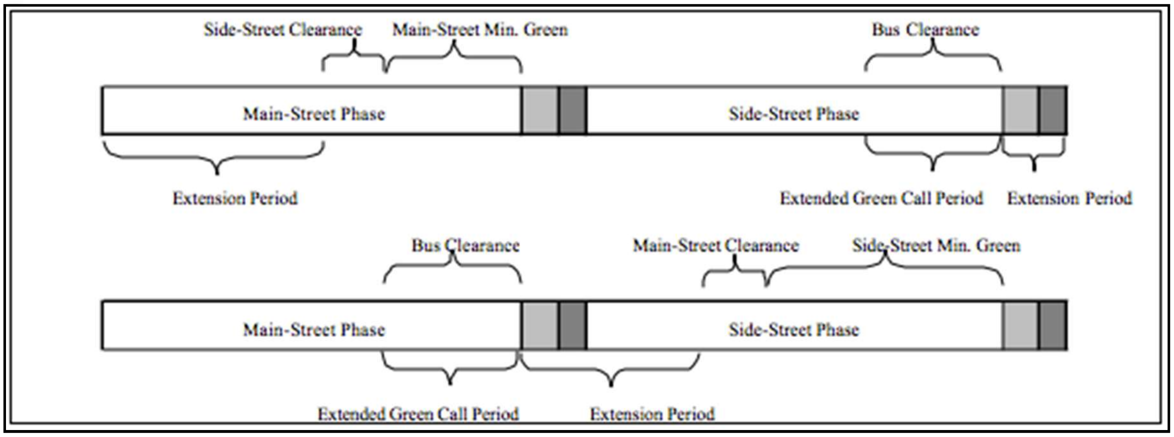


Figure 23*. Illustration of Extended Green Logic Concept*

Upon a call by the bus, the current force off for the priority phase will be extended by an interval equal to the bus clearance time. In the case of multiple calls, if the transit phase is being extended, additional calls will extend the green only if there is enough time to service the bus clearance time. The extended green method for the side-street approach does allow for interruption of traffic coordination. This method seemed like an acceptable practice since there are few occurrences of multiple buses on side-street movements and the green band for the main-street movements was large. It is expected that the early green strategy will provide greater benefits than the extended green strategy. This expectation is due to the greater time window an early green call can be recognized, which can be greater than one-half cycle length. In comparison, the extended green strategy can only recognize a call for a period equal to the bus clearance interval.

3.5 Evaluation of Implemented TSP Effectiveness

Evaluation of implemented TSP effectiveness is required so that benefits that such a system provide can be measurable and precise. Different types of TSP operations require evaluation of (FTA, 2008):

(i) Technology – evaluation of the working technology, maintenance costs required for that technology, technology compliance with the establish TSP specifications, etc.

(ii) Transit Performance – Measurable benefits provided for buses and passengers and possible effects on the reliability.

(iii) Arterial Performance – TSP impact on the other roadway users (cars, trucks and other multimodal users such as bicyclist and pedestrians

Transit and Arterial performance assessment by using different Measures of Effectiveness (MOE) should be quantifiable before and after implementation of TSP. Multiple Measures of Effectiveness are used for evaluation of TSP placed in several categories such as Reliability, Travel Time / Speed, Operating Cost, Pollutant Emission, Ridership, Safety, etc. Most relevant for this research is category of Travel Time / Speed where some of the Measures of Effectiveness are:

- Average travel time on segment and breakdown (dwelling time, intersection delay, running time, etc.)
- average travel speed on segment

- average delay at prioritized intersection (signal delay and other delay)
- number of stops at red
- reduced queue length
- number of cycle failures, where a failure refers to the inability of a signal cycle to clear all of the queued vehicles (FTA, 2008)
- average person delay at prioritized intersection

Measures of Effectiveness (MOE): The MOE chosen for evaluating the impacts of TSP strategies in the conducted case studies are travel time, and delay time of bus only and all other vehicles. The delay measures the time the bus and all other vehicles was below the desired velocity for a signalized intersection approach. To clarify the term approach in this study, it is most commonly referred to as the area from approximately one block upstream from the stop bar location. The MOEs used here are consistent with the reviewed studies and should provide a good representation of the TSP impacts to general traffic and transit operations.

- **Travel Time:** Travel time is an aggregate measurement of travel times on all bus and all other vehicles routes included in the analysis. Therefore, this measure will include benefits received by some bus movements and losses received by others arriving near the transition to or from a TSP strategy. Therefore, a bus arriving on a side street before a bus arriving on the main street will receive priority, causing delay to the main movement. It is also important to realize that multiple buses in the same direction may incur increased delay due to the transition from TSP strategies. Therefore, this MOE will provide a good representation of the performance of the entire system and the applied TSP strategy.

- **Delay Time:** Delay time is reflected in the travel time, but it is also a measurement of the effectiveness of the TSP strategy since it specifically examines delay due to traffic signal operations. A large decrease in bus delay equates to an increased number of priority calls received and processed by the traffic signal controller. This measure will also capture the effects from opposing priority bus movements.

Furthermore, the impacts on to the other road users should also be evaluated. As earlier stated; the intent of installing a TSP is to provide priority for transit vehicles; while limiting the impacts that the measure will have on other users. Therefore, the travel and delay time of all other vehicles is also evaluated.

CHAPTER 4
RESULTS & DICUSSION

This chapter presents the benefits achieved through implementation of Transit Signal Priority and queue jumps scenarios in the performed case studies. Achieved benefits are expressed by using different Measures of Effectiveness (MOE) and their evaluation before and after the implementation of the TSP at the specific corridor of each case study. The Measures of Effectiveness used in this project for evaluation are total travel time, travel time and delay time for all vehicles and for buses only. The MOE comparison for both scenarios where TSP was "Active" and "Inactive" is presented through tabular values as well as through appropriate graphs. The results are presented for each study separately. As stated earlier, more detailed sensitivity analysis was conducted for Case Study 3.

4.1 Results Obtained from the Okeechobee Boulevard Case Study

The results of the evaluation of the effectiveness of TSP applied on Okeechobee Blvd, West Palm Beach from Haverhill Road (West Border) and Church Street (East Border) are presented in this section. The results are presented for both directions. In this evaluation of effectiveness of TSP, the results are presented for all vehicles in the system, as well as, for busses only. With the results for all vehicles, the influence of TSP on all vehicles is presented in Table 12.

Table 12. *Okeechobee Blvd. - All Vehicles Travel Time Comparison*

Travel Time (Seconds) - All Vehicles					
Westbound			*Eastbound*		
Segment	*TSP Inactive*	*TSP Active*	**Segment**	*TSP Inactive*	*TSP Active*
Military / Haverhill	99.63	104.32	Haverhill / Military	98.91	101.77
Biscayne / Military	55.35	69.89	Military / Biscayne	32.67	40.67
Indian / Biscayne	44.4	44.73	Biscayne / Indian	29.4	29.07
Palm Beach Lakes / Indian	28.72	29.39	Indian / Palm Beach Lakes	47.31	55.08
Spencer / Palm Beach Lakes	67.57	67.68	Palm Beach Lakes / Spencer	63.34	47.89
Loxahatchee / Spencer	49.26	34.79	Spencer / Loxahatchee	29.65	27.54
Congress / Loxahatchee	30.04	28.85	Loxahatchee / Congress	54.3	34.72
Church / Congress	44.92	35.39	Congress / Church	48.26	39.04
Total	419.89	415.04		403.84	375.78

In the figures presented below (Figure 23 & Figure 24) travel times between the intersections are presented for all vehicles in the system. Comparison for all vehicles shows that travel time was higher for some intersections and lower for others when the TSP was active.

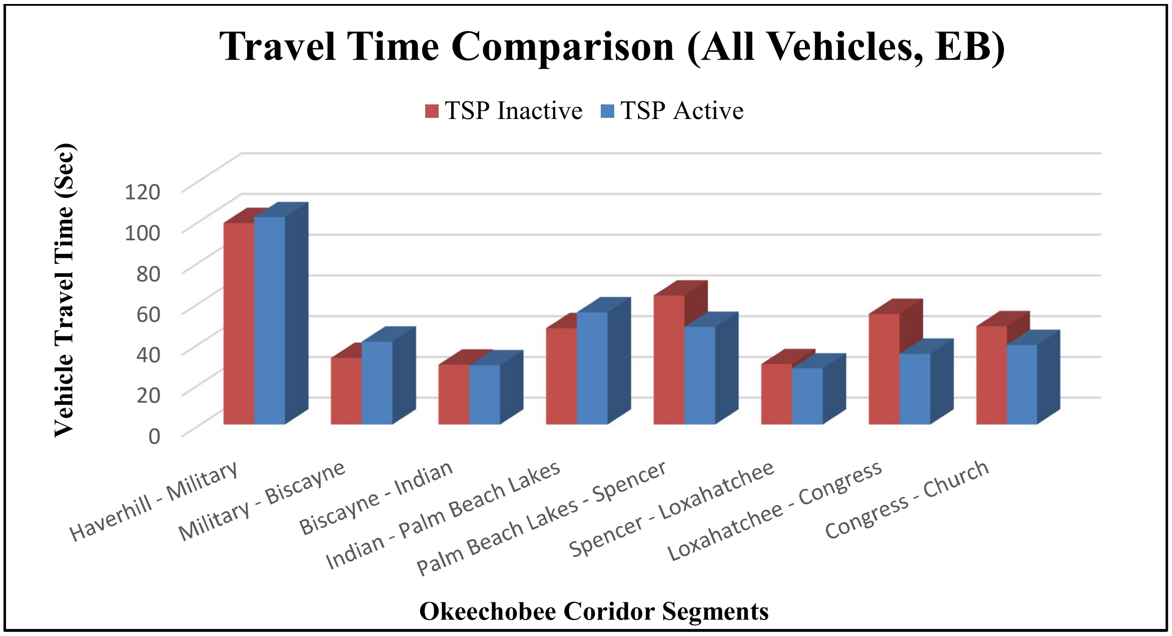


Figure 24. *Okeechobee Blvd. - Travel Time comparison for All Vehicles for EB direction*

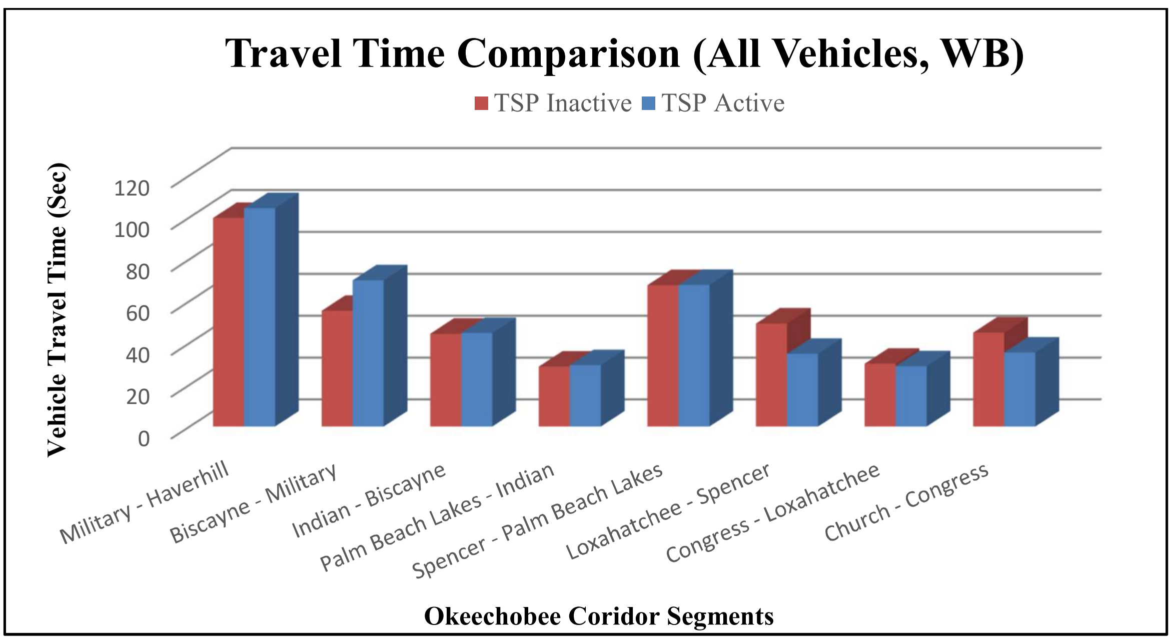


Figure 25. *Okeechobee Blvd. - Travel Time Comparison for All Vehicles for WB direction*

Travel Time Comparison for westbound direction shows that segments have more benefits when the TSP was active comparing to the eastbound direction. Figure 24 shows that segments with the largest difference in travel times for westbound direction are the ones between the Biscayne and Military intersections and the ones between streets Loxahatchee and Spencer. The average travel time without TSP is 50.48 sec while with TSP is 46.97 sec for the eastbound direction. The average travel time without TSP is 53.49 sec while with TSP is 51.80 sec for the westbound direction. All vehicle delay time comparisons for both studied directions is presented in the following table.

Table 13. *Okeechobee Blvd. - All Vehicles Delay Time Comparison*

Intersection	***Delay Time (Seconds) - All Vehicles***			
	Westbound		***Eastbound***	
	TSP Inactive	***TSP Active***	***TSP Inactive***	***TSP Active***
Okeechobee / Haverhill	45.84	48.91	32.78	34.01
Okeechobee / Military	33.56	38.16	37.94	38.18
Okeechobee / Biscayne	20.32	16.37	7.38	10.35
Okeechobee / Indian	1.45	2.57	4.53	4.46
Okeechobee / Palm Beach Lakes	17.9	22.13	16.19	15.18
Okeechobee / Spencer	24.00	8.98	15.29	1.80
Okeechobee / Loxahatchee	4.08	3.76	6.04	5.05
Okeechobee / Congress	15.25	5.85	27.88	10.21
Okeechobee / Church	13.37	10.63	17.36	11.46
Total	175.77	157.36	165.39	130.70

Delay time comparison for all vehicles is presented in the following figures where it is noticeable that for the TSP active scenarios, the delay of each segment is less compared with the results for the scenario with the TSP inactive (Figure 25 & Figure 26). The average delay is without TSP 18.38 s, while with TSP is 14.52 s for the eastbound direction. Average delay without TSP is 19.53 sec while with TSP is 17.48 sec for the westbound direction. Figure 25 provides detail comparison of the delay time for eastbound direction and shows that the least difference between delay times occurs at the intersections Okeechobee Blvd. and Indian Street and Okeechobee Blvd. and Loxahatchee. The largest difference between delay times occurs at the intersections of Okeechobee and Spencer as well as at the intersection of Okeechobee and Congress Avenue.

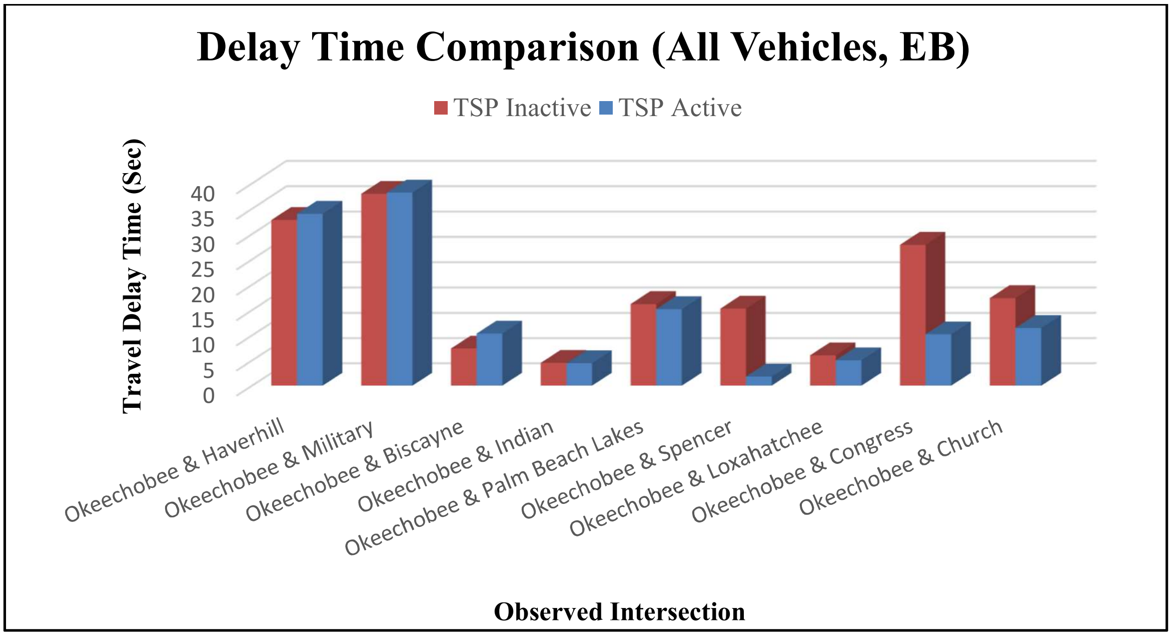


Figure 26*. Okeechobee Blvd. - Delay Time Comparison for All Vehicles for EB direction*

Figure 26 provides a detailed comparison of the delay time for westbound direction and shows that the least difference between delay times occurs at the intersections Okeechobee Blvd. & Indian Street and Okeechobee Blvd. and Loxahatchee. The largest difference between delay times occurs at the intersections of Okeechobee and Spencer as well as at the intersection of Okeechobee and Congress Avenue. The least and the largest difference of delay time are at the same intersections at both directions.

