Final Report

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Evaluation of Freight and Transit Signal Priority Strategies in Multi-Modal Corridor for Improving Transit Service Reliability and Efficiency

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SI Modern Metric (Conversion Factors)

APPROXIMATE CONVERSIONS TO SI UNITS				
Symbol	**When You Know**	**Multiply By**	**To Find**	**Symbol**
LENGTH				
in	inches	25.4	millimeters	mm
ft	feet	0.305	Meters	m
yd	yards	0.914	Meters	m
mi	miles	1.61	Kilometers	km
AREA				
in^2	square inches	645.2	square millimeters	mm^2
ft^2	square feet	0.093	square meters	m^2
yd^2	square yards	0.836	square meters	m^2
ac	acres	0.405	Hectares	ha
mi^2	square miles	2.59	square kilometers	km^2
VOLUME				
fl oz	fluid ounces	29.57	Milliliters	mL
gal	gallons	3.785	Liters	L
ft^3	cubic feet	0.028	cubic meters	m^3
yd^3	cubic yards	0.765	cubic meters	m^3
NOTE: volumes greater than 1000 L shall be shown in m3				
MASS				
oz	ounces	28.35	Grams	g
lb	pounds	0.454	Kilograms	kg
T	short tons (2000 lb)	0.907	megagrams ("metric ton")	Mg
FORCE and PRESSURE or STRESS				
lbf	Pound-force	4.45	Newtons	N
lbf/in^2	Pound-force per square inch	6.89	kilopascals	kPa
APPROXIMATE CONVERSIONS FROM SI UNITS				
LENGTH				
mm	millimeters	0.039	Inches	in
m	meters	3.28	Feet	ft
m	meters	1.09	Yards	yd
km	kilometers	0.621	Miles	mi
AREA				
mm^2	square millimeters	0.0016	square inches	in^2
m^2	square meters	10.764	square feet	ft^2
m^2	square meters	1.195	square yards	yd^2
ha	hectares	2.47	Acres	ac
km^2	square kilometers	0.386	square miles	mi^2
VOLUME				
mL	milliliters	0.034	fluid ounces	fl oz
L	liters	0.264	Gallons	gal
m^3	cubic meters	35.314	cubic feet	ft^3
m^3	cubic meters	1.307	cubic yards	yd^3
MASS				
g	grams	0.035	Ounces	oz
kg	kilograms	2.202	Pounds	lb
Mg	megagrams ("metric ton")	1.103	short tons (2000 lb)	T
FORCE and PRESSURE or STRESS				
N	newtons	0.225	poundforce	lbf
kPa	kilopascals	0.145	poundforce per square inch	lbf/in^2

SI is the symbol for the International System of Units. Appropriate rounding should be made to comply with Section 4 of ASTM E380. (Revised March 2003)

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16. Abstract

The rise in freight movements in metropolitan areas can be regarded as one of the crucial concerns of the near future. Traffic congestion attributed to elevated freight flows impacts both private and public vehicle operations. Therefore, it is of considerable significance to reduce congestion on multimodal routes with heavy freight and transit volumes. Intelligent Transportation System (ITS) components such as Freight Signal Priority (FSP) and Transit Signal Priority (TSP) can help to overcome these conditions. The primary objective of this project is to establish guidelines for the application of signal priorities by traffic agencies focusing on defined decision factors on the considered corridors. In addition, this analysis assesses the efficacy of FSP and TSP in enhancing freight and transit network efficiency. This research laid out recommendations for different scenarios. Finally, a detailed guideline framework is established based on the literature review and the experiments being performed. The developed guideline relates to corridors where freight delay plays a critical role in determining the performance of the corridors.

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Executive Summary

One of the critical issues of the near future can be deemed the increased number of freight movements in urban areas. Moreover, traffic congestion caused by the increased movement of freight impacts the flow of both private and transit vehicles. Therefore, reducing congestion along multi-modal corridors with high volumes of freight and transit is of great importance. Operational Intelligent Transportation System (ITS) strategies such as Transit Signal Priority (TSP) and Freight Signal Priority (FSP) can promote the movements of transit vehicles and freight vehicles through signalized intersections by mitigating the number of stops, travel time, and delays. The primary objective of this research is to develop guidelines and criteria for transportation agencies to implement signal priorities based on identified decision factors on certain corridors. Moreover, this study evaluates the effectiveness of FSP and TSP in improving the performance of public transportation and freight movements at the same time. As a result of implementing FSP and TSP, the outcomes indicate significant enhancement in reducing the travel times and delays for both buses and trucks without deteriorating the networks' condition. This research established specific recommendations for different systematic situations, such as the implementation of TSP and FSP, implementation of TSP, and the implementation of FSP for both major road and minor roads Finally, a comprehensive TSP/FSP implementation guideline is drawn up based on the literature analysis and the simulation conducted during this study. The developed guideline applies to certain projects where the freight signal is considered, and freight delay plays a vital role in the assessment of corridor performance.

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List of Acronyms

ARC-IT	Architecture Reference for Cooperative and Intelligent Transportation
ATSP	Adaptive Transit Signal Priority
AVI	Automatic Vehicle Identification
AVL	Automatic Vehicle Location
BlueTOAD	Bluetooth Travel-time Origin and Destination
BRT	Bus Rapid Transit
BSM	Basic Safety Messages
BSP	Bus Signal Priority
BTS	Bureau of Transportation Statistics
CONOPs	Concept of Operations
CV	Connected Vehicle
DOT	Department of Transportation
FDOT	Florida Department of Transportation
FDOT	Florida Department of Transportation
FHWA	Federal Highway Administration
FLHSMV	Florida Department of Highway Safety and Motor Vehicles
FSP	Freight Signal Priority
FTA	Federal Transit Administration
GIS	Geographic Information Systems
GPS	Global Positioning System
HCM	Highway Capacity Manual
ITS	Intelligent Transportation Systems
MAP	Mobile Application Part
MAS	Multi-Agent Systems
MILP	Mixed-Integer Linear Program
MMITSS	Multi-Modal Intelligent Traffic Signal System
MPO	Metropolitan Planning Organizations
NCHRP	National Cooperative Highway Research Programs
NGSIM	Next Generation SIMulation
NTCIP	National Transportation Communications for ITS Protocol
OBE	On-Board Equipment
PAMSCOD	Platoon-based arterial multi-modal signal control with online data
RBC	Ring Barrier Controllers
RFID	Radio Frequency Identification
RSE	Road Side Equipment
SPaT	Signal Phasing and Timing
TMC	Traffic Management Center
TPO	Transportation Planning Organizations
TSM&O	Transportation System Management and Operations
TSP	Transit Signal Priority
V/C	Volume/Capacity Ratio
WIM	Weigh in Motion

1 Introduction

1.1 Background

During the past decades, the increasing growth of the attractiveness of cities led to the increase of vehicle movements from and to those cities. The augmented movements around the cities' areas resulted in risen mobility needs for the transportation system users. An additional result of the increased mobility on the arterial networks is the development of traffic congestion. Congestion has become one of the main issues of modern life in large cities. Time spent on drivers in traffic is not simply time wasted, it is time wasted inefficiency and it is dollars wasted. Every year, people in the U.S. spend frustrating hours in congested roads, costing the country billions of dollars annually and influencing people's decisions about where to live and work.

However, the limited capacity of networks is often not able to accommodate the growing traffic volume. The consequence of this situation is the formation of significant queues and traffic congestion that can even block a part of the city. Thus, the intense rise of traffic over the past decades due to population and economic growth led to heavy congestion and has expanded to more cities and towns, affecting more people than ever before.

Moreover, freight transportation is considered as one of the fundamental stones for the economic system of the United States. It holds almost 9% of the Nation's economic activity as measured by gross domestic product, while four percent of the U.S. labor force is working on the wider area of freight transportation (Freight Facts and Figures, 2017). Recently, the need for freight mobility has been rapidly surged mainly due to the expansion of the population. As a result, the increased need for freight transportation along the national highway system urges for efficient freight mobility operations in order to deliver the products to their destination on time.

In addition to the congestion caused by the growth in passenger vehicles and public transit, the freight movements in urban areas created a detrimental role in the network's traffic conditions. The congestion caused by trucks has a negative impact on the existing congested conditions on the roads, creating long queues and delays on all the transport modes. Simultaneously, it weakens the reliability and successful operations of the freight industry.

These detrimental traffic conditions, due to their mobility and safety impacts to all transport modes, urge for immediate corrective solutions and necessitate the development of new approaches to these issues. Some common and successful existing solutions are dealing with the continuous interactions of the traffic and transit operations along the urban area. The efficient implementation of the above solutions is completed using the operational control systems and traffic management based on newly developed technological achievements. Intelligent Transportation Systems (ITS) technologies are considered a successful approach to improve system performance.

The term ITS, is used to name the integration of control, information and communication technologies with transport infrastructure into vehicles. ITS covers all modes of transport and takes into account the dynamic interaction of all constituents of the transport system. It uses many wireless and traditional communications-based information and electronic technologies. Traffic signal coordination, red light camera, and traveler information systems are some components of

ITS which are commonly applied to many arterial networks and improved the overall traffic conditions and safety (USDOT's Intelligent Transportation Systems (ITS) ITS Strategic Plan 2015- 2019, 2014).

Smoother operation of freight transportation is critical to the nation, as well for the state economy since it plays a significant role in achieving mobility objectives and reducing congestion. The considerable impact of trucks on traffic flows is undeniable, especially at intersections, because of their low acceleration/deceleration rates, large sizes, and high emissions. Therefore, a truck requires a longer time to resume its full speed after stopping and more deceleration distance to stop before a red light at intersections in comparison to other vehicles. The traffic delay generated by truck stops is much larger than the delay of the same number of passenger car stops due to the slow dynamics of trucks. In addition, trucks' braking distance is much longer than passenger cars' resulting in longer dilemma zone and thus a higher crash rate, when the traffic changes to red.

However, today's traffic lights do not consider the presence of trucks but instead treat them like the rest of the vehicles for traffic light control purposes. This kind of treatment of the trucks is considered a critical problem not only for freight transportation but also for the efficient operation of the traffic and road network in general. Given the importance of the overgrowing freight transportation system, engineers and planners are faced with the challenge of improving freight service in the urban area using low-cost measures.

A viable solution to the freight mobility problem is a method, under the umbrella of ITS called Freight Signal Priority (FSP). Freight or Truck Signal Priority is a strategy aiming for the improvement of the operational efficiency and safety of freight services. The goal of the FSP implementation is the elimination of travel delays and simultaneously the increase of travel time reliability for the freight traffic, in order to preserve a safe and less congested environment at signalized intersections. This ITS component is designed to prioritize the detected truck movements along an arterial corridor in order to reduce unnecessary stops and travel delays of trucks. The implementation of the FSP technology provides a beneficial outcome not only to the freight vehicles but to the rest of the transport modes operating on a multi-modal corridor.

Traffic signal control aims to optimize the performance of the system and provide a smooth progression of vehicle platoons through the determination of traffic plans that contain the appropriate offsets, splits, and cycle times for each intersection in the road network. Multi-modal signal control systems that include FSP can be considered as a natural extension of traditional signal priority control systems, which also include emergency vehicle preemption and transit signal priority (TSP).

Transit systems, and specifically buses, are also affected by the congested traffic conditions. The traffic congestion increases the costs of bus operations and downgrades their level of service, efficiency, and reliability. The traffic engineers are faced with the urgent need to resolve the problem that the buses are dealing with, due to less than satisfactory traffic conditions. An additional and more efficient solution for improving the provided services of buses on arterial corridors is also an ITS tool suitable for making transit service more reliable, faster, and more cost-effective. This ITS technology is called TSP. Transit Signal Priority is a traffic operational strategy that prioritizes the movement of transit vehicles, through the signalized intersections. The main purpose of the TSP is to improve the schedule adherence and the transit travel time efficiency while minimizing the effects on normal traffic operations. The main advantage of the TSP is its minor effects on the overall traffic conditions of an arterial network and simultaneously makes this mode of transportation more competitive by improving the level of service of transit vehicles.

Each of the travel modes including automobiles, transit vehicles, emergency vehicles, freight vehicles, bicycles, and pedestrians, consists of unique characteristics, such as travel speed and priority level. Thus, traffic operations are treated differently for each mode of transportation. However, the existence of multiple ways of treatment might create a negative effect on the operation performance of a road network.

In order to avoid any negative effects due to the multiple ways of treatment, depending on the travel mode, it is necessary to conduct an efficient urban traffic management plan. The traffic management plan will include the application of a precise installation and control strategy in order to improve both traffic throughput, mobility, and safety for all road users. A possible solution is the application of a multi-modal traffic control system to combine all of the different traffic operations that might exist on a road network.

Traffic Control system plays an important role in traffic management. The main purpose of a traffic control system is to eliminate conflicts between crossing traffic with a minimum possible system loss (e.g. delay, emission, etc.). The signal split between different directions is primarily determined based on traffic demands. This traditional signal design system considers that all different vehicle classes, such as emergency vehicles, cars, buses, freight, and pedestrians, has the same priority. However, if the signal system is designed considering a priority hierarchy, then the system loss could be further minimized. With the advancement of technologies and computational power, some modern signal system such as Multi-Modal Intelligent Traffic Safety System (MMITSS) (USDOT, 2019) provides a comprehensive traffic information framework to service all modes of transportation, including general vehicles, transit, emergency vehicles, freight fleets, and pedestrians and bicyclists utilizing connected vehicle environment.

Agencies increasingly desire to operate traffic signal systems with priority control policy that can favor one mode of transportation over another for a specific time of day and specific roadway section. For instance, a traffic signal control system may be divided into several control sections. One section might be in a region where there are many commercial trucks moving goods from a port to warehouses. Another section could be in a residential area where transit is a popular mode of transportation. The operating agency may want to provide priority for trucks in the first section and priority for transit in the second section. In a third section, both truck and transit priority may be required and the ability to favor one travel mode over another is a desirable traffic control system characteristic.

Since different agencies have different policies to implement priorities for a specific vehicle class, the introduction of TSP and FSP could potentially decrease system loss if it is implemented properly. Overall, TSP reduces the transit vehicle delay resulting in a decrease of delay per person and FSP could provide additional benefit by providing reliable freight delivery, especially for perishable items that need to be at the destination on time. If the agency considers both TSP and FSP in the same corridor, then a proper analysis is required to ensure the maximum benefits to the system. This study focusses on developing a guideline to determine the optimal configuration of the signal priority system for TSP and FSP considering the maximum system benefit.

1.2 Freight Signal Priority

As mentioned above, freight transportation holds a fundamental position for the satisfaction of the economic system's demand in the US. The movements of products across the country are based on trains and trucks. The volume of freight movement was growing rapidly over the past few decades and it will continue growing for the years come.

The achievement of providing smoother operation of freight movements along arterial corridors is significant for the economy on a state's level and on the nation's level as well, due to the importance of freight transportation on mobility and congestion.

Furthermore, the impact of trucks on traffic flows can be detrimental to arterial corridors and especially on signalized intersections, where their steady flow can be interrupted by the traffic lights. The negative impacts of freight vehicles are due to their large size, large weight, and slow dynamic and high levels of emissions.

Consequently, a truck needs more time for recovering its previous speed and longer distance for decelerating and stopping at a red light in comparison to the passenger vehicles. The result of the above truck needs affects directly, and on a high scale, the overall traffic delay and congestion that is generated by truck stops, compared to the traffic delay generated by passengers' vehicle stops.

For traffic light control purposes, today's traffic operations consider all traffic movements as passenger vehicle movements, without taking into consideration the trucks along an arterial corridor. However, the rapid growth of the freight transportation system around the world has led engineers to focus on planning an improved freight service in urban areas. Freight signal priority is a traffic operation that is able to improve freight transportation worldwide and the efficient operation of the traffic and road network in total.

Specifically, a freight signal priority strategy is designed to give priority to truck movements along a corridor near a freight facility. By using this strategy, the travel time of freight vehicles will potentially be decreased and consequently the cost of freight movement as well.

In addition, the reduction of truck stops arriving at an intersection at the end of the green phase has safety benefits due to the reduction of red-light running. The elimination of traffic delays of passenger vehicles and the transit system is another advantage of the reduction of prioritizing truck movements, as well as the elimination of truck emissions, noise, and pavement damages. Finally, FSP could be applied for assigning truck drivers specific routes that they need to follow.