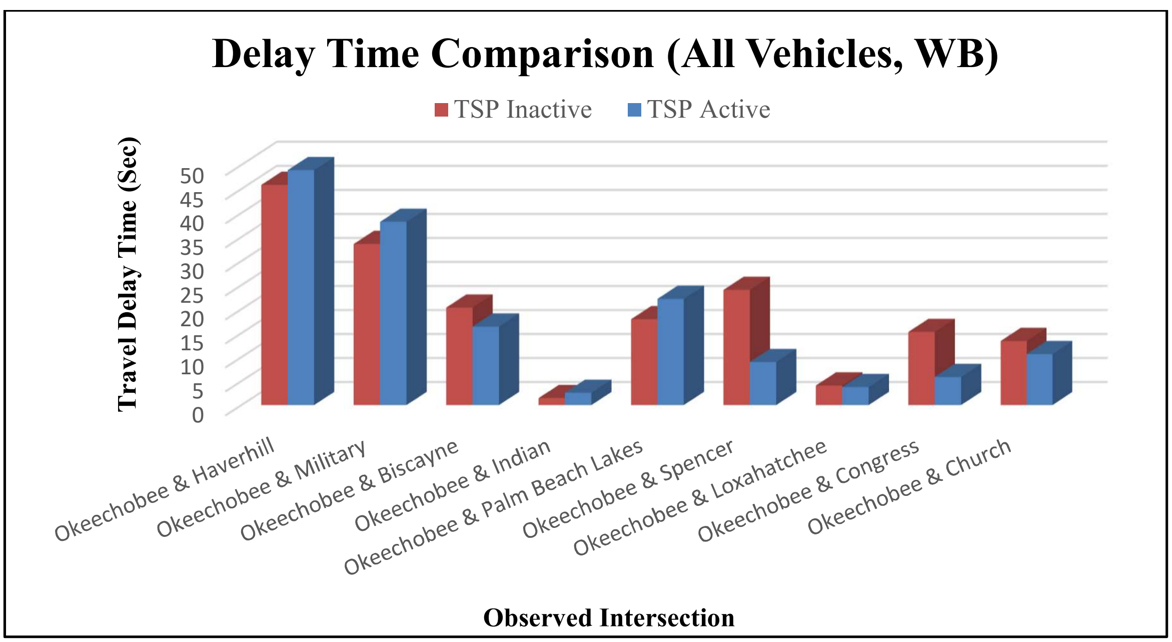


Figure 27*. Okeechobee Blvd. - Delay Time Comparison for All Vehicles for WB direction*

In the figure presented below (Figure 27 and Figure 28), the travel times between the intersections are presented for the busses in the system. In the tabular display (Table 14), it is noticeable that the travel times for buses are less when the TSP was active in the westbound direction. This may be caused due to large number of vehicles in the network were system was not able to react in the appropriate way. Total Average travel time is better when the TSP was active.

Table 14. *Okeechobee Blvd. - Bus Only Travel Time Comparison*

Travel Time (Seconds) - Buses Only					
Westbound			***Eastbound***		
Segment	***TSP Inactive***	***TSP Active***	***Segment***	***TSP Inactive***	***TSP Active***
Military / Haverhill	172.92	152.31	Haverhill / Military	155.89	143.53
Biscayne / Military	90.80	63.77	Military / Biscayne	68.18	76.05
Indian / Biscayne	53.42	42.65	Biscayne / Indian	57.73	58.21
Palm Beach Lakes / Indian	83.62	85.53	Indian / Palm Beach Lakes	55.63	69.57
Spencer / Palm Beach Lakes	129.50	117.40	Palm Beach Lakes / Spencer	116.03	110.99
Loxahatchee / Spencer	115.32	59.95	Spencer / Loxahatchee	75.57	74.32
Congress / Loxahatchee	74.64	69.56	Loxahatchee / Congress	59.75	58.83
Church / Congress	82.80	66.27	Congress / Church	83.72	64.82
Total	803.02	657.44		672.50	656.32

Figure 27 below shows travel time comparison for buses only for the eastbound direction. It indicates that the highest benefits achieved with the implementation of TSP occur on Military and Haverhill, Church Street and Congress Avenue segments. It is also noticeable that on many segments TSP system was not able to be responsive enough and small benefits in bus travel time was achieved with the introduction of TSP.

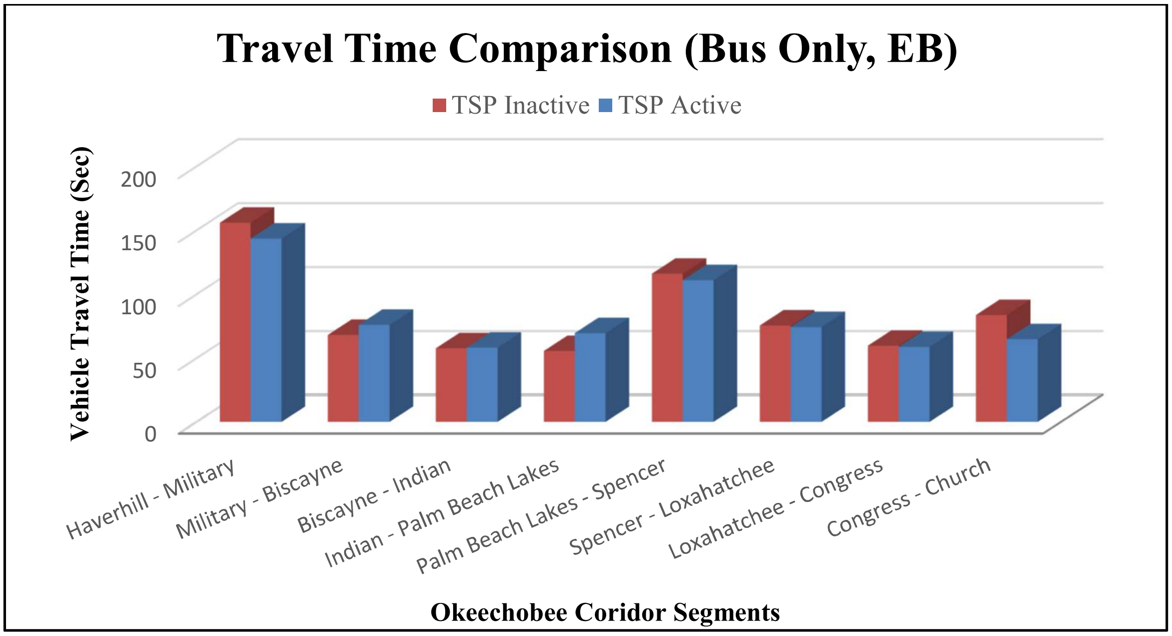


Figure 28. *Okeechobee Blvd. - Travel Time Comparison for Bus Only for EB direction*

Figure 28 below shows travel time comparison for buses only for the westbound direction. It indicates that the highest benefits achieved with the implementation of TSP occur on segments between the Congress and Church St, Haverhill Road and Military intersections. It is also noticeable that their larger differences among travel times exist when the westbound direction is observed.

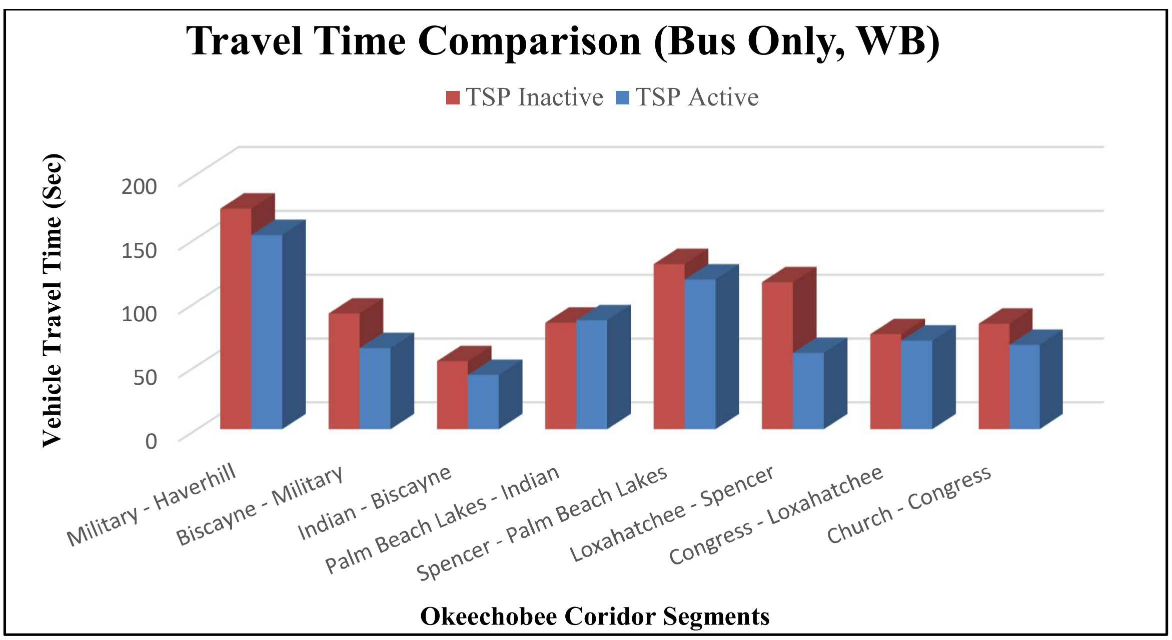


Figure 29. *Okeechobee Blvd. - Travel Time Comparison for Bus Only for WB direction*

The average travel time for buses without TSP is 84.06 sec while with the TSP is 82.04 sec for the eastbound direction and the average travel time for buses without TSP is 100.38 s, while with TSP is 82.18 sec for the westbound direction. Tabular display of the delay time comparison for the scenarios where TSP was Active and Inactive for busses only is presented in Table 15 below.

Table 15. *Okeechobee Blvd. - Bus Only Delay Time Comparison*

Intersection	***Delay Time (Seconds) - Buses Only***			
	Westbound		***Eastbound***	
	TSP Inactive	***TSP Active***	***TSP Inactive***	***TSP Active***
Okeechobee / Haverhill	42.98	15.88	30.47	38.5
Okeechobee / Military	47.02	19.22	15.45	12.11
Okeechobee / Biscayne	23.42	4.21	13.02	20.26
Okeechobee / Indian	21.98	20.03	12.10	14.91
Okeechobee / Palm Beach Lakes	19.70	10.65	21.62	23.36
Okeechobee / Spencer	57.43	4.71	6.43	1.23
Okeechobee / Loxahatchee	16.50	10.53	11.85	9.98
Okeechobee / Congress	24.73	2.55	27.58	13.76
Okeechobee / Church	11.80	1.05	20.01	0.59
Total	265.56	88.83	158.53	134.70

Delay time comparison for buses only using graphs are presented in the next figures where it is more than obviously shown that for TSP active simulation model delay of each segment is much less comparing with the simulation model where TSP is inactive (Figure 29 & Figure 30). In the Figure 29 that provides detail comparison of the delay time for the eastbound direction for busses only it is noticeable that the least difference between the delay times occurs at the intersections Okeechobee Blvd. & Palm Beach Lakes and Okeechobee Blvd. and Loxahatchee. The largest difference between delay times occurs at the intersections of Okeechobee and Church as well as at the intersection of Okeechobee and Congress Avenue.

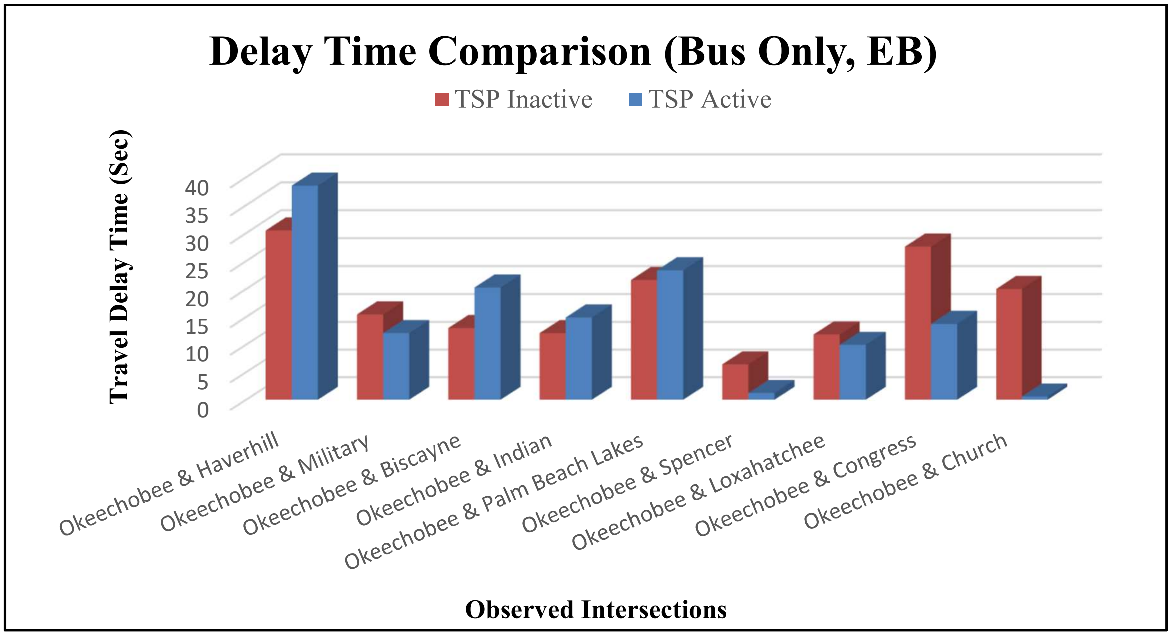


Figure 30. *Okeechobee Blvd. - Delay Time Comparison for Bus Only for EB direction*

Figure 30 provides detail comparison of the delay time for westbound direction it is noticeable that the least difference between delay times occurs at the intersections Okeechobee Blvd. & Indian Street and Okeechobee Blvd. and Loxahatchee. The largest difference between delay times occurs at the intersections of Okeechobee and Spencer as well as at the intersection of Okeechobee and Congress Avenue.