1.3 Transit Signal Priority

Transit signal priority is an acclaimed and commonly used strategy, applied to prioritize bus movements for improving their reliability, punctuality, speed, and cost-effectiveness. The main advantages of TSP are the little impacts that the strategy has on the rest of the traffic network and its low cost that makes it very competitive with the automobile. It is used extensively around the world, providing priority to transit vehicles that are detected on an arterial network and request priority to cross a signalized intersection.

TSP is a traffic operation strategy that provides priority to the movement of transit vehicles on signalized intersections. It is usually confused with the preemption strategy that facilitates the right of way at and through a signal for the most important classes of vehicles such as fire trucks. Preemption is different from signal priority, which alters the existing signal operations to shorten or extend phase time settings to allow a priority vehicle to pass through an intersection. The preemption strategy always interrupts the normal traffic operations of a signalized intersection, while signal priority tries to facilitate specific types of vehicles without completely interrupting the coordination for the signalized intersection. The main purpose of TSP is to improve the schedule adherence and the transit travel time efficiency while minimizing the effects to normal traffic operations (Urbanik, et al., 2015).

1.3.1 TSP Strategies

Transit signal priority is applied to the arterial networks in various ways. The most common strategies are passive and active priority.

Passive transit signal priority is a continuous process that is not interacting with real-time information. Specifically, the passive priority does not include any detection system for providing priority, because it relies on predictable transit operations. The signal timing plan of the signalized intersections with passive priority strategy takes into consideration the timetables, schedules, and some additional characteristics (such as dwell time) of transit vehicles in order to adjust the cycle length and the coordination to provide priority to the transit vehicles.

Active transit signal priority is the opposite of passive priority. The operation of the active priority depends on the utilization of the detection of the transit vehicles to request priority on a signalized intersection. The most commonly used active strategies are the green extension and the early green. The green extension strategy provides priority to the transit vehicles by prolonging the duration of the green time. This type of active strategy is usually applied for facilitating the transit vehicle movements when the time that the vehicle is approaching the intersection is green. On the other hand, the early green is activated when the headlight is green on the opposite approach of the one that requested priority. As a result, the preceding phase terminates earlier than it should be and the approach that the priority request applied, turns green in order to facilitate the priority movement.

1.3.2 TSP technology

Transit signal priority, as mentioned before, does not have the same mechanism as preemption, since the strategy’s purpose is to facilitate the movements of specific vehicles by interrupting as little as possible the coordinated operations of the signalized intersections that are affected. The technology that lies behind this strategy consists of four major components.

The first component is the detection of the transit vehicle. The network is equipped with a system that is designed to detect the transit vehicles and to deliver all the necessary data (such as location) for that specific vehicle to the next component of the strategy, in order to request priority. The second component is known as Priority Request Generator/Server. Priority Request Generator consists of a system that receives the message from the first component that the transit vehicle is approaching and requests priority from the traffic control system for that vehicle.

The third component is the priority control strategies that consist of traffic control system software that processes the request of the transit vehicle and provides the best possible strategy out of a range of TSP control strategies, in order to facilitate the transit movement successfully and preserve a good level of service for the rest of the network. The final component of the transit signal priority strategies is the TSP system management. This system manages both the traffic and transit conditions along with TSP and collects data from the overall network operation and generates reports.

1.4 Combination of Freight Signal Priority and Transit Signal Priority

The Transit Signal Priority is considered the precursor of Freight Signal Priority. Thus, Freight Signal Priority systems can be similar to Transit Signal Priority systems. Besides the on-time arrivals and number of passengers considered in TSP, the application of FSP should consider the freight vehicle weights, road grade, and engine types to minimize the energy consumption and the emissions along corridors with high freight movements.

The freight signal priority is facing some additional challenges, different from the ones of transit signal priority. These challenges are presented below:

i. Near a port area, the frequency of trucks is higher than that of buses;
ii. The arrival of trucks on an intersection is difficult to be predicted, due to the lack of fixed schedules for buses;

The common factor for Freight and Transit Signal Priority is their support by ITS technologies. ITS expresses the implementation of electronics, communications, and information processing aiming to upgrade the efficiency and the safety of transportation systems. There are several applications of ITS which are useful for transit and freight management and play a fundamental role in the success of Freight and Transit signal priority strategies.

1.5 Multimodal corridors and Signal control systems

Multi-modal corridors are the corridors that appear to have an increased number of passenger vehicles, freight and transit vehicles and sometimes pedestrians. Each one of these modes of transportation plays a different role in the overall operation of the arterial network and has different demands regarding its way of operating especially the transit and freight movements. Therefore, the presence of an augmented number of transit and freight vehicles on a single corridor can contribute to the development of different and usually worse traffic conditions compared to networks without transit or/and freight movements.

The main reason lies in the fact that transit and freight vehicles are heavy vehicles that do not have the same moving flexibility as passenger vehicles. In addition, since they are moving with lower speeds, they need more time for accelerating and decelerating, and sometimes there are specific points on the road network that they need to make a stop. Thus, transportation engineers should face the multi-modal corridors from a different perspective than the usual corridors.

In general, the people responsible for coordinating and controlling the traffic signal system operations on multi-modal corridors seek to facilitate more than one mode simultaneously while implementing the priority strategies. For example, a part of a multi-modal corridor that is close to a port will have a high number of truck movements and an additional part of the same corridor, which is included in residential areas, will have a high number of pedestrians and buses. Thus, the traffic engineers and planners need to find a solution for simultaneously providing priority to the trucks near the port and to the buses and pedestrians near the residential areas.

As a result, signal control systems were developed as an extension of the traditional signal priority control systems. The main goal of the multi-modal signal control systems is to successfully control the operations of the multi-modal corridors. The multi-modal signal control systems utilize advanced communications and data for providing a high level of mobility throughout signalized corridors that facilitate all the different types of movements (passenger vehicles, pedestrians, transit, freight, and emergency vehicles). So, the multi-modal signal control systems provide the ability to establish different types of priority to different travel modes on an arterial network.

As an example of a multi-modal signal control systems, the components of the MMITSS system mentioned earlier are e presenting below:

i. I-SIG provides signal priority and preemption by applying an overarching optimization system;
ii. TSP and FSP provide priority to transit or freight vehicles at intersections;
iii. PED-SIG allows for an automated call from the smartphone of a visually impaired pedestrian to the traffic signal; and
iv. Emergency Vehicle Preemption (PREEMPT) provides priority on an intersection to emergency vehicles and accommodates multiple emergency requests.

1.6 Project Objectives

The goal of the research project is to explore methods to improve freight mobility and sustain good transit services without deteriorating the traffic conditions of the overall network. For efficiently achieving these goals, the simultaneous implementation of Freight and Transit Signal Priority strategies is suggested. The evaluation of the impact of the strategies on all vehicles and to each transport mode separately is considered as an objective of such implementation. This research is developing strategies and guidelines to plan, design, and implement FSP and TSP simultaneously

In order to accomplish the goal of the project, the study is divided into four parts. Firstly, the study examines implementing the FSP strategies along an arterial corridor in order to favor the flow of the freight vehicles unconditionally or under specific conditions, taking into consideration the trucks' characteristics. The purpose of applying the FSP is to provide priority to truck movements, to eliminate any delays, and to improve their efficient operation. In the second phase, the commonly used TSP strategy is applied to the corridor, for prioritizing the transit vehicles. The TSP application aims to improve the buses' travel time, reliability and to provide better transit services.

The third phase of the study focuses on the simultaneous implementation of the Freight and Transit Signal Priorities along with the studied corridor unconditionally and conditionally. The interaction of the two priority technologies is assessed and after evaluating the cooperation of these two strategies, a thorough examination regarding the effect that the TSP and FSP have on the network traffic conditions is conducted. Finally, the variables related to the freight and transit vehicles are analyzed in detail for identifying the variables that have the most significant impact on the efficient operation of the FSP and TSP strategies along the studied corridor. Afterward, the effectiveness of the newly developed criteria will be evaluated using an advanced simulation platform for the proposed case study in Florida.