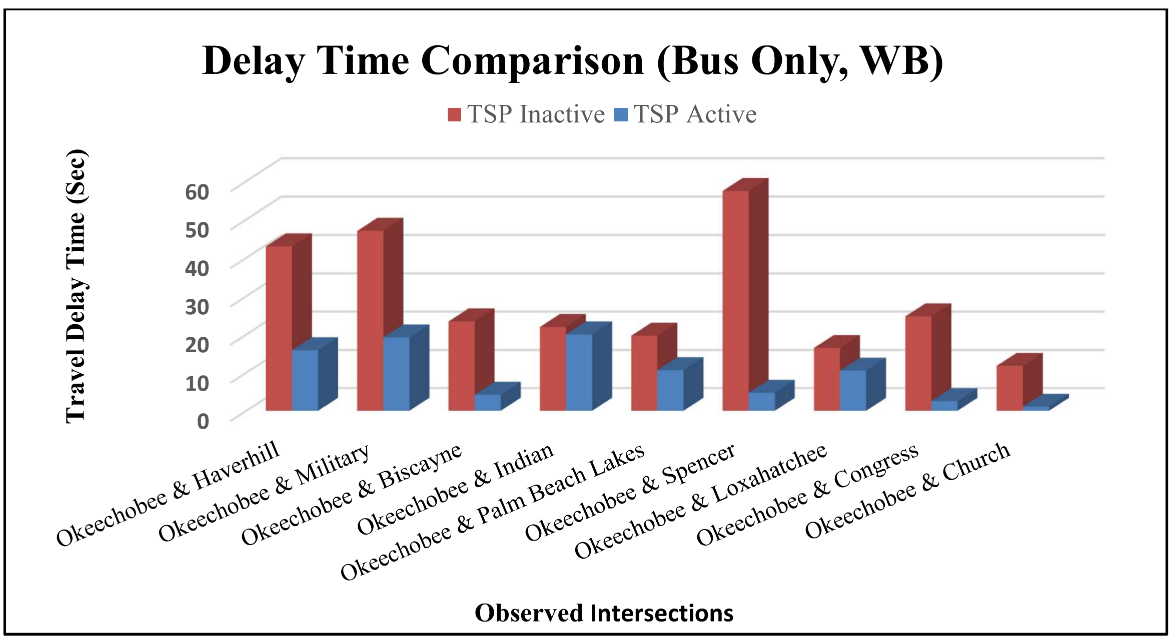


Figure 31. *Okeechobee Blvd. - Delay Time Comparison for Bus Only for WB direction*

The average delay without TSP is 17.61 s, while with TSP is 14.97 s for the eastbound direction. For the westbound direction, the average delay without TSP is 29.51 s, while with TSP is 9.87 s.

In percentage, the average delay time is 20% less for the eastbound direction and 70% less for the westbound direction. Although TSP has minimal impact on vehicle travel time (bus only) in the westbound direction, it significantly reduces the vehicle travel time (bus only) in the eastbound direction. From the travel delay time, there is a significant decrease in the travel delay time for the westbound direction for bus only.

The total time for all vehicles in seconds for the Eastbound without TSP is 403.84 whereas with TSP is 375.78 and the average time for the Eastbound without TSP is 84.06 whereas with TSP it is 82.04. The total time in seconds for the Westbound without TSP is 419.89 whereas with TSP is 415.04 and the average time for the Westbound without TSP is 53.49 whereas with TSP it is 51.80. Similarly, the total time for bus only in seconds for the Eastbound without TSP is 672.50 whereas with TSP is 656.32 and the average time for the Eastbound without TSP is 20.09 whereas with TSP it is 15.82. The total time in seconds for the Westbound without TSP is 803.02 whereas with TSP is 657.44 and the average time for the Westbound without TSP is 100.38 whereas with TSP it is 82.18.

4.2 Results obtain from Nebraska Avenue case study

Evaluation of effectiveness of Transit Signal Priority applied on Nebraska Avenue Corridor, Tampa from Busch Blvd. (South Border) and Hillsborough Blvd. (North Border) is presented in this chapter. For easier understanding, results are obtained and presented for both northbound and southbound directions. The tabular display of the comparison of all vehicle travel times is shown in Table 16.

Table 16. *Nebraska Ave. - All Vehicles Travel Time Comparison*

Directions	*Intersections*	*Node*	*Without TSP*	*With TSP*
NORTHBOUND	Nebraska Ave & Busch Blvd	1	43.84	46.91
	Nebraska Ave Yukon St	2	31.56	36.16
	Nebraska Ave & Walters Ave	3	18.32	14.37
	Nebraska Ave & Bird St	4	3.45	4.57
	Nebraska Ave & Sitka St	5	15.90	20.13
	Nebraska Ave & Broad St	6	21.57	6.98
	Nebraska Ave & Slight Ave	7	2.08	1.76
	Nebraska Ave & Hanna Ave	8	13.25	3.85
	Nebraska Ave & Hillsborough Blvd	9	11.37	8.63
SOUTHBOUND	Nebraska Ave & Busch Blvd	1	30.78	32.01
	Nebraska Ave Yukon St	2	35.94	36.18
	Nebraska Ave & Walters Ave	3	5.38	8.35
	Nebraska Ave & Bird St	4	2.53	2.46
	Nebraska Ave & Sitka St	5	14.19	13.18
	Nebraska Ave & Broad St	6	13.29	3.8
	Nebraska Ave & Slight Ave	7	4.04	3.05
	Nebraska Ave & Hanna Ave	8	25.88	8.21
	Nebraska Ave & Hillsborough Blvd	9	15.36	9.46
Total	***Northbound***	From 1 to 9	***161.34***	***143.36***
	Southbound	From 1 to 9	***147.39***	***116.70***
Average	***Northbound***	From 1 to 9	***17.92***	***15.92***
Average	***Southbound***	From 1 to 9	***16.37***	***12.96***

In the figure presented below (Figure 31 & Figure 32) travel times between the intersections are presented for all vehicles in the system. Figure 31 below shows travel time comparison for all vehicles for northbound direction. It indicates that the highest benefits achieved through implementation of TSP occur on segments between streets Slight Avenue and Broad Street as well as on segment between streets Hillsborough Blvd. and Hanna Avenue. It is also noticeable that on many segments TSP system was not able to be responsive enough and small benefits or in contrary loss in travel time would be achieved with introduction of TSP.

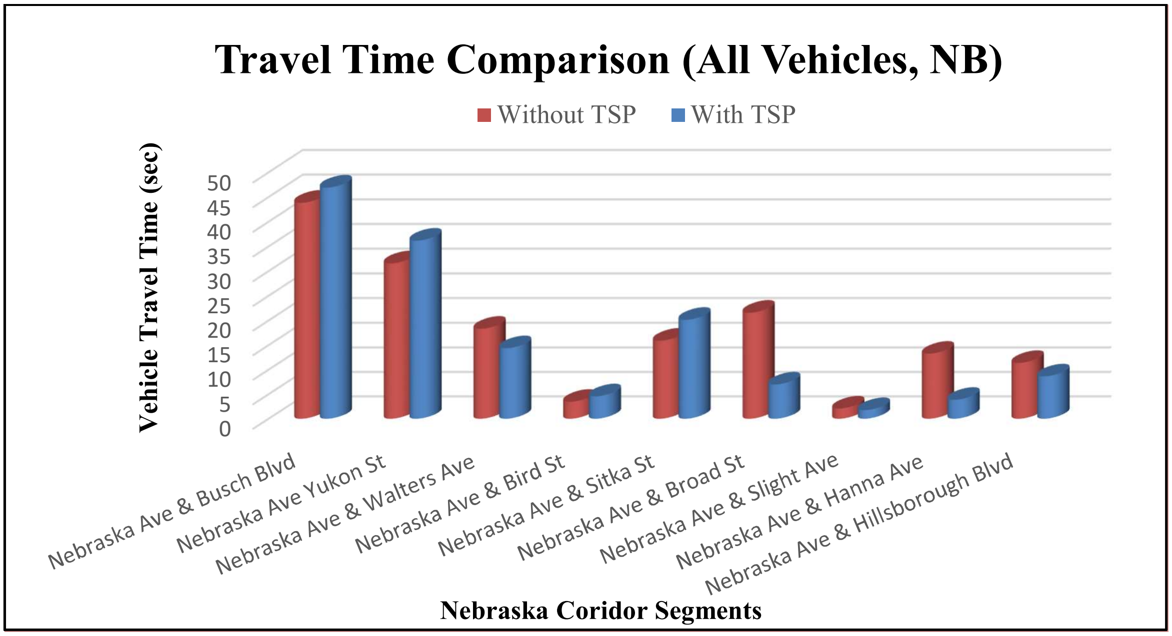


Figure 32. *Travel Time Comparison for All Vehicles for NB direction, Nebraska Avenue*

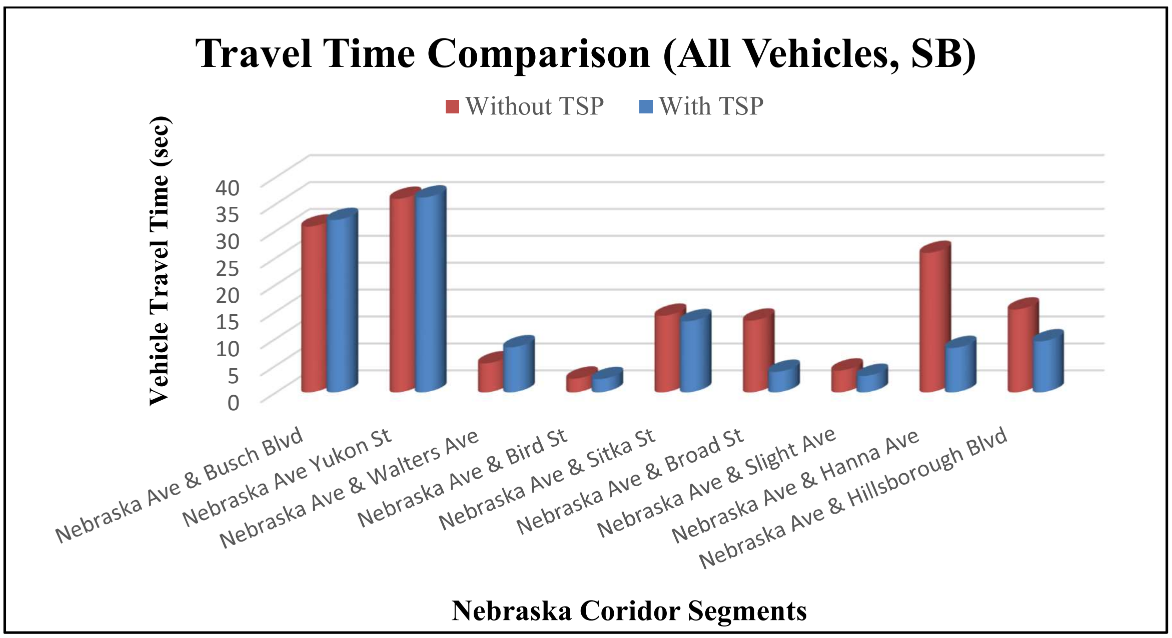


Figure 33. *Nebraska Ave. - Travel Time for All Vehicles for SB direction*

Figure 32 shows travel time comparison for all vehicles for southbound direction. It indicates that the highest benefits achieved through implementation of TSP occur on segments between streets Slight Avenue and Broad Street as well as on segment between streets Hillsborough Blvd. and Hanna Avenue.

In order to interpret the travel time results for private vehicles to evaluate the impact of transit signal priority, and come up with a total travel time a summation was developed from the node 1 to node 9. The Table 17 below showed the results over the scenarios with TSP and without TSP.

Table 17. *Nebraska Ave. - Total Travel Time for all Vehicles for both NB & SB directions*

Summation	***Directions***	***Node***	***Without TSP***	***With TSP***
Total	***Northbound***	From 1 to 9	***161.34***	***143.36***
	Southbound	From 1 to 9	***147.39***	***116.7***

Figure 33 & Figure 34 presents graphical representation of the total travel time comparison for all vehicles at the corridor for both northbound and southbound directions. They present in a clear way the benefits achieved with implementing TSP when it comes to total travel time for all vehicles.

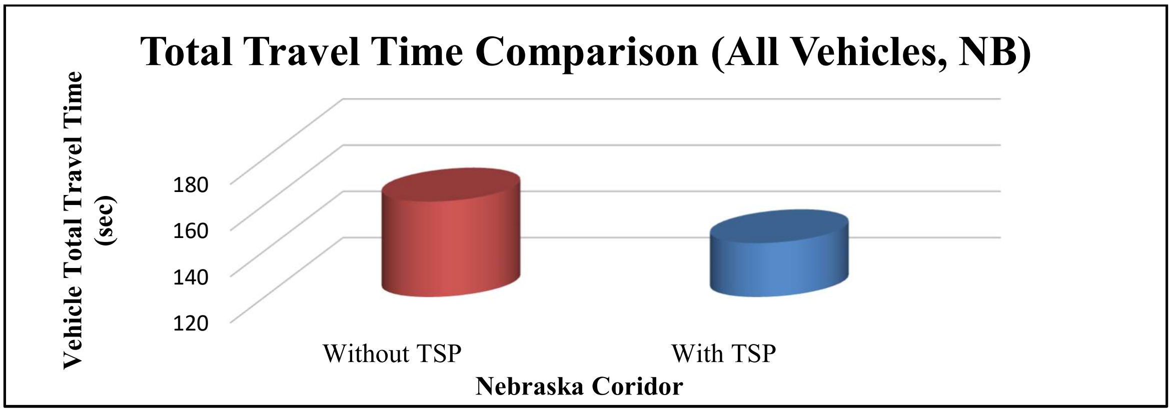


Figure 34. *Nebraska Ave. - Total Travel Time for All Vehicles for NB direction*

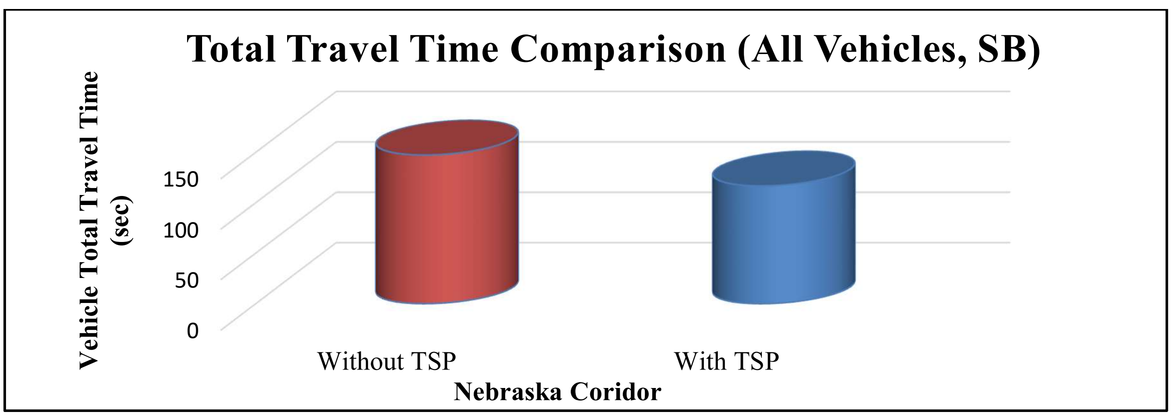


Figure 35. *Nebraska Ave. - Total Travel Time Comparison for All Vehicles for SB direction*

All vehicle delay time comparison for both studied directions is presented in the following table.

Table 18. Nebraska Ave. - All Vehicles Delay Time Comparison

Directions	Intersections	Node	Without TSP	With TSP
NORTHBOUND	Nebraska Ave & Busch Blvd	1	35.94	36.18
	Nebraska Ave Yukon St	2	35.94	36.18
	Nebraska Ave & Walters Ave	3	5.38	8.35
	Nebraska Ave & Bird St	4	2.53	2.46
	Nebraska Ave & Sitka St	5	14.19	13.18
	Nebraska Ave & Broad St	6	13.29	3.80
	Nebraska Ave & Slight Ave	7	4.04	7.05
	Nebraska Ave & Hanna Ave	8	25.88	8.21
	Nebraska Ave & Hillsborough Blvd	9	20.56	16.56
SOUTHBOUND	Nebraska Ave & Busch Blvd	1	28.47	36.50
	Nebraska Ave Yukon St	2	28.47	36.50
	Nebraska Ave & Walters Ave	3	13.45	10.11
	Nebraska Ave & Bird St	4	11.02	18.26
	Nebraska Ave & Sitka St	5	10.10	12.91
	Nebraska Ave & Broad St	6	19.62	21.36
	Nebraska Ave & Slight Ave	7	4.43	4.11
	Nebraska Ave & Hanna Ave	8	9.85	7.98
	Nebraska Ave & Hillsborough Blvd	9	25.58	11.76
Total	***Northbound***	From 1 to 9	***157.75***	***131.97***
	Southbound	From 1 to 9	***150.99***	***154.61***
Average	***Northbound***	From 1 to 9	***17.52***	***14.66***
Average	***Southbound***	From 1 to 9	***16.77***	***17.72***

Delay time comparison for all vehicles is presented in the following figures where it is noticeable that for TSP active simulation model delay of each segment is less compering with simulation model where TSP is inactive (Figure 35 & Figure 36). In the Figure 35 that provides detail comparison of the delay time for northbound direction it is noticeable that the least difference between TSP Active and Inactive delay times occurs at the intersections Nebraska Avenue & Busch Blvd. and Nebraska Avenue and Yucon Street. Largest difference between delay times occurs at intersections of Nebraska Avenue and Hanna Avenue as well as at the intersection of Nebraska Avenue and Broad Street.

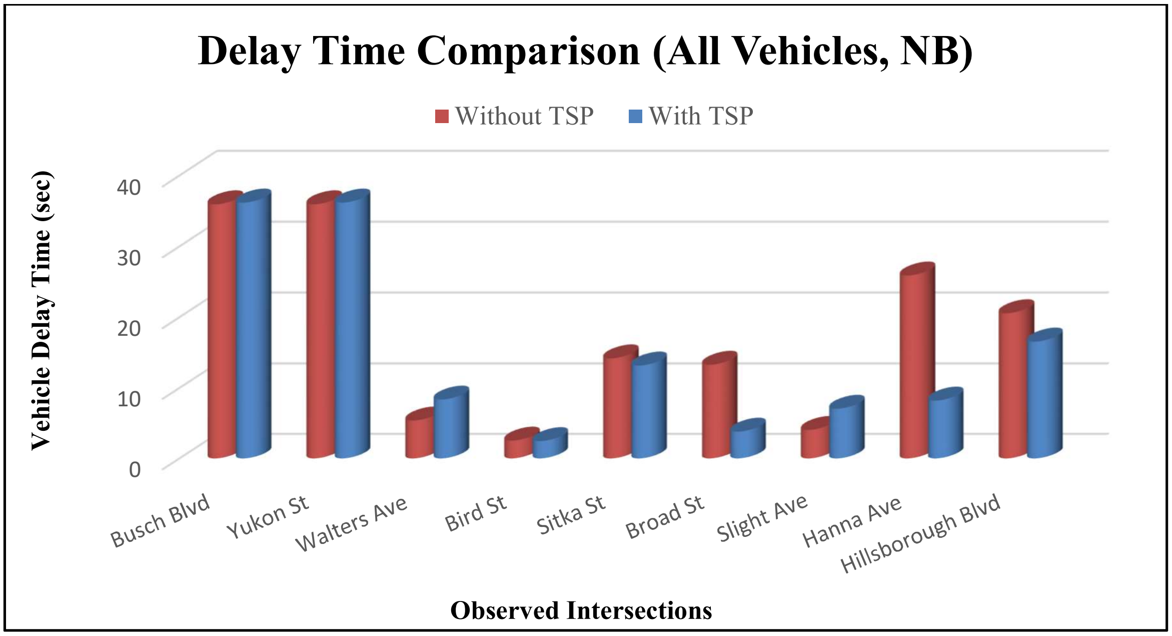


Figure 36. *Nebraska Ave. - Delay Time Comparison for All Vehicles for NB direction*

In the Figure 36 that provides detail comparison of the delay time for southbound direction it is noticeable that the least difference between TSP Active and Inactive delay times occurs at the intersections Nebraska Avenue & Broad Street and Nebraska Avenue and Slight Avenue. Largest difference between delay times occurs at intersections of Nebraska Avenue and Hillsborough Blvd. as well as at the intersection of Nebraska Avenue and Bird Street.

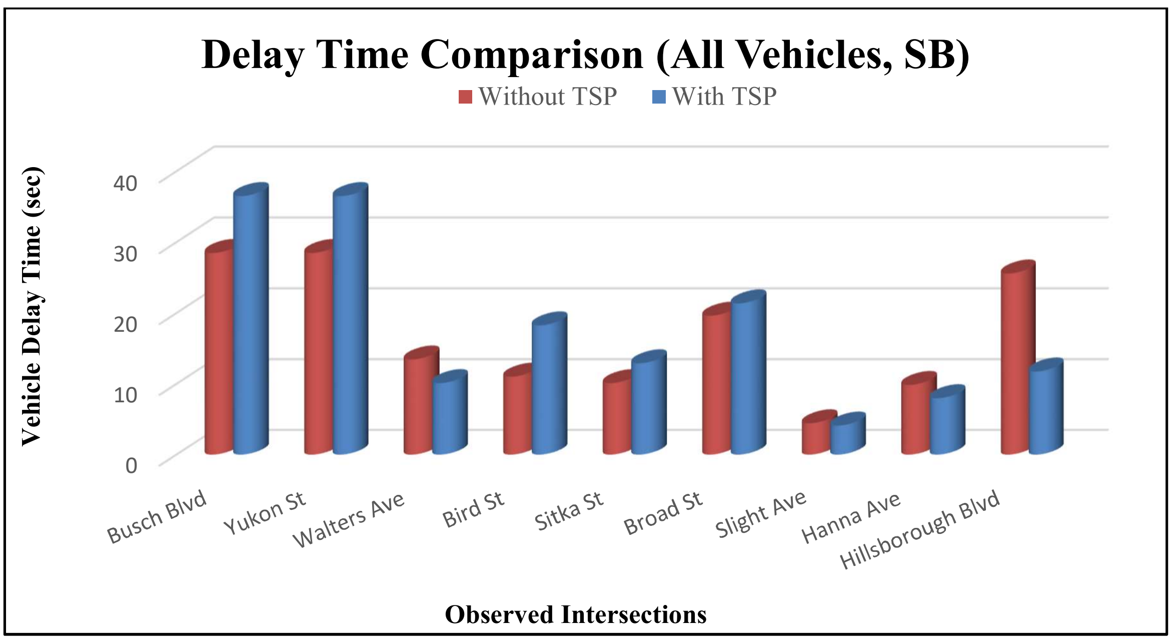


Figure 37. *Nebraska Ave. - Delay Time Comparison for All Vehicles for SB direction*

It is noticeable that for NB direction intersection Nebraska Avenue and Slight Avenue has largest difference between TSP Active and Inactive delay times while in the SB that difference is minimal.

The travel time and delay time comparisons between the buses using same rout with and without implemented TSP are presented in the following section. Travel time comparison for busses only for both studied directions is presented in the following table.

Table 19. *Nebraska Ave. - Bus Only Travel Time Comparison*

Directions	***Intersections***	***Node***	***Without TSP***	***With TSP***
NORTHBOUND	Nebraska Ave & Busch Blvd	1	37.44	32.47
	Nebraska Ave Yukon St	2	13.86	11.24
	Nebraska Ave & Walters Ave	3	26.20	21.77
	Nebraska Ave & Bird St	4	14.01	15.84
	Nebraska Ave & Sitka St	5	23.98	21.77
	Nebraska Ave & Broad St	6	8.54	3.34
	Nebraska Ave & Slight Ave	7	11.74	9.52
	Nebraska Ave & Hanna Ave	8	25.45	14.88
	Nebraska Ave & Hillsborough Blvd	9	19.66	11.59
SOUTHBOUND	Nebraska Ave & Busch Blvd	1	40.98	27.88
	Nebraska Ave Yukon St	2	37.02	21.22
	Nebraska Ave & Walters Ave	3	13.42	5.03
	Nebraska Ave & Bird St	4	20.04	21.97
	Nebraska Ave & Sitka St	5	19.07	10.65
	Nebraska Ave & Broad St	6	27.43	15.71
	Nebraska Ave & Slight Ave	7	16.50	10.53
	Nebraska Ave & Hanna Ave	8	22.73	12.55
	Nebraska Ave & Hillsborough Blvd	9	8.88	5.05
Total	***Northbound***	From 1 to 9	***180.88***	***142.42***
	Southbound	From 1 to 9	***206.07***	***130.59***
Average	***Northbound***	From 1 to 9	***20.09***	***15.82***
Average	***Southbound***	From 1 to 9	***22.89***	***14.51***

Figure 37 & Figure 38 below showed difference values in travel times with the two scenarios, with TSP, and without TSP along the Nebraska Avenue, from Busch Blvd to Hillsborough Blvd for both directions. Figure 37 below shows travel time comparison for busses only for northbound direction. It indicates that the highest benefits achieved through implementation of TSP occur on segments segment between streets Hillsborough Blvd. and Hanna Avenue as well as between streets Slight Avenue and Broad Street. It is also noticeable that on many segments TSP system was not able to be responsive enough and small benefits or in contrary loss in travel time would be achieved with introduction of TSP.

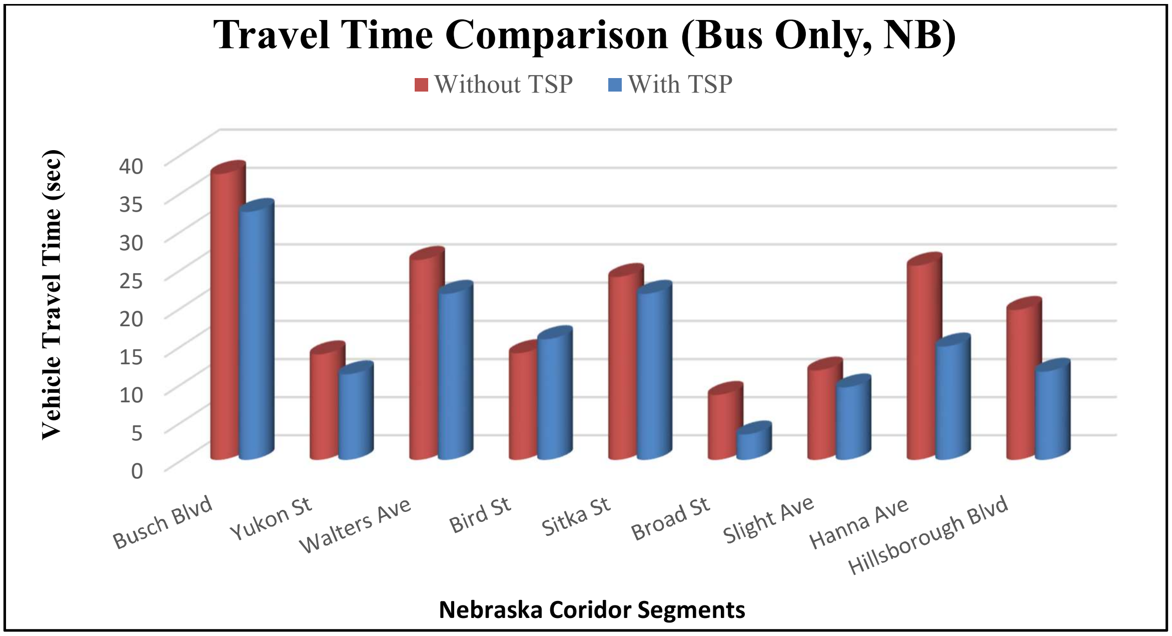


Figure 38. Nebraska Ave. - Travel Time Comparison for Bus Only for NB direction

Figure 38 shows travel time comparison for all vehicles for southbound direction. It indicates that the highest benefits achieved through implementation of TSP occur on segments between streets Slight Avenue and Broad Street as well as on segment between streets Hillsborough Blvd. and Hanna Avenue.

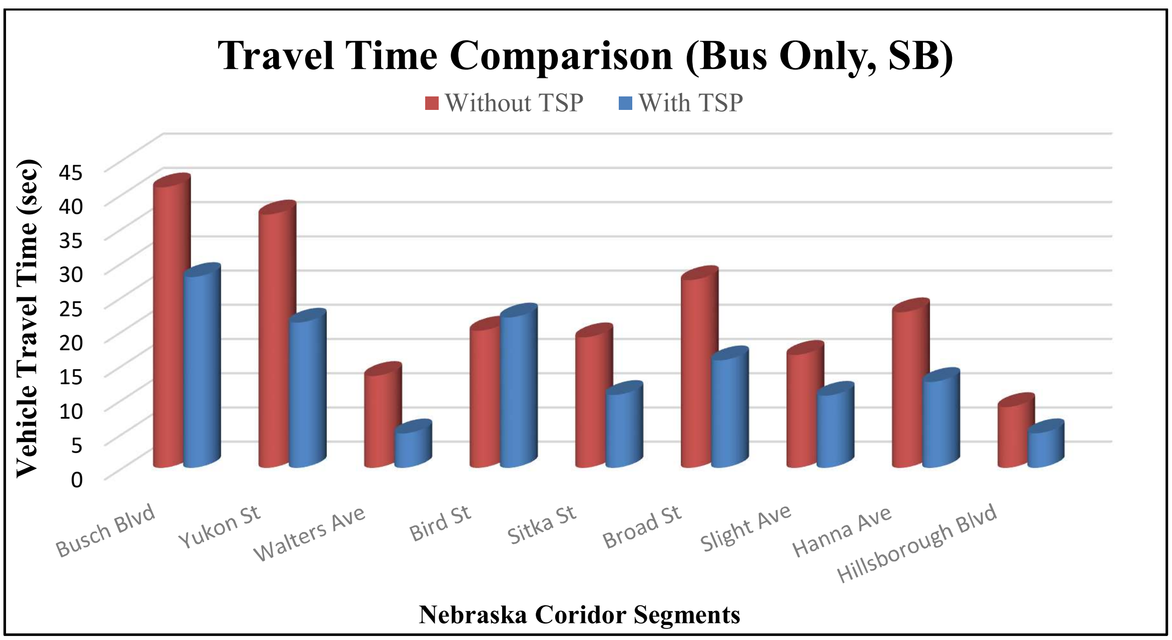


Figure 39. Nebraska Ave. - Travel Time for Bus Only for SB direction

In order to interpret the travel time results, and come up with a total travel time a summation was developed from the node 1 to node 9 for buses only. The Table 20 below showed the results over the scenarios with TSP and without TSP.

Table 20. *Nebraska Ave. - Total Travel Time for Bus Only for both NB & SB directions*

Summation	*Directions*	*Node*	*Without TSP*	*With TSP*
Total	*Northbound*	From 1 to 9	*180.88*	*142.42*
	Southbound	From 1 to 9	*206.07*	*130.59*

Figure 39 and Figure 40 presents graphical representation of the total travel time comparison for busses only at the corridor for both northbound and southbound directions. They present in a clear way the benefits achieved with implementing TSP when it comes to total travel time for busses only.

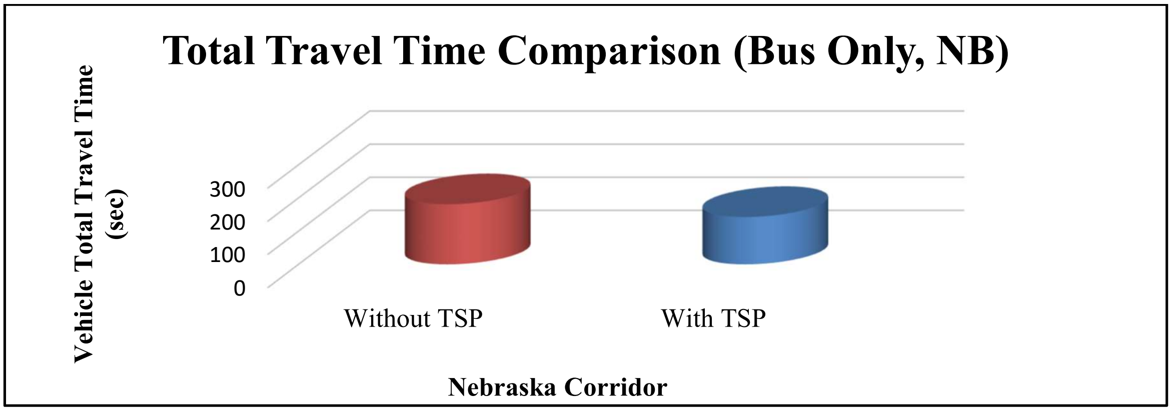


Figure 40. *Nebraska Ave. - Total Travel Time Comparison for Bus Only for NB direction*

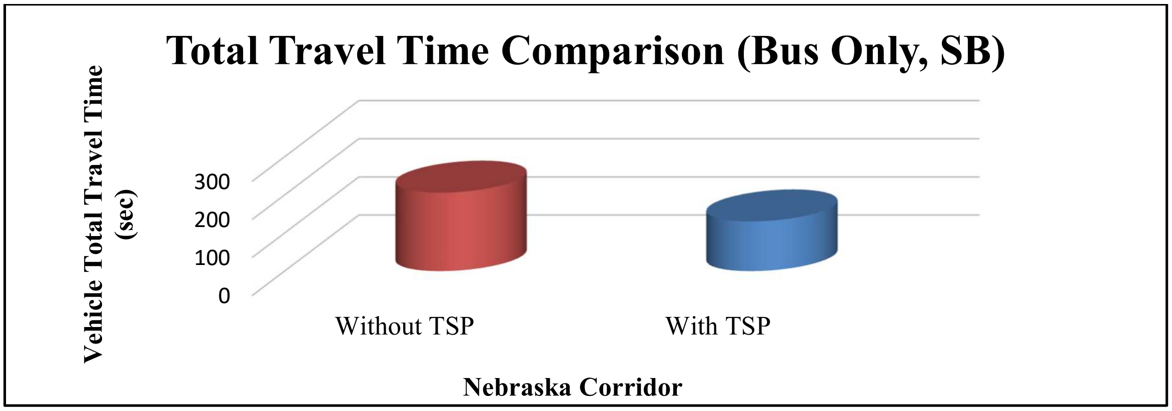


Figure 41. *Nebraska Ave. - Total Time for Bus Only for SB direction*

Delay time comparison for each signalized intersection for busses only for both directions from this case study is presented in the table below.