2 Literature review

2.1 Overview

The objective of the literature review is to provide a summary of freight and transit signal priority and the multi-modal traffic control system. The historic background, the techniques, the benefits and the impacts around the studies related to TSP and FSP are presented below. Significant progress was made on transit signal priority from 1962, while freight signal priority strategies were mostly developed in the past decades and they are not so widely known, but still well developed to a certain extent.

Freight and transit signal priority use similar technologies since the idea of FSP was based on the application of TSP. Specifically, for the transit signal priority, the means of public transportation, usually buses, are prioritized in order to reduce travel time and delays primarily to the transit movements and secondly to the overall road network conditions. For the freight signal priority, the trucks are prioritized to reduce the number of truck stops and red-light running. The most common techniques for providing priority to the trucks at the signalized intersections are through green extension and early green, with the green extension reported as being more effective.

To our best knowledge, there is a limited number of studies conducted to examine the evaluation of the combined freight and transit priority problems and the application of multi-modal signal control to optimize the traffic operations of the network. The literature review is separated into four sections: freight signal priority, transit signal priority, their combination, and multi-modal signal control.

2.2 Freight Signal Priority

The review indicated limited research on freight signal priority. The studies conducted during the past years on freight signal priority are presented below.

A prototype truck signal priority system presented by Saunier 2009 (Saunier, Sayed, & Lim, 2009); used video sensors to detect, identify and track trucks, in order to ensure the efficient and safe movement of freight. The method was system tested using real-world data from the Next Generation SIMulation project (NGSIM). The study showed that the truck detection rate was between 78% and 95%, with a false alarm rate below the 0.5% value. Therefore, the performance required for effective truck signal priority is reached or is within reach of automated video-based sensors.

A distinctive freight signal priority system was introduced in another study (Kari, Wu, & Barth, 2014). The authors developed a multi-agent systems (MAS) based freight signal priority algorithm aiming to reduce network-wide energy and emissions. The proposed algorithm was implemented and evaluated on an isolated intersection in a microscopic simulation environment. The results indicated that the application of the proposed Eco-Friendly Freight Signal Priority algorithm improved upon traditional traffic signal priority by providing fuel and travel time savings to both freight and non-freight traffic.

The same year, a master thesis prepared by Maisha Mahmud 2014 (Mahmud, 2014); at Portland State University analyzed the benefits of freight services on a high truck density intersection. Using a simulation tool, VISSIM, the author evaluated the FSP by extending the green light duration. Results from this simulation analysis indicated that the evaluated priority can support ensuring service reliability and reducing red-light running. In addition, overall safety, travel and stop delays, and carbon emissions were improved with little to no impact on other vehicular traffic.

Afterward, Petros Ioannou 2015 (Ioannou, 2015) reported on two different solution methods for dealing with the problems caused by the trucks. Specifically, the researchers took into account the presence of trucks in controlling the traffic lights at intersections in order to minimize delays for all vehicles and reduce pollution by applying a neural network-based controller and an integrated priority strategy. The first controller is an adaptive controller that models the vehicle delays by distinguishing between different classes of vehicles with the use of optimization to reduce the vehicle delays by properly controlling the lights. The second controller is similar to the transit priority approach combining passive and active strategies in order to minimize vehicle delays, by providing priority to freight vehicles in situations that the action benefits the overall system. Both proposed controllers improved the network performance, including delay and vehicle stops, as well as environmental impact, compared to the fixed time control that is the commonly used controller.

Finally, Yanbo Zhao et al. 2016 (Zhao & Ioannou, 2016); proposed a new truck priority system. The researchers developed a simulation-based optimization control approach to find intersection signal sequences using real-time simulators for traffic state prediction. The results demonstrated improvements for both trucks’ and passengers' vehicles’ movements, especially on the reduction of traffic delays and stops, fuel consumption and vehicle emissions.

A research report by G. Giuliano, et al. 2018 (Giuliano, Showalter, Yuan, & Zhang, 2018) presented the development of a method for identifying the congestion caused by freight. This method was applied to estimate the impacts on passenger vehicles and other modes.

2.3 Transit Signal Priority

A comprehensive review of transit signal priority studies in the US and abroad was performed to evaluate the role of transit signal priority strategies on road networks. On-street transit service can be significantly delayed by traffic congestion and traffic signals. TSP can reduce the time that transit vehicles spend delayed at intersections, and therefore, reduce delay, improve transit service reliability, and improve the quality of transit service.

Numerous studies and reports were conducted during the 1970-2000 decades aiming to approach the priority of buses from different angles. T. Urbanik et al. (Urbanik, Holder, & Fitzgerald, 1977); focused on the evaluation of the priority techniques for buses and carpools to arterial streets in terms of their capital and operating costs, time of implementation and the enforcement requirements. Various studies were based on developing new bus priority strategies on signalized intersections taking into consideration the traffic signal coordination and evaluating their impacts, for example, S. Sunkari et al. (Sunkari, Beasley, Urbanik, & Fambro, 1995);, G. Chang et al. (Chang, Vasudevan, & Su, 1995), and M. Garrow et al (Garrow & Machemehl, 1999).

A project report for the New Jersey Department of Transportation by J. Daniel et al. (Daniel, Lieberman, Srinivasan , & Szalaj, 2005), assessed the impacts and the implementation issues associated with TSP and the benefit and costs of signal priority. They conducted an extended literature review regarding the priority concepts and components, past implementations of TSP, the negative and positive effects of these implementations to transit and vehicle movements, as well as the costs related to them. Afterward, the researchers identified the location for conducting the study at Broad Street in Newark. The traffic simulation that was used to quantify travel time impacts and transit operational benefits led to the conclusion that TSP could effectively be applied, but not in locations with heavy traffic with numerous bus stops. In general, the authors pointed out the importance of conducting separate analyses for each potential location that the TSP strategy will be implemented.

V. Ngan et al. (Ngan, Sayed, & Abdelfatah, 2004) evaluated the impacts of numerous traffic parameters on the effectiveness of TSP. The case study was selected with the consideration of the bus approach volume, cross street volume/capacity (v/c) ratio, bus headway, bus stop location, bus check-in detector location, left turn condition, and signal coordination. The results of the study showed that the efficiency of TSP relies mostly on signal coordination for peak hours, no hindering for turning movements, and long distances between bus stops.

Furthermore, the Minneapolis-St. Paul metropolitan transit agency installed a Global Positioning System (GPS) equipment in transit vehicles in order to monitor vehicle locations and schedules for providing more reliable transit services. The research project focused on taking advantage of the vehicle-mounted GPS and developed a priority strategy for buses depending on their schedule, number of passengers, location and speed aiming to improve transit travel & operation. The report prepared by Chen-Fu Liao et al. (Liao & Davis, 2006) indicated reductions of buses travel times and delays and a slight increase in the non-transit vehicles' travel times for peak hours.

A passive TSP was proposed and evaluated by Wanjing MA et al. (Ma & Yang, 2007) for bus rapid transit (BRT) system by analyzing the relationship of the departure frequency of a BRT bus line, the cycle length of signalized intersection, and number of different signal statuses when buses arrive at the intersection. The results of the VISSIM microsimulation software indicated the TSP application decreased the average bus delay and bus headway deviation without significantly affecting motor vehicle delay.

A U.S. Department of Transportation report created by Y. Li et al. (Li, et al., 2008) analyzed numerous TSP systems, including centralized TSP, two discrete TSP systems based on loop detection and GPS technologies, and an Adaptive Transit Signal Priority (ATSP) system. Afterward, a comparison of the implementation of the different systems was presented and various TSP evaluation methodologies were assessed regarding their efficiency. The benefits of TSP on transit and vehicle movements are documented through the presentation of numerous evaluations on TSP deployments. The report summarizes the guidance necessary for planning, analyzing and applying TSP, such as simulation and regional modeling tools.

One year later, K. Gardner et al. (Gardner, Hounsell, Shrestha, & Bretherton, 2009); completed a report including a review of bus priority used at traffic signals around the world. The authors analyzed all the existing approaches for providing priority to transit movements, as well as the components and the necessary tools for implementing the priority methods into the roadways. In addition, the report provided examples of numerous cases that various bus priority strategies have been implementing around the world and presented in detail a case study for the development of a priority strategy in London. The conclusions of the report confirmed that TSP is increasingly being adopted around the world with applications ranging from small towns to big cities and it is the most useful tool where opportunities for segregated systems are limited and/or where numerous traffic signals exist.

A planning and implementation handbook for TSP has been prepared by H. R. Smith et al. (Smith, Hemily, & Ivanovic, 2005). The first part of the handbook analyzed thoroughly the process of planning, designing and implementing a TSP project. The procedures presented later on in the handbook are related to the operation, maintenance, evaluation and validation of a TSP strategy. The second part presented a survey on numerous TSP strategies, documented plenty of case studies in order to highlight the variety of issues that arise and the solutions that have been developed and suggested future directions, while the third part describes the technical, simulation, and optimization tools necessary for the TSP implementation. This handbook is a useful tool for transit planners and traffic engineers to get familiar with TSP since it includes an overview of the TSP strategies.

A study was presented by K. Vlachou et al. (Vlachou, Collura, & Mermelstein, 2010) on the planning and deploying TSP in small and medium-sized areas. After the authors conducted an extended literature review on TSP strategies and the planning and deployment procedures, they assessed through microsimulation the impacts of TSP. A comparison between small-medium sized cities and metropolitan areas was performed in regard to planning and applying TSP strategies. The conclusions drawn based on the results were that in the majority the travel times and delays the two most significant parameters for efficiently applying TSP and the difference in small or medium-sized cities and metropolitan areas lies in technical and institutional issues. The study also provided some guidelines for future TSP implementations.

The application of TSP was examined in case of a no-notice urban evacuation by S. A. Parr et al (Parr, Kaisar, & Stevanovic); aiming to examine the benefits of transit signal priority on buses and on non-transit evacuees. The evacuation model developed and applied on a microsimulation software and the results showed that the implementation of TSP had little to no interference with the evacuation process of the urban area, but he pointed out that the exact benefits of transit signal priority will ultimately depend on a variety of case-specific factors.

Additionally, an evaluation of conditional TSP was conducted by F. A. Consoli et al. (Consoli, et al., 2015) on a test corridor along the International Drive in Orlando, Florida. In their study, the researchers demonstrated the effectiveness of TSP in improving bus corridor travel time in a simulated environment by using real-world data for the International Drive corridor. Specifically, the evaluation was conducted with microsimulation to compare unconditional and conditional TSP with the no TSP scenario. The performance metrics used for the evaluation include average speed profiles, average travel times, the average number of stops, and crossing street delay, while various scenarios were conducted with buses following their schedules or having a 3-5-minute delay. The results showed an improvement in the bus travel times for the conditional TSP strategy, and regarding the unconditional TSP implementation, the street delays increased. The environmental analysis results showed that TSP technology reduces the environmental emissions in all the scenarios analyzed.

In recent years, many researchers have focused not only on the implementation and evaluation of TSP but on the optimization of the TSP strategies. An optimization study was conducted by M.

Xu et al (Xu, Ye, & Sun, 2016). In their study, the authors proposed an optimization model to resolve conflicting transit signal priority requests. The measurement of the priority level of a TSP request depended on the bus travel delay, transit route level, and transit mode. The model applied to VISSIM and COM interface and the results indicated that the proposed model significantly outperformed the baseline model without priority.

The same year, R. Li et al. formulated a transit signal priority optimization model aiming to optimize the phases on a signalized intersection in Nanjing China. The goal of the study was to minimize the accessibility-based passenger delay at the intersection and to increase the waiting delay at the downstream bus stop simultaneously (Li, Zheng, & Li, 2016).

After a year, the same group of researchers developed a decision model for resolving conflicting TSP requests by selected in-bus passenger delay and passenger waiting delay at next bus stops as the indexes to measure the priority level, aiming to reduce schedule deviation and enhance the reliability of bus service. The decision model developed to favor a bus with a long delay and adds in-bus passenger delay and passenger waiting delay at the next stops for buses requesting the same TSP actions. The simulation results compared with other alternatives and the conclusions indicate that the developed model is able to serve multiple TSP requests and to balance the operational efficiency between transit vehicles and other vehicles, even on oversaturated conditions (Ye & Xu, 2017).

A study presenting guidance for identifying corridor conditions that warrant deploying transit signal priority was prepared by MD Ali et al. (Ali, Kaisar, & Hadi, 2017). The objectives of the research were to compare and evaluate existing guidelines on the transit movements by comparing the travel times and delays before and after the TSP implementation and propose new guidelines for TSP. The results provided that transit signal priority is a reliable option for reducing transit travel time and delay on buses.

The same year, L. Zhou et al. suggested an active transit signal priority method for improving the efficiency and safety and reducing the delays of BRT on exclusive lanes based on connected vehicles in Jinan City, China. The main purpose of the study was to maximize the average passenger benefit of BRT and other road users and to provide various signal priority control scenarios for all the BRT arrival modes. The factors considered in the study are BRT vehicle travel time, delay, energy efficiency and passengers' comfort of BRT vehicles, and community vehicles' efficiency. The scenarios applied to VISSIM microsimulation software and the results indicate a reduction in the average passenger delay and improvements on the travel speed of BRT vehicles (Zhou, Wang, & Liu, 2017).

Lee et al. presented a field experiment on combining TSP and connected vehicle technology for evaluating its performance at the Smart Road testbed at the Virginia Tech Transportation Institute (Blacksburg, Virginia). The CV- based TSP strategy used an algorithm for extending the green time for buses and the results of the study showed a reduction of delays (Lee, Dadvar, Hu, & Park, 2017). Also, they pointed out the possibility of implementing TSP on a large-scale case study, since the regular and differential GPS devices demonstrated that there is no statistically significant difference in the TSP performance. Finally, the authors recommended that this method should be tested on real traffic conditions for examining the performance in reality.

Recently, K. Shaaban et al. evaluated the impact of the existence and the absence of transit signal priority along a major arterial built on the VISSIM microsimulation software for assessing the performance of the traffic network. The authors concluded that the transit services, including travel time and reliability, were improved by applying TSP and the negative effect of the TSP to the rest of the traffic network was very low (Shaaban & Ghanim, 2018).

A recent study on transit signal priority was conducted by Z. Mei et al. examining the impacts of cycle and priority green length, gap time and red truncation, while implementing active TSP on an intersection with a stable cycle length (Mei, Tan, Zhang, & Wang, 2018). The simulation analysis results revealed that under special flow combination, increasing the cycle time could increase additional benefits. The factor influencing the gap time and the initial green time of the TSP phase is the volume, while the most efficient TSP strategy appeared to be the red truncation. Last, the application of a single-phase priority call was able to optimize all the parameters, but the application of multiple TSP calls the optimization process became more complicated.

2.4 Freight Signal Priority and Transit Signal Priority

Although the research on FSP and TSP strategies separately is very extensive, no significant progress has been made regarding the combination of Freight and Transit signal priorities. The application of both priority strategies simultaneously was not widely examined in the past, but in the last five years, some research was conducted on this subject.

A project of the Florida Department of Transportation (FDOT) was conducted by Elizer regarding the ways that Intelligent Transportation Systems (ITS) could be used for safety and mobility of all modes (Elizer, 2015). After the authors provided an overview of ITS and their significance, they analyzed the involvement of the intelligent transportation systems on the management of freight and transit movements and on the efficient application of FSP and TSP as well.

2.5 Multi-Modal Signal Control

In most of the cases, the traffic components on corridors consist of various transport modes in addition to the passengers' vehicles. The volumes of transit and freight vehicles can be high on many roadways, urging for extra attention of the operations of these vehicles at signalized intersections to avoid severe problems and issues. Thus, the signal control procedures should focus on the smooth co-existence of all the different modes of transport and on preserving an efficient network operation. Studies and projects related to multi-modal signal control are presented below.

Qing He et al. developed a mathematical formulation called PAMSCOD (Platoon-based arterial multi-modal signal control with online data) to optimize arterial traffic signals for multiple travel modes, given the assumption that advanced communication systems are available between vehicles and traffic controllers. The results showed that PAMSCOD could successfully coordinate traffic signals considering two traffic modes including buses and automobiles and significantly reduce vehicle delay for both modes (He, Head, & Ding, PAMSCOD: Platoon-based arterial multi-modal signal control with online data, 2012).