Table 21. *Nebraska Ave. - Bus Only Delay Time Comparison*

Directions	***Intersections***	***Node***	***Without TSP***	***With TSP***
NORTHBOUND	Nebraska Ave & Busch Blvd	1	40.98	13.88
	Nebraska Ave Yukon St	2	45.02	17.22
	Nebraska Ave & Walters Ave	3	21.42	16.21
	Nebraska Ave & Bird St	4	23.98	22.03
	Nebraska Ave & Sitka St	5	17.70	8.65
	Nebraska Ave & Broad St	6	55.43	43.71
	Nebraska Ave & Slight Ave	7	14.50	8.53
	Nebraska Ave & Hanna Ave	8	22.73	15.55
	Nebraska Ave & Hillsborough Blvd	9	23.54	17.44
SOUTHBOUND	Nebraska Ave & Busch Blvd	1	38.98	11.88
	Nebraska Ave Yukon St	2	43.02	15.22
	Nebraska Ave & Walters Ave	3	19.42	12.21
	Nebraska Ave & Bird St	4	17.98	16.03
	Nebraska Ave & Sitka St	5	15.70	6.65
	Nebraska Ave & Broad St	6	53.43	44.71
	Nebraska Ave & Slight Ave	7	12.50	6.53
	Nebraska Ave & Hanna Ave	8	20.73	4.86
	Nebraska Ave & Hillsborough Blvd	9	17.54	13.54
Total	***Northbound***	From 1 to 9	***265.30***	***233.22***
	Southbound	From 1 to 9	***239.30***	***205.63***
Average	***Northbound***	From 1 to 9	***29.47***	***18.13***
Average	***Southbound***	From 1 to 9	***26.58***	***14.62***

Delay time comparison for busses only is presented in the following figures where it is noticeable that for TSP active simulation model delay of each segment is less compering with simulation model where TSP is inactive (Figure 41 and Figure 42). In the Figure 41 that provides detail comparison of the delay time for busses only for northbound direction it is noticeable that the least difference between TSP Active and Inactive delay times occurs at the intersections Nebraska Avenue & Bird Street and Nebraska Avenue and Hillsborough Blvd. Largest difference between delay times occurs at intersections of Nebraska Avenue and Broad Street as well as at the intersection of Nebraska Avenue and Yukon Street. Delay time is significantly reduced on the most of the observed intersections.

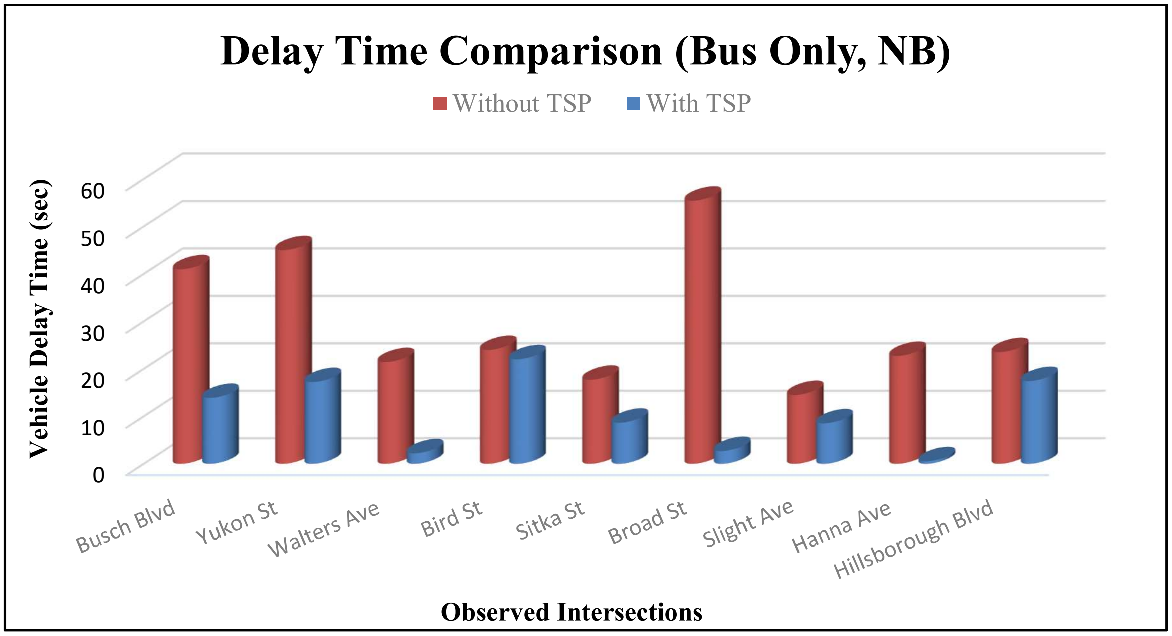


Figure 42. *Nebraska Ave. - Delay Time Comparison for Bus Only for NB direction*

In the Figure 42 that provides detail comparison of the delay time for busses only for southbound direction it is noticeable that the least difference between TSP Active and Inactive delay times occurs at the intersections Nebraska Avenue & Bird Street and Nebraska Avenue and Hillsborough Blvd. Largest difference between delay times occurs at intersections of Nebraska Avenue and Broad Street as well as at the intersection of Nebraska Avenue and Yukon Street.

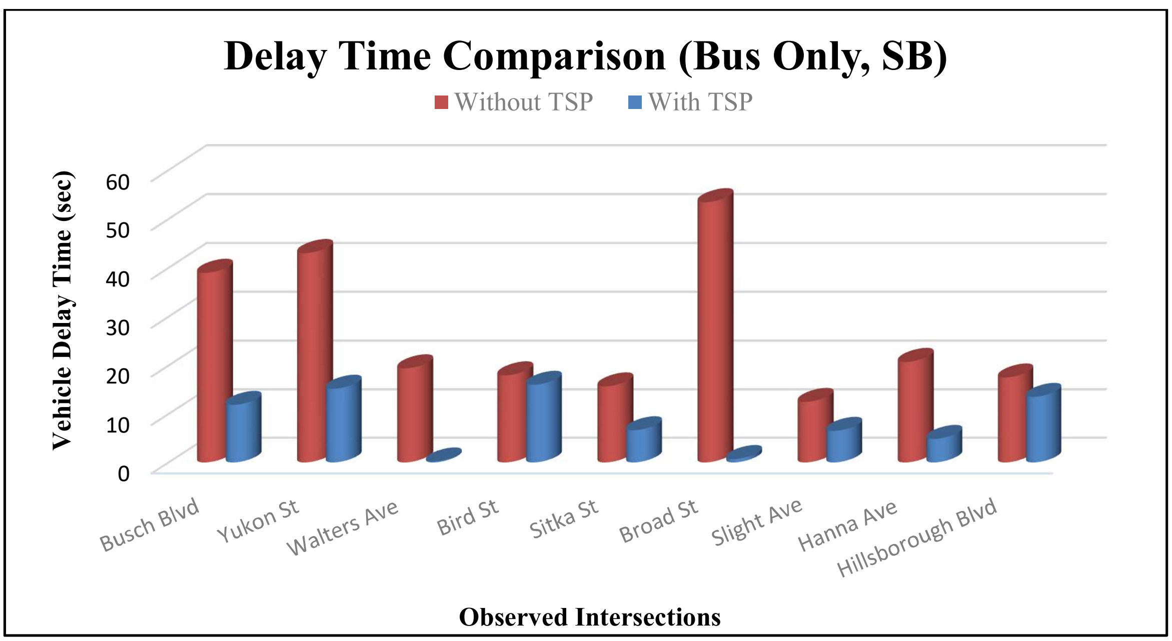


Figure 43. *Nebraska Ave. - Delay Time for Bus Only for SB direction*

Total delay time without TSP in the NB direction is 265.33, and for the SB direction is 239.3 being the travel time values for the SB direction significantly less against the NB direction. However, the travel time for the NB with TSP is 233.22, and for the SB direction is 205.63. The reduction in delay time is between 12.2 % – 16 % showing an important improvement for the scenario with the active TSP.

The total time for all vehicles in seconds for the Northbound without TSP is 161.34 whereas with TSP is 143.36 and the average time for the Northbound without TSP is 17.92 whereas with TSP it is 15.92. The total time in seconds for the Southbound without TSP is 147.39 whereas with TSP is 116.70 and the average time for the Southbound without TSP is 16.37 whereas with TSP it is 12.96. Similarly, the total time for bus only in seconds for the Northbound without TSP is 180.88 whereas with TSP is 142.42 and the average time for the Northbound without TSP is 20.09 whereas with TSP it is 15.82. The total time in seconds for the Southbound without TSP is 206.07 whereas with TSP is 130.59 and the average time for the Southbound without TSP is 22.89 whereas with TSP it is 14.51.

4.3 Results obtain from State Road 7 Corridor Case Study

The SR 7 (US 441) between SW 8th St. and Golden Glades Interchange in Miami, in addition, SR 7 is parallel to the I-95 limited access facility in Miami, FL, a major north-south corridor in Miami, FL. Table 22 shows the results of travel time for all the vehicles traveling in each subsegment as well as along the whole study segment without and with TSP.

Table 22. *All Vehicles Travel Time Comparison*

Directions	Subsegment	Subsegment Number	Without TSP (Min)	With TSP (Min)
NORTHBOUND	From SW 8th St. to NW 6th St.	7	5.00	5.04
	From NW 6th St. to NW 46th St.	8	8.53	8.44
	From NW 46th St. to NW 79th St.	9	6.17	6.11
	NW 79th St. to NW 119th St.	10	7.89	7.78
	From NW 119th St. to NW 143rd St.	11	4.32	4.33
	From NW 143rd St. to Florida Turnpike Off-ramp	12	2.67	2.68
SOUTHBOUND	From Florida Turnpike Off-ramp to NW 143rd St.	1	2.25	2.25
	From NW 143rd St. to NW 119th St.	2	3.91	3.86
	From NW 119th St. to NW 79th St.	3	6.48	6.40
	From NW 79th St. to NW 46th St.	4	5.11	5.05
	From NW 46th St. to NW 6th St.	5	9.10	8.99
	From NW 6th St. to SW 8th St.	6	6.71	6.68
Total	**Northbound**	From 7 to 12	34.59	34.39
	Southbound	From 1 to 6	33.56	33.23

The same results are also presented in Figures 43 and 44 for a better visualization. As shown in these table and figures, the travel times for all the vehicles traveling along both the NB and SB directions are reduced for most of the subsegments. The resulted total travel time is slightly reduced from 34.59 minutes to 34.39 minutes for the northbound vehicles, and from 33.56 minutes to 33.23 minutes for the southbound vehicles.

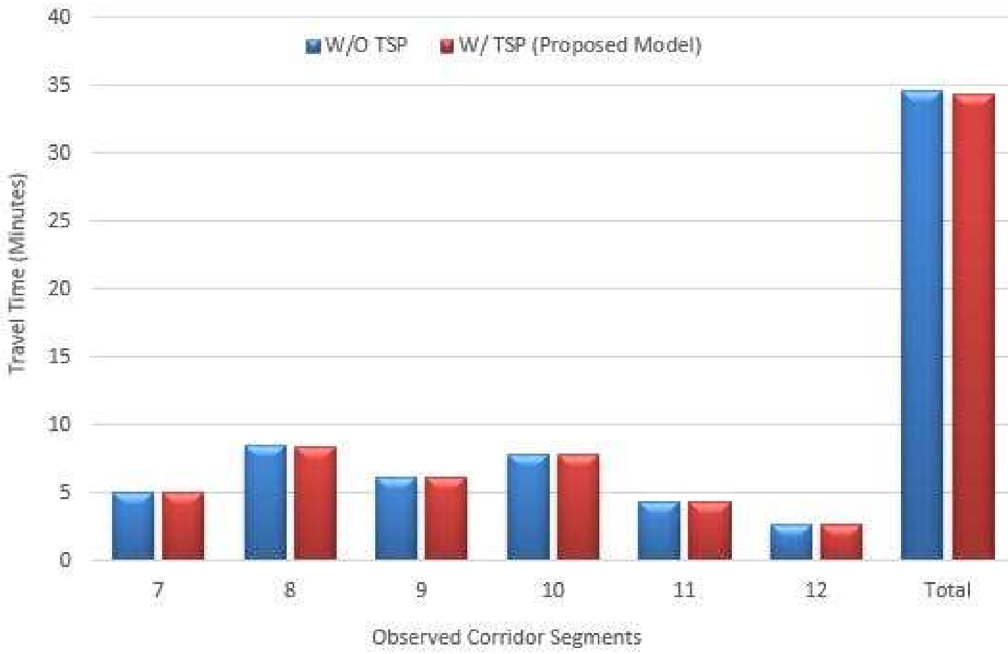


Figure 44. *Travel Time Comparison for All Vehicles along the NB Direction for SR 7 Study Segment*

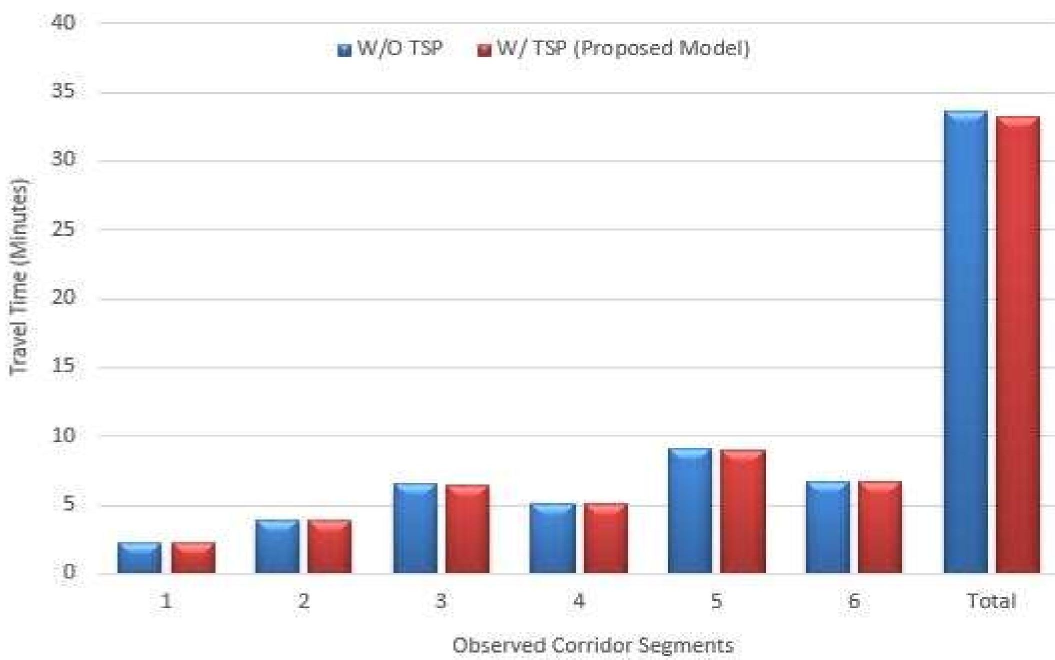


Figure 45. *Travel Time Comparison for All Vehicles along the SB Direction for SR 7 Study Segment*

Table 23 shows the results of delay based on all the vehicles traveling in each subsegment as well as along the whole study segment without TSP and with TSP by utilizing the proposed model.