Qing He et al. presented the multi-modal traffic signal priority control problem under the assumption that vV2I communication is available for different traffic modes (He, Head, & Ding, Multi-modal traffic signal control with priority, signal actuation and coordination, 2014). The study aimed to address the conflicting issues between actuated-coordination and multi-modal priority control, developed a request-based mixed-integer linear program (MILP) for accommodating multiple priority requests from different modes of vehicles and pedestrians while simultaneously considering coordination and vehicle actuation. The proposed approach was compared with state-of-practice coordinated-actuated traffic signal control with TSP over several scenarios and the results showed a reduction on the average bus delay, average pedestrian delay, and average passenger vehicle delay, especially for the highly congested condition with a high frequency of transit vehicle priority requests.

A report by Kyoungho Ahn et al. with the main purpose to evaluate the potential network-wide impacts of the Multi-Modal Intelligent Transportation Signal System (MMITSS) based on a field data analysis utilizing data collected from an MMITSS prototype and a simulation analysis (Ahn, Rakha, & Kang, 2016). The authors attempted to improve mobility through signalized corridors using advanced communications and data to facilitate the efficient travel of passenger vehicles, pedestrians, transit, freight, and emergency vehicles through the system. The results from the field data analysis demonstrated improvements in the travel time and the delay of the equipped vehicles. Specifically, the implementation of the FSP reduced the trucks' delays but occasionally increased the delays on the side streets. The application of TSP effectively saved travel time for both transit and passenger vehicles, while the simultaneous application of TSP and FSP showed a positive outcome regarding assigning priority to trucks based on a pre-defined hierarchy of control.

Mehdi Zamanipour et al. published a paper regarding a model for multimodal traffic signal priority control based on an analytical model and a flexible implementation algorithm that considers real-time vehicle actuation. The model provides an optimal signal schedule that minimizes the total weighted priority request delay, while the flexible implementation algorithm is designed for preserving that the optimal signal schedule is applied with a minimum negative impact on regular vehicles. The simulation experiments showed that the model, when compared with fully actuated control, was able to reduce average delay and travel times for priority vehicles without a significant negative impact on passenger cars (Zamanipour, Head, & Feng, 2016).

A report on the MMITSS, mentioned earlier, was completed by the University of Arizona (University of Arizona, University of California PATH Program, Savari Networks, Inc and Econolite, 2016). The project's objective was to define and develop the MMITSS, and then implement it for evaluating the different signal control systems and their collaboration. The report provided a detailed analysis of all the procedures for the design until the implementation of the MMITSS prototypes. The case studies that the field tests took place were in Arizona and California. Regarding the implementation of FSP and TSP as a part of the MMITSS impact assessment, the first scenario prioritized only transit movements and the second scenario prioritized both the transit and freight movements. The field-testing results for the first scenario showed that the priority is beneficial for every individual transit vehicle, by decreasing both delays and travel times. Regarding the second scenario, the improvements on the travel times of transit movements were higher than the ones on the freight movements, due to the priority that buses had over the trucks.

2.6 Guideline for Implementing TSP and/or FSP

TSP and/or FSP may not be effective for all traffic and geometric conditions. Therefore, proper studies are recommended before implementing TSP and/or FSP. Existing literature provides a guideline on how to implement either TSP or FSP for a corridor. This study has focused on determining if both TSP and FSP can be implemented into the system or not.

Garrow and Machemehl conducted research to evaluate different transit signal strategies (Garrow & Machemehl, 1999). A micro-simulation program was used to simulate and evaluate different strategies. Based on the results of the simulation, the study suggested guidelines for peak and off-peak period TSP implementations. For off-peak hours, the study recommended green extension/red truncated value based on the cross-street saturation level (Table 2-1). Similarly, for peak hours the study also provides a guideline considering the negative impact on side road traffic (Table 2-2).

Table 2-1. Guideline for Off-Peak Hour (Garrow and Machemehl, 1999)

Cross street Saturation Level	Recommended Green Extension/Red Truncation Length
<0.25	Unbounded
0.25-0.35	20 Seconds
0.35-0.70	10 Seconds

Table 2-2. Guideline for Peak Hour (Garrow and Machemehl, 1999)

Cross Street Saturation	Green Extension = 10 seconds	Green Extension = 20 seconds
Saturation Level = 0.8	Minimal	Moderate
Saturation Level = 0.9	Moderate	Significant
Saturation Level = 1.0	Significant	Significant

* *Minimal Impacts:*	Signal priority appropriate.
**Moderate Impacts:*	Signal priority should be used with caution;
* *Significant Impacts:*	Signal priority should be avoided.

Chada and Newland (2002) conducted a details study to examine the impact TSP on traffic operations. They developed a guideline to determine when TSP is beneficial to implement. They also conducted a survey on transit professionals (Chada & Newland, 2002). Table 2-3 and Table 2-4 show findings from the study.

Table 2-3.: Pre-Implementation Checklist Point System (Chada and Newland, 2002)

Pre-Implementation Checklist	Yes	No
Express bus service?	1	0
Express bus service during off peak?	1	0
Farside bus stops?	1	0
Highly saturated cross streets over 1.0 v/s ratio?	0	1
Heavy volume intersections in the network?	0	1
Many instances of two transit vehicles approaching one intersection?	0	1
Do you have AVL technology installed?	1	0

Table 2-4. Recommendation Based on Point (Chada and Newland, 2002)

Point Range	Recommendation
0	No recommendation
1 - 2	Changes needed for priority
3	Somewhat recommended
4	Recommendation to pursue priority
> 4	Strongly recommended

Chada and Newland (2002) also provided an intersection specific guideline based on the saturation level of a specific intersection. Table 2-5 shows the details of the recommendation.

Table 2-5. Intersection Specific Guideline (Chada and Newland, 2002)

Saturation Level	Strategy
<0.25	Unlimited Priority
0.25-0.8	Priority with Limit
0.8-1.0	10 seconds priority
>1.0	Priority may not be effective

As mentioned previously, the USDOT TSP planning and implementation handbook for TSP suggested the first step of TSP project planning is the needs assessment (Smith, Hemily, & Ivanovic, 2005). The needs assessment process includes benefit estimation, feasibility assessment, cost and budget assessment, and the return on investment analysis. The study suggested to measure the delay and reliability of transit from the field measurements and do a simulation to estimate the benefit of TSP implementation. Although the study described the concept of operation and detail guidelines of TSP planning, design, implementation, maintenance, and evaluation process, it does not provide quantitative values of different field conditions when an agency should consider implementing the TSP. TSP guideline developed by Tindale-Oliver & Associates, Inc. (Ryus, et al., 2015) for the Florida Department of Transportation (FDOT) adopted the same principle mentioned in the USDOT handbook.

In another USDOT project, Li et al. mentioned three main aspects of TSP evaluations: technical performance, transit operation performance, and arterial operation performance (Li, et al., 2008). Technical performance focus on evaluating the technology used for TSP, transit operation performance measures the benefits for the transit, and arterial operation measures the impact of TSP on other roadway users. The study suggested evaluating the travel time and travel time reliability for measuring the benefit of the transit. In addition, the impact of TSP on other roadways should be measured by evaluating intersection delay, corridor travel time, throughput, and the numbers of cycle failure.

Li et al. (2008) suggested using a microscopic and macroscopic simulation tool to evaluate the TSP implementation. This study suggested using a macroscopic simulation model for initial screening-level evaluation. At this stage, potential corridors or intersections are selected for further analysis by the microscopic model. They have also provided a guideline for determining the TSP implementation opportunity based on vehicle delay and volume-to-capacity ratio (Table 2-6).

Table 2-6. Delay and Volume-to-Capacity Thresholds (Li et. al., 2008)

Opportunity Ranking	Vehicle Delay (sec/veh)	Volume-to-Capacity Ratio
Low	< 25	> 0.90
Medium	< 25	< 0.90
	25-60	> 0.75
High	> 25	< 0.75

Hu et al. (2014) proposed a new TSP logic utilizing Connected Vehicle technology (Hu, Park, & Parkany, 2014). The methodology considered delay per person as the measure of effectiveness in order to consider TSP as a feasible option. If delay per person decreases with the TSP, then TSP solution is implemented. Their methodology is shown in Figure 2-1.