Table 23. *All Vehicles Delay Time Comparison*

Directions	Subsegment	Subsegment Number	Without TSP (Min)	With TSP (Min)
NORTHBOUND	From NW 6th St. to NW 46th St.	8	3.24	3.17
	From NW 46th St. to NW 79th St.	9	1.21	1.15
	NW 79th St. to NW 119th St.	10	2.03	1.94
	From NW 119th St. to NW 143rd St.	11	1.32	1.27
	From NW 143rd St. to Florida Turnpike Off-ramp	12	0.46	0.47
SOUTHBOUND	From Florida Turnpike Off-ramp to NW 143rd St.	1	0.38	0.38
	From NW 143rd St. to NW 119th St.	2	0.94	0.90
	From NW 119th St. to NW 79th St.	3	1.47	1.38
	From NW 79th St. to NW 46th St.	4	0.64	0.62
	From NW 46th St. to NW 6th St.	5	1.94	1.90
Total	**Northbound**	From 8 to 12	8.26	8.00
	Southbound	From 1 to 5	5.37	5.18

The results in this table indicate that the implementation of TSP based on the proposed model can slightly reduce the delays for all the vehicles along most of the sub segments in both directions.

As shown in Table 23, the delay reduction is 0.26 minutes for the NB vehicles and 0.19 minutes for the SB vehicles. The same conclusions can be drawn from Figures 45 and 46.

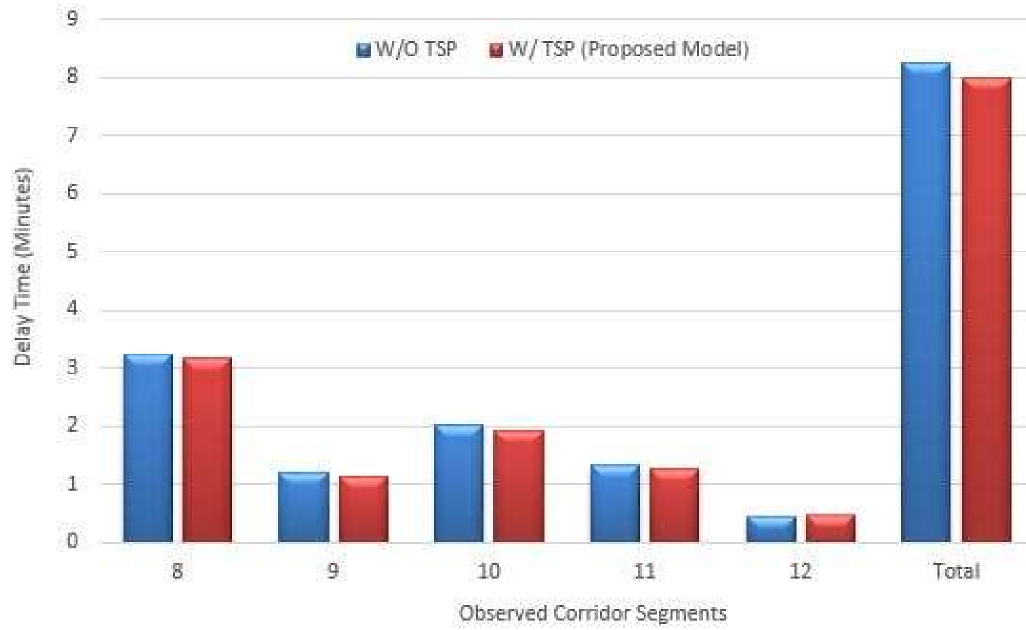


Figure 45. *Delay Time Comparison for All Vehicles along the NB Direction for SR 7 Study Segment*

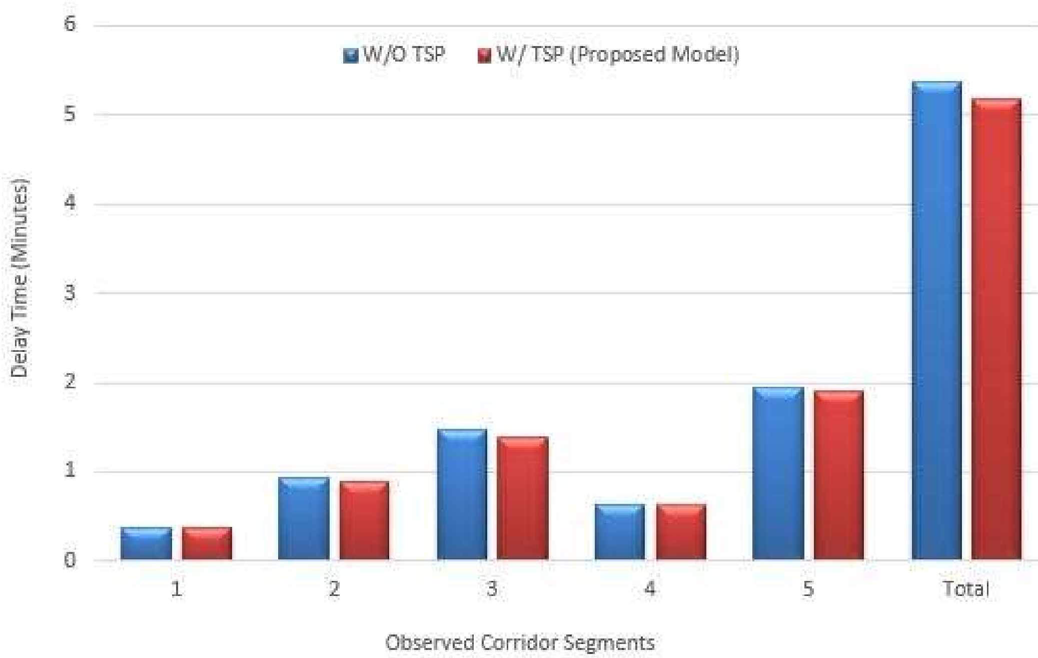


Figure 46. *Delay Time Comparison for All Vehicles along the SB Direction for SR 7 Study Segment*

Table 24 and Figures 47 and 48 show the similar travel time results as Table 22 and Figures 43 and 44 but for buses.

Table 24. *Bus Travel Time Comparison*

Directions	Subsegment	Subsegment Number	Without TSP (Min)	With TSP (Min)
	From NW 6th St. to NW 46th St.	8	11.81	11.43
	From NW 46th St. to NW 79th St.	9	8.00	7.54
	NW 79th St. to NW 119th St.	10	9.67	9.00
	From NW 119th St. to NW 143rd St.	11	6.86	6.36
	From NW 143rd St. to Florida Turnpike Off-ramp	12	3.27	3.30
SOUTHBOUND	From Florida Turnpike Off-ramp to NW 143rd St.	1	2.93	2.91
	From NW 143rd St. to NW 119th St.	2	6.01	5.88
	From NW 119th St. to NW 79th St.	3	7.77	7.46
	From NW 79th St. to NW 46th St.	4	8.14	7.77
	From NW 46th St. to NW 6th St.	5	11.86	11.35
Total	**Northbound**	From 8 to 12	39.61	37.64
	Southbound	From 1 to 5	36.71	35.37

As shown in Table 24 and Figures 47 and 48, the bus travel time is significantly reduced for both directions and for most of the sub segments. The total travel time is decreased from 39.61 minutes to 37.64 minutes for the NB buses, while the total travel time is reduced from 36.71 minutes to 35.37 minutes.

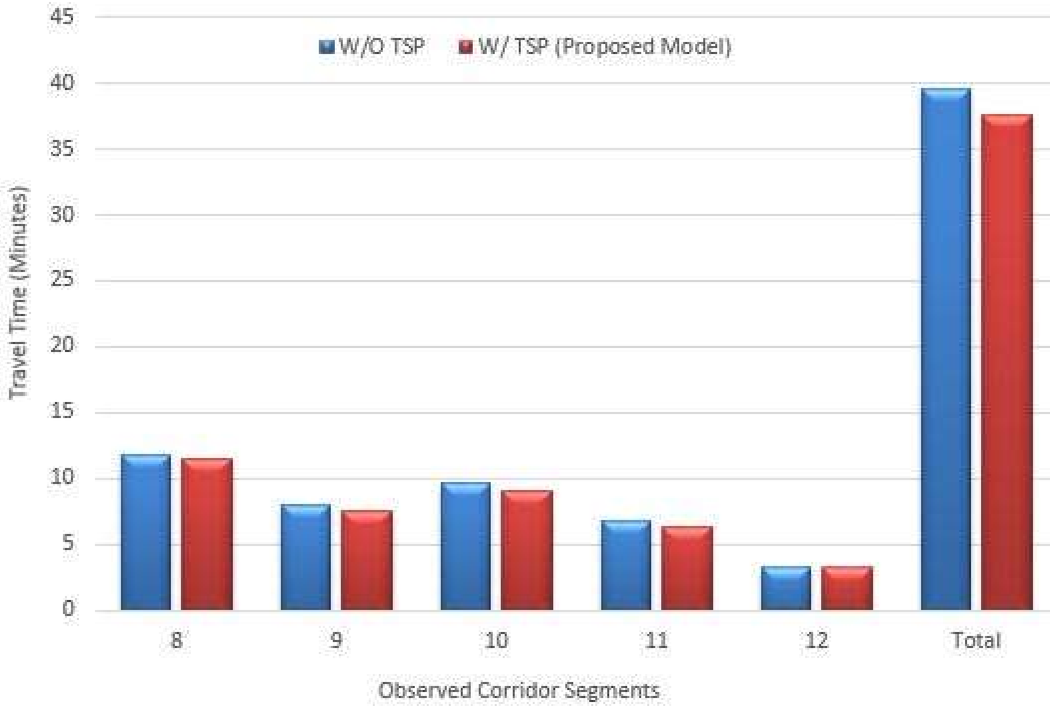


Figure 47. *Travel Time Comparison for Buses along the NB Direction for SR 7 Study Segment*

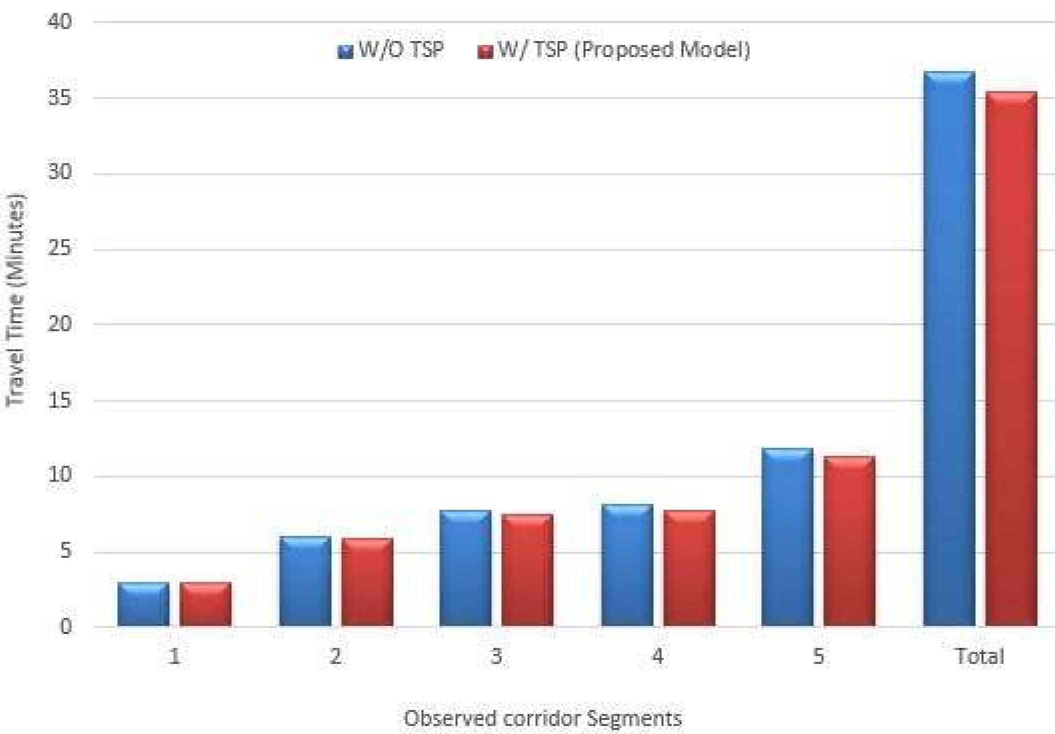


Figure 48. *Travel Time Comparison for Buses along the SB Direction for SR 7 Study Segment*

The results of bus delay times are presented in Table 25 and Figures 49 and 50. As shown in these table and figures, the bus delay times are greatly reduced, especially compared to the results of delay for all the vehicles that are presented in Table 23 and Figures 45 and 46.

Table 25. *Bus Delay Time Comparison*

Directions	Subsegment	Subsegment Number	Without TSP (Min)	With TSP (Min)
NORTHBOUND	From NW 6th St. to NW 46th St.	8	3.42	2.99
	From NW 46th St. to NW 79th St.	9	1.46	1.03
	NW 79th St. to NW 119th St.	10	2.65	1.98
	From NW 119th St. to NW 143rd St.	11	2.02	1.49
	From NW 143rd St. to Florida Turnpike Off-ramp	12	0.69	0.68
SOUTHBOUND	From Florida Turnpike Off-ramp to NW 143rd St.	1	0.42	0.41
	From NW 143rd St. to NW 119th St.	2	1.48	1.34
	From NW 119th St. to NW 79th St.	3	1.72	1.39
	From NW 79th St. to NW 46th St.	4	1.78	1.34
	From NW 46th St. to NW 6th St.	5	2.52	1.96
Total	**Northbound**	From 8 to 12	10.24	8.17
	Southbound	From 1 to 5	7.92	6.43

The implementation of TSP based on the proposed model can save buses 2.07 minutes delay when traveling along the NB direction of SR 7 while TSP can save 1.49 minutes delay for buses when traveling along the SR 7 SB.

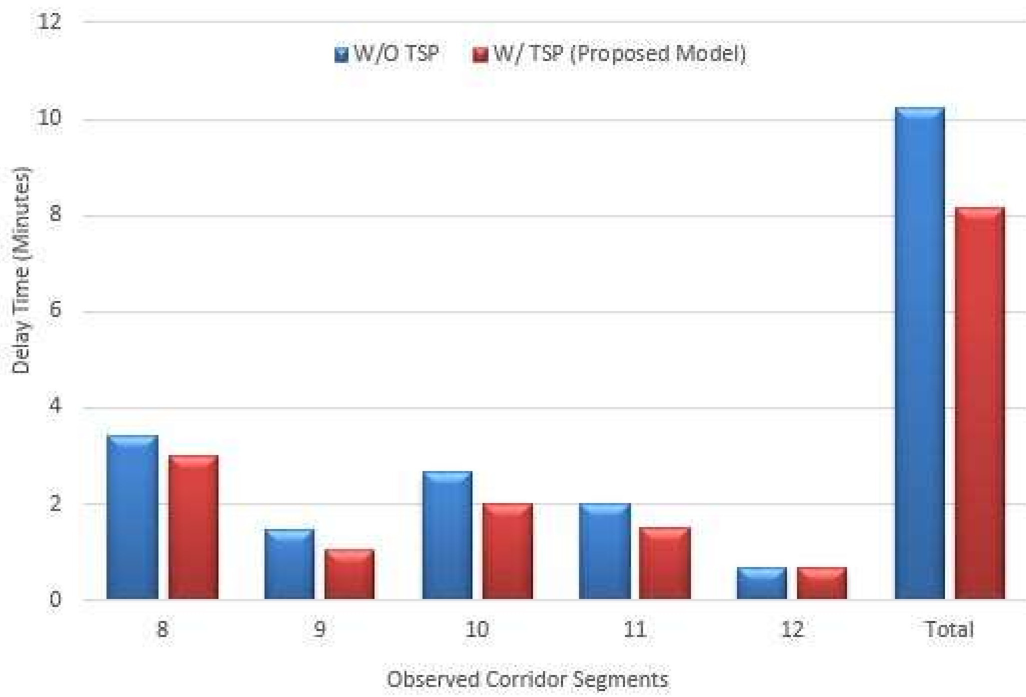


Figure 49. *Delay Time Comparison for Buses along the NB Direction for SR 7 Study Segment*

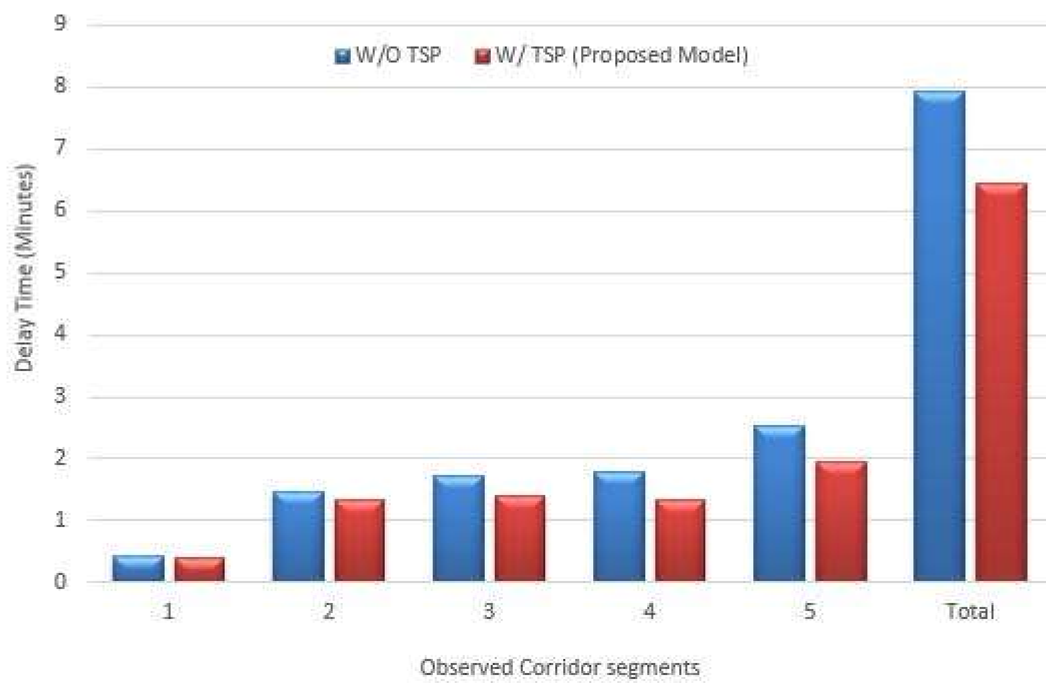


Figure 50. *Delay Time Comparison for Buses along the SB Direction for SR 7 Study Segment*

4.3.1 Results achieved through Sensitivity Analysis for State Road 7 corridor case study

The proposed TSP guidelines in this study were applied to the SR 7 study corridor. Table 25 lists the intersections that are identified by the proposed guideline for TSP implementation. It is seen that the proposed TSP guideline results in recommending a total number of 12 out of 25 signalized intersections for TSP implementation, which is more than 4 intersections identified by using Montgomery County guideline if the main approach critical v/c ratio is used as criteria, and less than the 16 intersections identified by using Montgomery County guideline based on using intersection critical v/c ratio, as a criterion.