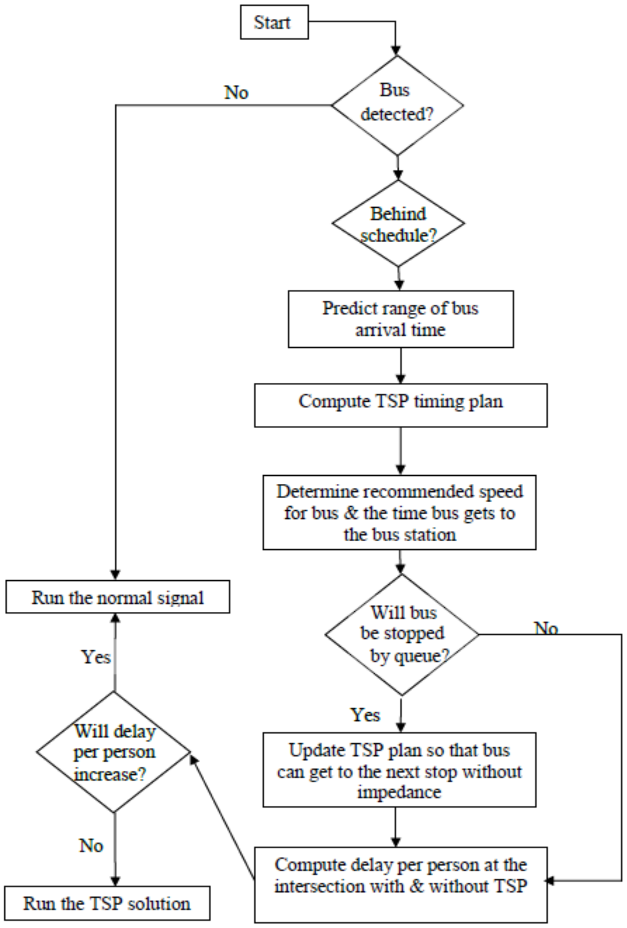


Figure 2-1. TSP Implementation Methodology (Hu et al., 2014)

Vlachou et al. also suggested some guidelines for TSP implementation especially for small and medium-sized cities based on literature and simulation models done in VISSIM (Vlachou, Collura, & Mermelstein, 2010). They have provided two different guidelines for planning and deployment. At the planning level, they have suggested the following considerations:

i. Institutional Issues, Local Needs Assessment, and System Objectives and Requirements,
ii. Pre-Deployment Impact Analysis,
iii. Traffic Flow,
iv. Safety for Pedestrians,
v. Economic Analysis, and
vi. Financing.

At the deployment stage, the provided guidelines are:

i. Procurement,
ii. Identification of Systems Objectives and Requirements,
iii. RFP Preparation/Proposal Evaluation,
iv. Pre-Installation Site Survey,
v. System Installation, and
vi. Evaluation.

In a recent study done by Kaisar et al. also developed a guideline based on simulation data. Figure 2-2 shows the guideline for selecting TSP (Kaisar, Ali, Hadi, & Xiao, 2018). The guideline has three different parts: Existence of bus delay, geometric and traffic feasibility for TSP, and impact on other movements. Existence of bus delay is checked based on the following criteria:

i. Bus approaching speed is less than 25% of the approaching speed limit
ii. Bus frequency is more than 10 per hour per direction
iii. Bus ridership is more than 100 passenger per hour per direction

Geometric and traffic feasibility check the different geometric and traffic conditions such as:

i. Bus stop location is at the far side/ midblock location. If not check whether it is possible to relocate the bus stop.
ii. Signal slack time is more than 5 seconds. Signal slack time is defined as the cycle time minus all minimum pedestrian clearance and minimum left turn green times.

Finally, the impact of signal priority on other movements is checked considering:

i. Other critical movement v/c is less than 0.85
ii. Cross street bus frequency is less than 10 per hour per direction
iii. Cross street bus ridership is less than 100 per hour per direction

The above criteria were selected based on sensitivity analysis. When all the above criteria are met, the guideline recommends implementing TSP at that intersection.

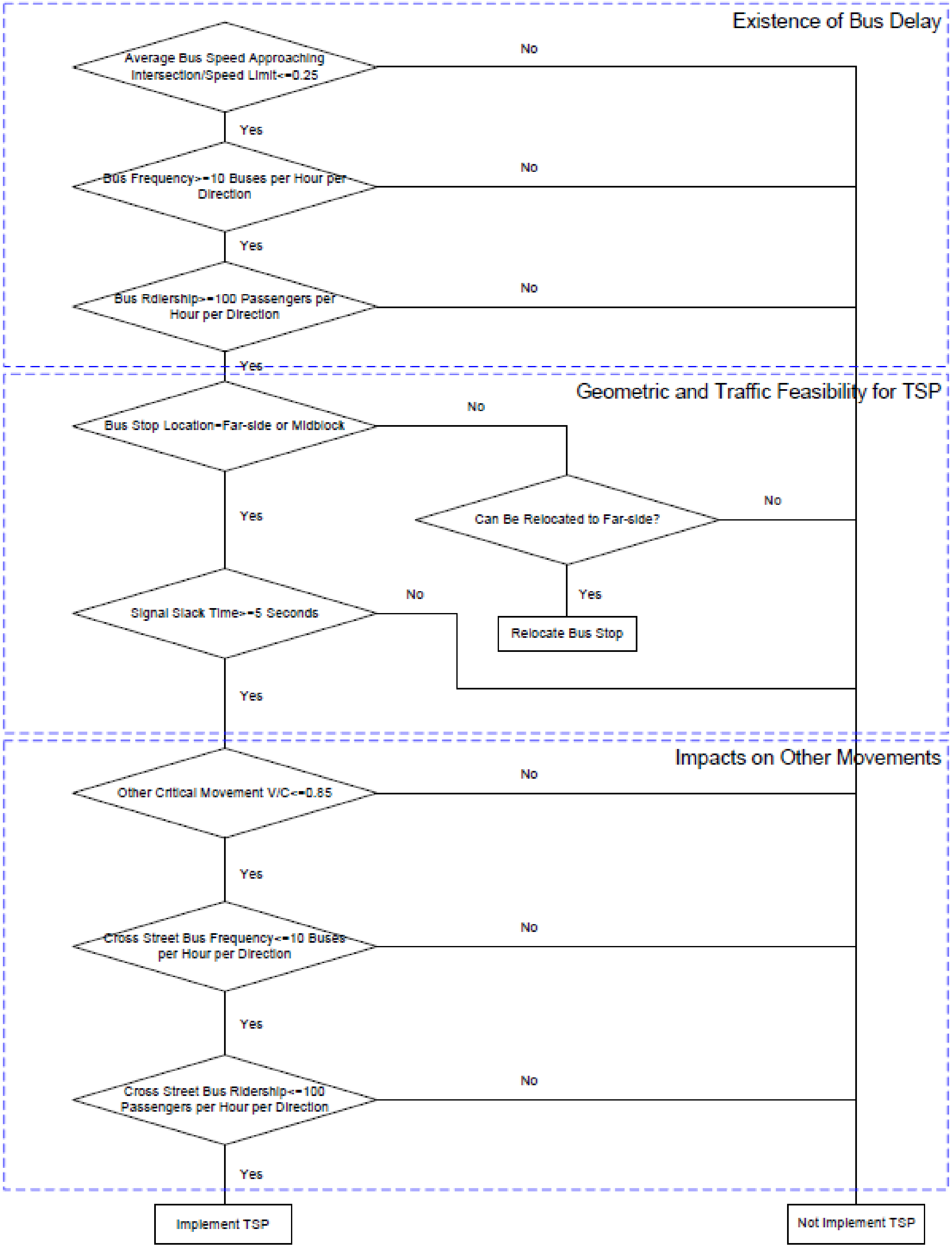


Figure 2-2. Proposed Guideline for TSP Implementation (Kaiser et al., 2017)

In case of FSP, there are very limited literatures available for preparing the guideline. WSDOT (2019) recommended the following consideration when FSP could be implemented for a corridor:

i. A corridor is an important freight route that is used by a lot of trucks. Important freight routes may be designated truck routes near ports, industrial areas, or distribution centers.
ii. The approach to a traffic signal is uphill where the time to accelerate from a red light is longer.
iii. The approach to a traffic signal is downhill and trucks may have to brake harder to stop in time for a red light.