Table 26. *Summary of Intersections that can be Implemented with TSP Based on the Proposed Guideline*

Nbr.	***Intersection***	***Intersections for TSP Based on Proposed Guideline***
1	*NW 6th St.*	0
2	*NW 8th St.*	1
3	*NW 11th St.*	1
4	*NW 14th St.*	0
5	*NW 17th St.*	1
6	*NW 20th St.*	0
7	*NW 29th St.*	0
8	*NW 32nd St.*	0
9	*NW 36th St.*	1
10	*NW 46th St.*	0
11	*NW 54th St.*	1
12	*NW 62nd St.*	0
13	*NW 71st St.*	1
14	*NW 79th St.*	1
15	*NW 81st St.*	1
16	*NW 95th St.*	0
17	*NW 103rd St.*	1
18	*NW 111th St.*	1
19	*NW 119th St.*	1
20	*NW 125th St.*	0
21	*NW 135th St.*	1
22	*Opa Locka Blvd*	0
23	*NW 143rd St.*	0
24	*NW 151st St.*	0
25	*NW 159th St.*	0
Total		**12**

Figures 51 to 54 present the results of the NB and SB travel times for buses as well as all the vehicles when using different approaches to identify intersections for TSP including the proposed guidelines. The results of the scenarios considered in the previous section, based on utilizing the Montgomery County TSP guideline, are also included in these figures for comparison purpose. Note that the Montgomery County TSP guideline was implemented in three of the scenarios but with different v/c ratio criterions: average intersection v/c ratio-based scenario, maximum main street through movement v/c ratio-based scenario, and intersection critical v/c ratio-based scenarios.

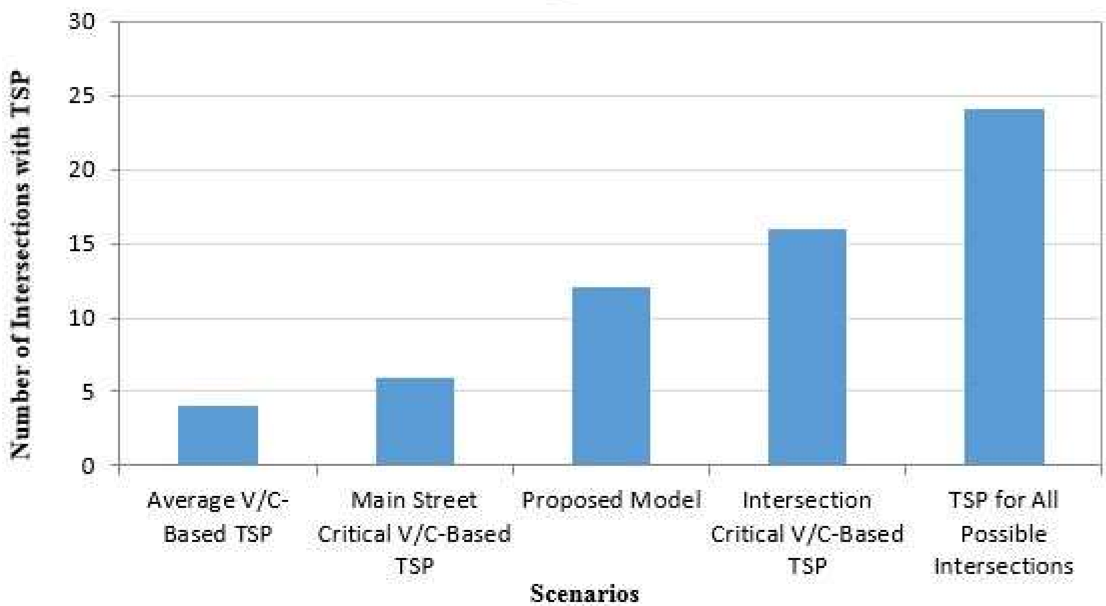


Figure 51. *Comparison of Number of Signalized Intersections Identified in Different Scenarios*

The results in Figure 51 show that the percentage reduction in NB bus travel time is about 2.8% for the scenarios based on maximum main street through movement v/c ratio and the average intersection v/c ratios. This value is about 7.8% when implementing the TSP at all possible intersections. Implementing the TSP based on the guideline developed in this study reduces the NB bus travel time by about 5%, which is close to the value produced by the scenario based on the intersection critical v/c ratio.

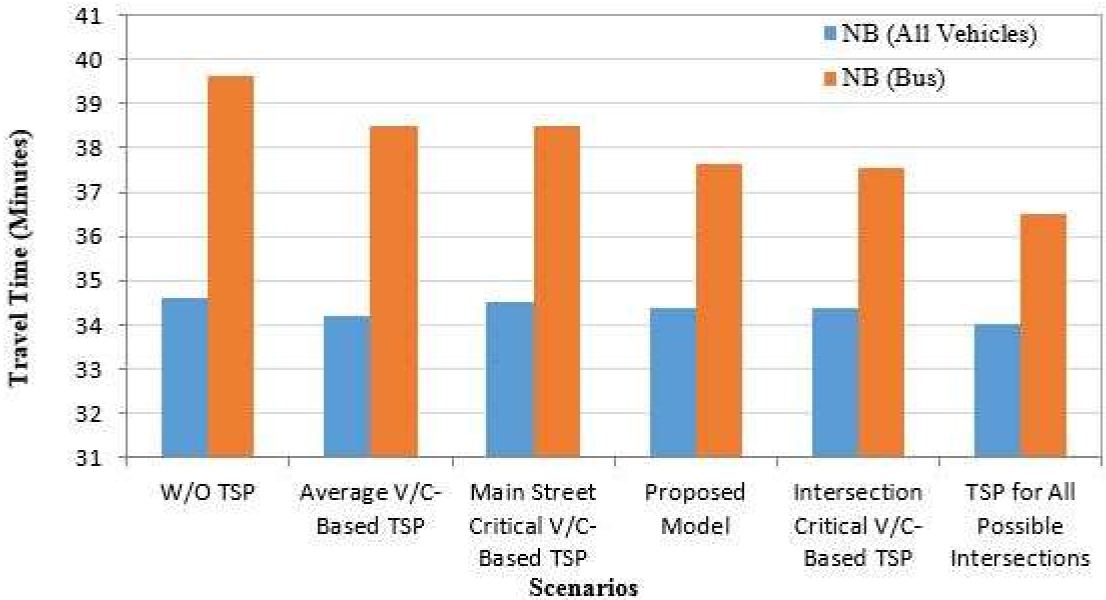


Figure 52. *Comparison of Northbound Travel Time along the SR 7 Study Corridor*

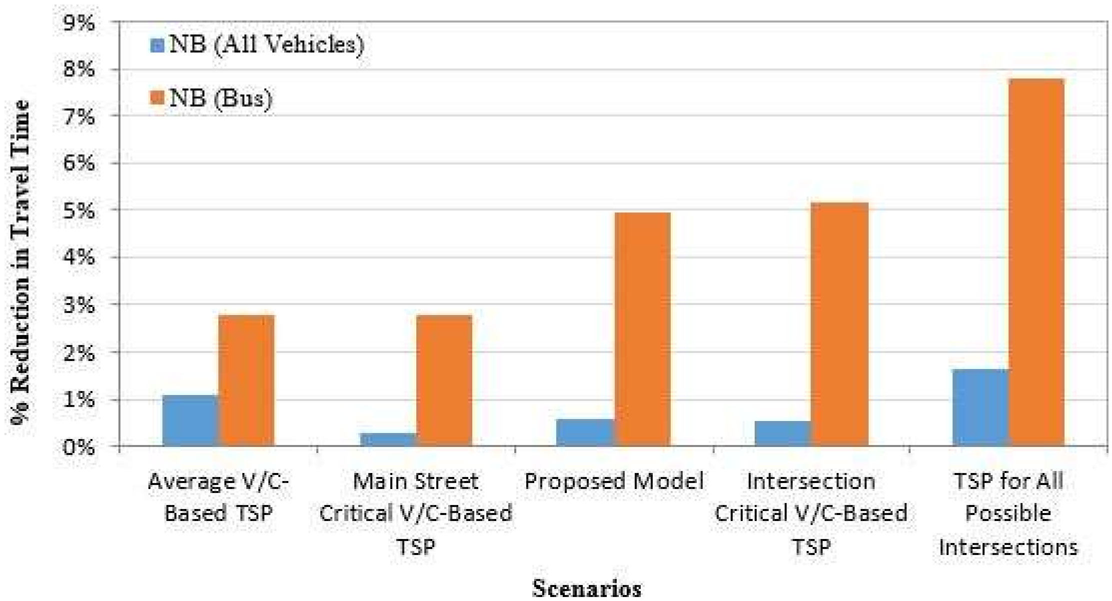


Figure 53. *Comparison of Percentage of Reduction in Northbound Travel Time along the SR 7 Study Corridor*

Similar trend can be observed in Figure 54 for the percentage reduction in the SB bus travel time, which also shows that the proposed guideline produces a slightly higher percentage reduction in SB bus travel time compared to the Montgomery County TSP guideline scenarios based on the maximum main street through movement v/c ratio and the average intersection v/c ratio, but a very close value to that produced by the intersection critical v/c ratio-based scenario.

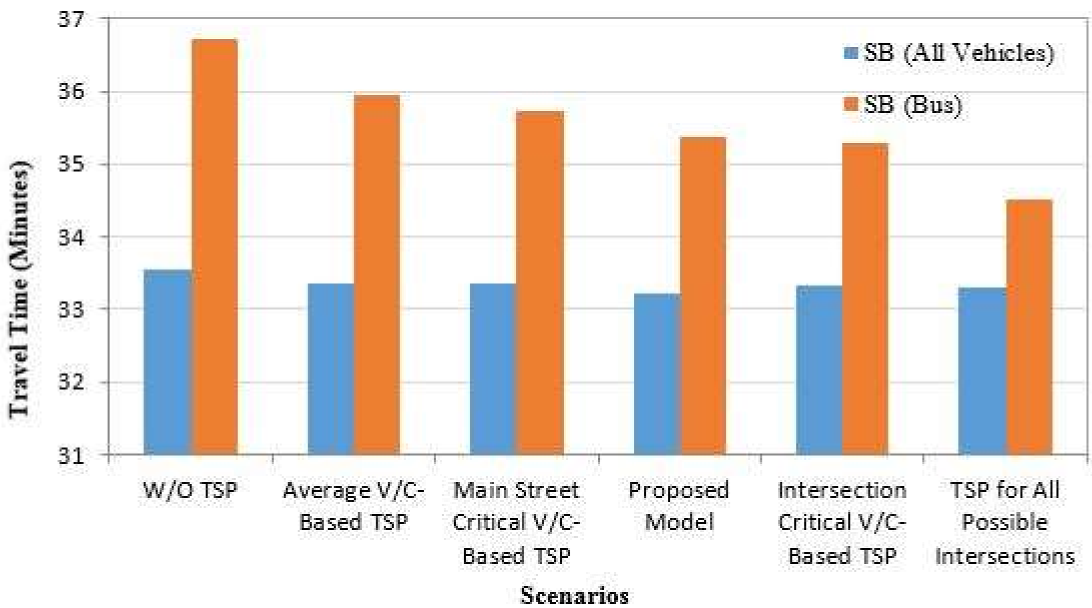


Figure 54. *Comparison of Southbound Travel Time along the SR 7 Study Corridor*

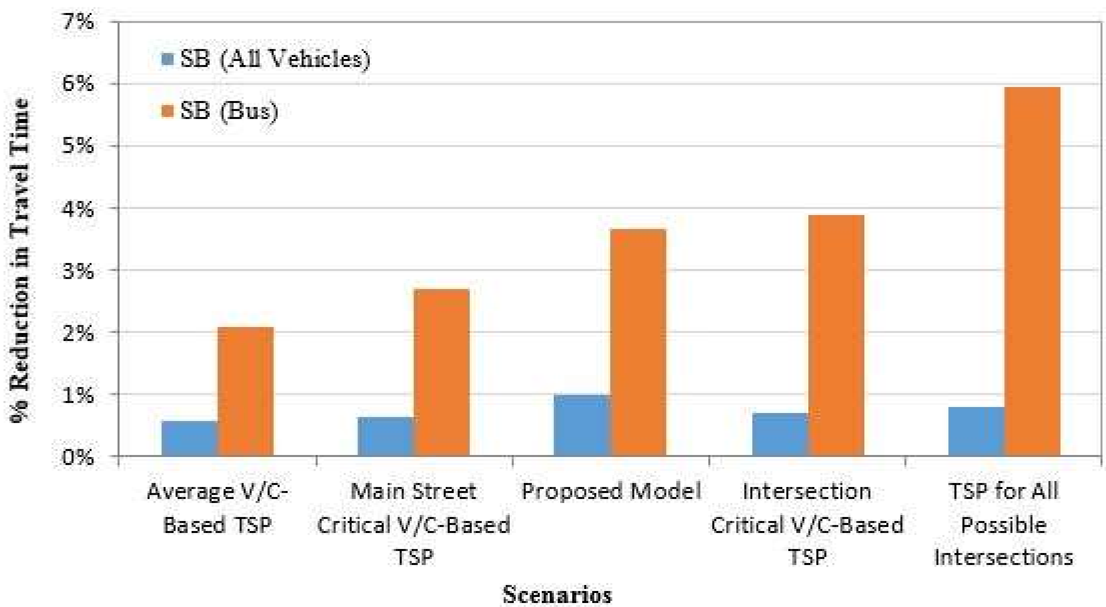


Figure 55. *Comparison of Percentage of Reduction in Southbound Travel Time along the SR 7 Study Corridor*

Figures from 56 to 59 show the total delays and percentage of delay reductions for main street thru movements at the intersections compared to the scenario without TSP, respectively.

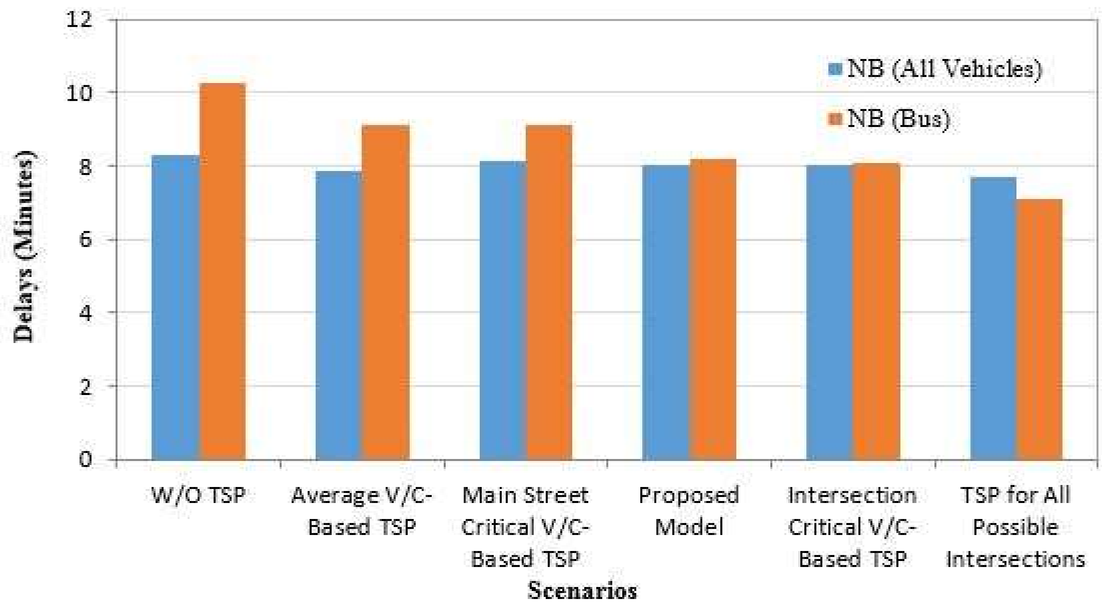


Figure 56. *Comparison of Northbound Delays along the SR 7 Study Corridor*

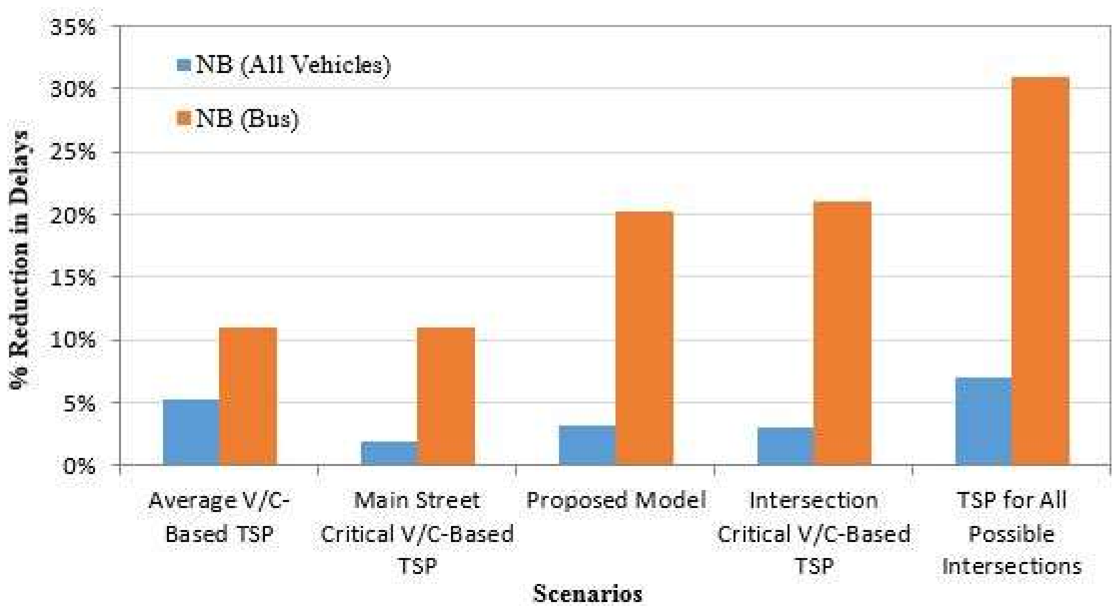


Figure 57. *Comparison of Percentage Reduction in NB Delays along the SR 7 Study Corridor Corridor*

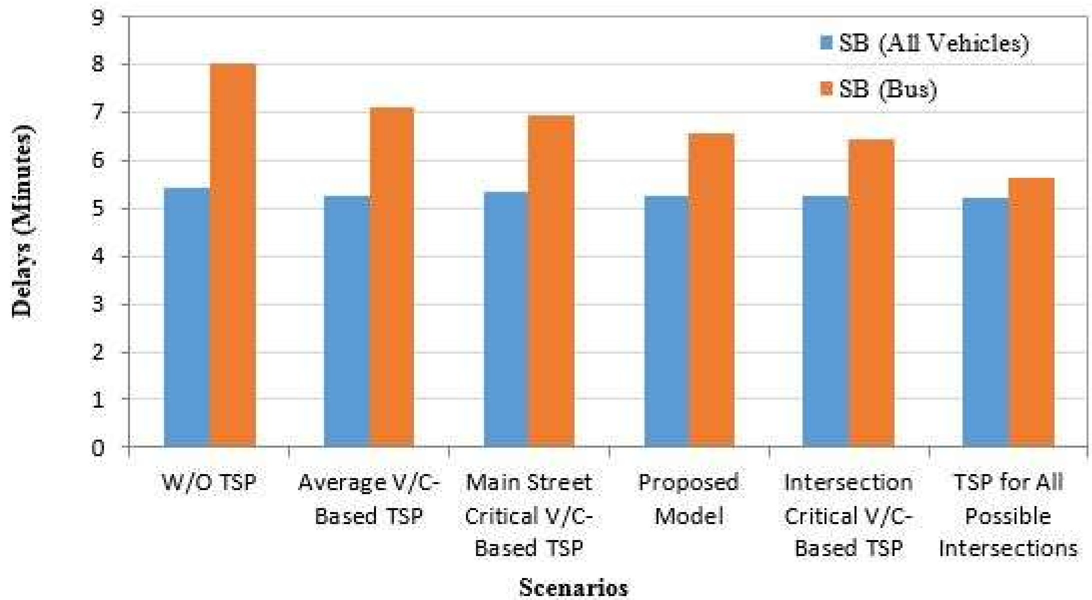


Figure 58. *Comparison of SB Delays along the SR 7 Study Corridor*

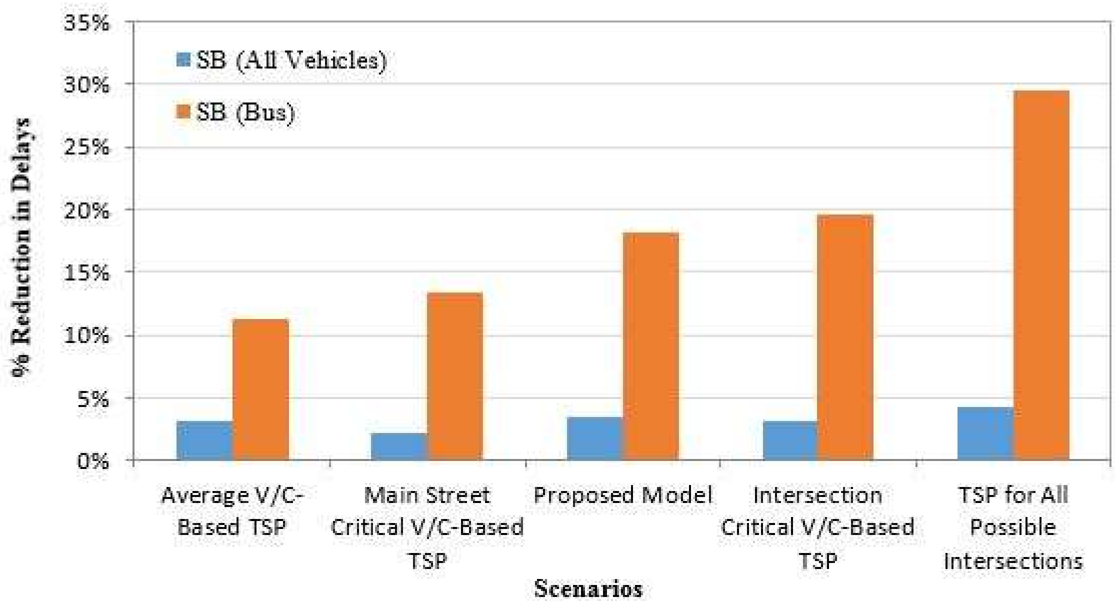


Figure 59. *Comparison of Percentage of Reduction in Southbound Delays along the SR 7 Study Corridor*

The average delay and percentage of increase in delay for the other movements affected by the TSP are shown in Figure 60 and Figure 61, respectively. Figure 61 shows that the percentage of increase in average delay for all the vehicles is about 5.3% when using the proposed TSP guideline, which is less than the value of 7% for the intersection critical v/c ratio-based scenario. However, it is also noted that there is an increase in the delays for buses traveling along the cross streets and the buses turning to the cross streets from the main street approaches.

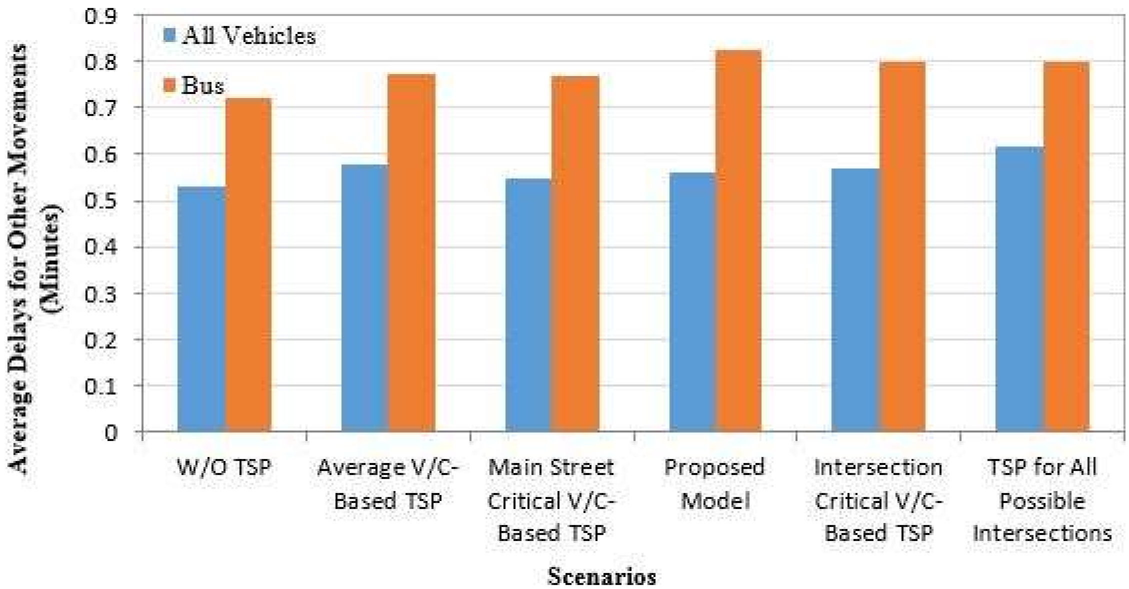


Figure 60. *Comparison of Average Delays for All the Other Movements*

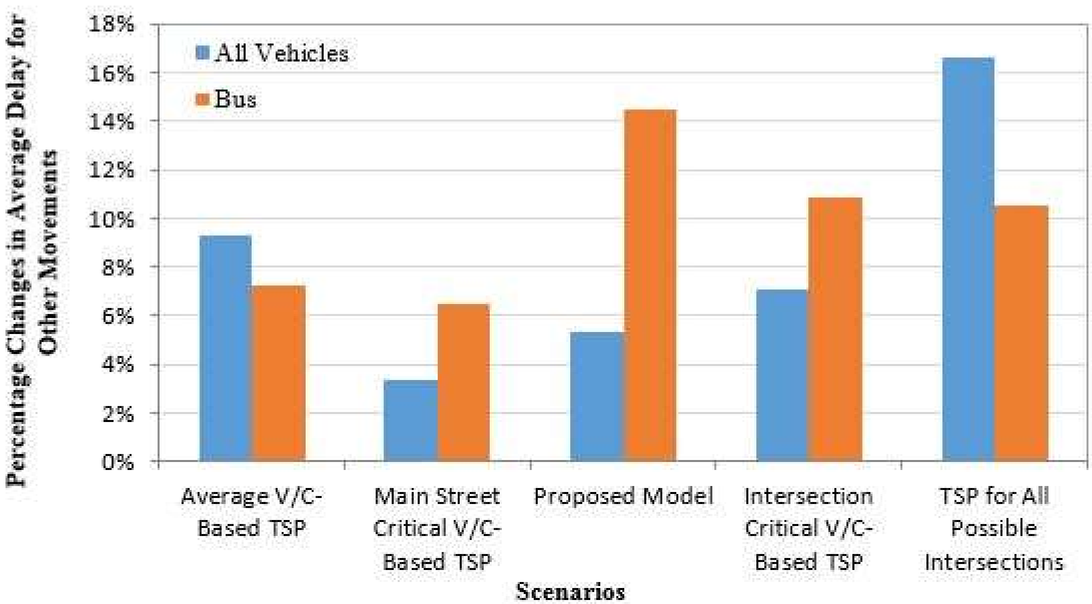


Figure 61. *Comparison of Percentage Change in Average Delay for All the Other Movements*

Compared to the other scenarios, the scenario based on intersection critical v/c ratio and the scenario with the proposed TSP guideline produce a relatively better-balanced solution for both maximizing main street buses travel time and minimizing delays for other affected movements. However, the number of TSP intersections is 12 with proposed guideline, which is less than the 16 TSP intersections identified in the scenario based on intersection critical v/c ratio of the Montgomery Guidance. This indicates a better performance of the proposed TSP guideline.

CHAPTER 5
CONCLUSION

The results obtained from this study confirmed that introducing the TSP according to the guidance for the case study corridors can provide benefits that justify TSP deployments. TSP appears to be a useful and reliable option for reducing transit travel and delay time. Close positions of the bus station to the intersections of this study are also a reason why TSP results are not even better. The TSP presents a cost-effective method to improve regional mobility by reducing transit travel times and delays and increasing reliability but in these case studies, cost of installation of the Transit Signal Priorities were not taken in consideration in this study.

Very little work has been done related to providing warrants and guidelines for TSP. By following proper guidelines of TSP and queue jump implementation it can help to achieve a more reliable, cost effective, and an enhanced performance system. The volume to capacity (V/C) ratio must be within the range from 0.60 to 0.95, as we have performed few tests runs in the simulation model for the V/C ratio below 0.60 and above 0.95, where the TSP application was not effective. The effectiveness of the newly developed criteria helps to reduce transit delays, improves travel time, cuts fuel cost, increase ridership, use of fewer vehicles on the road and eventually provides better service.

Transit signal priority supports a number of valuable objectives such as: reduced transit travel times, better schedule adherence, better transit efficiency, and increased road network efficiency by car mobility. Implementing transit signal priority, however, can face many challenges. One major concern is how to implement transit priority within the existing signal control system, and another is determining what impacts the priority implementation will have on other traffic.

Few of the key take ways from this research work are:

- The average bus travel time with TSP was reduced, as well as, the travel time for all vehicles had a small improvement with the application of TSP along a large proportion of the signalized intersections modeled.

- The average bus speed when the TSP active is higher than the average bus speed without TSP.

- The average bus delay time with TSP was reduced, resulting in a significant improvement providing benefits to the schedule adherence factor.

- While the TSP is active, the travel time of all vehicles for the three case studies is lower than when TSP is not active.

- While TSP is active the travel time of bus only for the 3 case studies is lower than when TSP is not active

- Similarly, while TSP is active the delay time of all vehicles for the 3 case studies is lower than when TSP is not active.

- While TSP is active the delay time of bus only for the 3 case studies is lower than when TSP is not active.
- Advanced sensitivity analysis results of the State Road 7 corridor case study show that the scenario based on intersection critical v/c ratio and the scenario with the proposed TSP guideline produce a relatively better-balanced solution for both maximizing main street buses travel time and minimizing delays.

In this research work, two strategies were applied, green extension, and early green/ red truncation and have followed the flow chart of Sabra-Wang for TSP implementation. However, several strategies reported that when phase insertion is included in the TSP strategy it shows better performance and service quality. Therefore, future research work can focus on the implementation of other TSP strategies.

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