In addition, the following safety benefits could be gained when and FSP is implemented:

i. Improves safety by reducing truck-related collisions at intersections. When trucks are unable to stop after a light turns yellow, they might enter the intersection after the light changes into red which may result in a serious collision.
ii. Reduces congestion by giving extra time to slower-moving vehicles. Trucks stopped at traffic signals contribute to congestion because it takes trucks longer than smaller vehicles to get up to speed when the light turns green. Keeping the trucks moving through a green light reduces traffic delays.
iii. Reduces road maintenance needs by limiting stop-and-go conditions. The amount of time truck stops and starts at intersections causes more wear and tear on pavement. Keeping trucks moving helps reduce maintenance costs and labor.
iv. Reduces emissions from trucks waiting at red lights and accelerating from a stop at the traffic signal.

The conclusion reached by reviewing the existing literature of freight signal priority and transit signal priority indicates the lack of their combination. Even though both of these priority systems were extensively analyzed in the past and were applied in different ways and strategies, a gap appears in the literature regarding the combined applications of FSP and TSP.

Hence, in order to contribute to the elimination of this gap, the main scope of this study is to conduct thorough research on FSP, since FSP strategies are not so widely explored. The second scope would be to assess the effectiveness of applying FSP and TSP in combinations. Finally, the study proposes guideline for the simultaneous application of FSP and TSP.

3 Concept of Operations

This chapter presents a concept of operations for the implementation of the FSP and dealing with the coexistence of FSP and TSP at the same time on an arterial network. The goal of freight signal priority is improving the mobility and reliability for freight vehicles, which can reduce the negative environmental impacts, reduce pavement damages, and enhance safety at intersections without impacting adversely the general traffic and TSP operations.

The specific objectives are:

i. Reduce freight delay and stops at the signalized intersection
ii. Reduce freight-intersection related crashes
iii. Reduce the probability of dilemma zone incursions
iv. Improved environment impacts and fuel saving
v. Improve freight/goods reliability
vi. Reduced pavement deterioration

3.1 Relationship to the Systems Engineering Process

The Federal Highway Administration (FHWA) published Rule 940, and the Federal Transit Administration (FTA) published a policy for utilizing Systems Engineering analyses for ITS projects that use highway trust funds. The systems engineering approach has also been strongly recommended for use in other ITS projects. The Systems Engineering Guide produced by the United States Department of Transportation provides guidance to agencies on how to use the systems engineering approach during the various stages of the ITS project life cycle. The activities of this project including the concept of operations produced in this document which provides information to support the FDOT in the early stages of the systems engineering process, shown in Figure 3-1. In particular, the information provided in this project is related to the Regional Architecture, Feasibility Study/Concept Exploration, and Concept of Operations (CONOPs) steps. The system requirements and design will be produced in Phase 2 of this project.

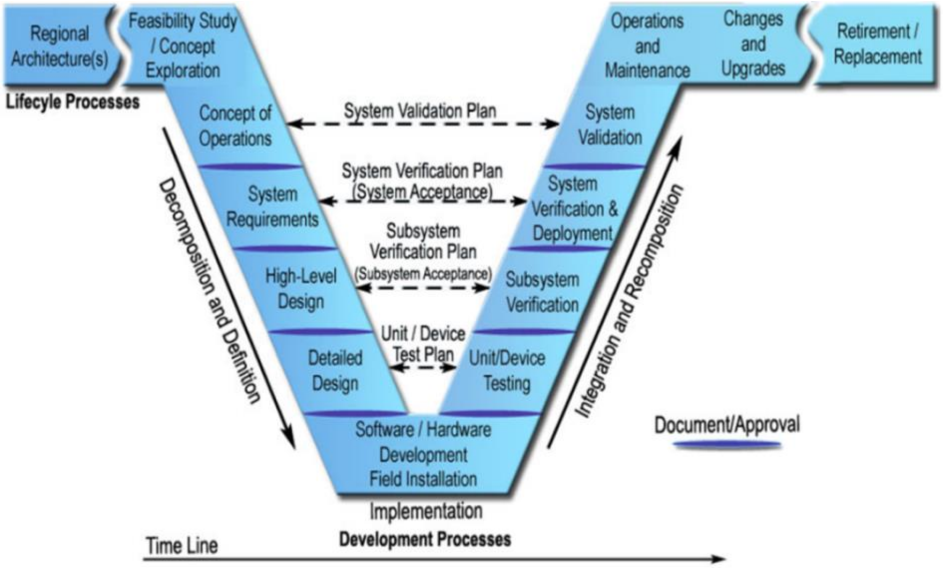


Figure 3-1. Systems Engineering Approach

Among other elements, the systems engineering approach requires the analysis of alternative system configurations and technology options based on identified stakeholder needs, goals, objectives, issues, and requirements. The main component of the systems engineering approach related to the subject of this research is the need to conduct a feasibility study, in which the technical, economic, and political feasibilities of the considered strategies and technologies are assessed, benefits and costs are estimated, and key risks and constraints are identified. As shown in Figure 3-2, according to the USDOT Systems Engineering Guide, the feasibility study will need to consider alternative solutions to satisfy the identified needs and select and justify the most viable option. The feasibility study is being conducted in parallel with the development of the initial version of the CONOPs developed in this document. The CONOPs will be updated at the end of this project to reflect this analysis.

The initial CONOPs presented in this document is a part of the system engineering process for a typical urban arterial in Florida with the consideration of Connected Vehicle (CV) applications.

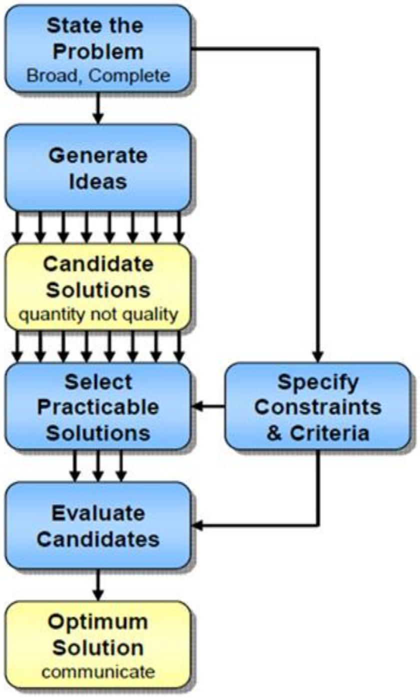


Figure 3-2. Basic Trade Study Techniques in the Concept Exploration as Presented in the System Engineering Guide (USDOT, 2007)

3.2 Relationship to the National and State Architecture

A good starting information to have an overview of the system needs to identify the changes outlined earlier in this deliverable is the information presented in the Architecture Reference for Cooperative and Intelligent Transportation (ARC-IT). The service packages and associated physical objects, functional objects, and information flows and the four views of the architecture that can be accessed at https://local.iteris.com/arc-it can be used as an important source of information that is supplemented by information from other sources to complete the system interviews. Figure 3-3 presents the FSP package as presented in ARC-IT. Which according to the architecture “provides traffic signal priority for freight and commercial vehicles traveling in a signalized network. The goal of the freight signal priority service package is to reduce stops and delays to increase travel time reliability for freight traffic, and to enhance safety at intersections.” It is interesting to note from the figure that the architecture allows both distributed (local) priority through center-to-roadside requests and central prioritization through center-to-center requests. The roadside request is referred to in the figure as “Signal Priority Service Request.” It can be accommodated using connected vehicle equipment. On the other hand, the center-to-center request is sent from what is envisioned as being made by an Intermodal Customer terminator that communicates with the Fleet and Freight Management Centers and the Transportation Management Centers. The 'Intermodal Terminal' is envisioned to represent “terminal areas corresponding to modal change points. This includes interfaces between roadway freight transportation and air, rail, and/or water shipping modes. The basic unit of cargo handled by the Intermodal Terminal physical object is the container; less-than-container load handling is typically handled at a different facility (i.e., Freight Consolidation Station). The Intermodal Terminal can include electronic gate control for entrance and exit from the facility, automated guidance of vehicles within the facility, alerting appropriate parties of container arrivals and departures, and inventory and location of temporarily stored containers.”

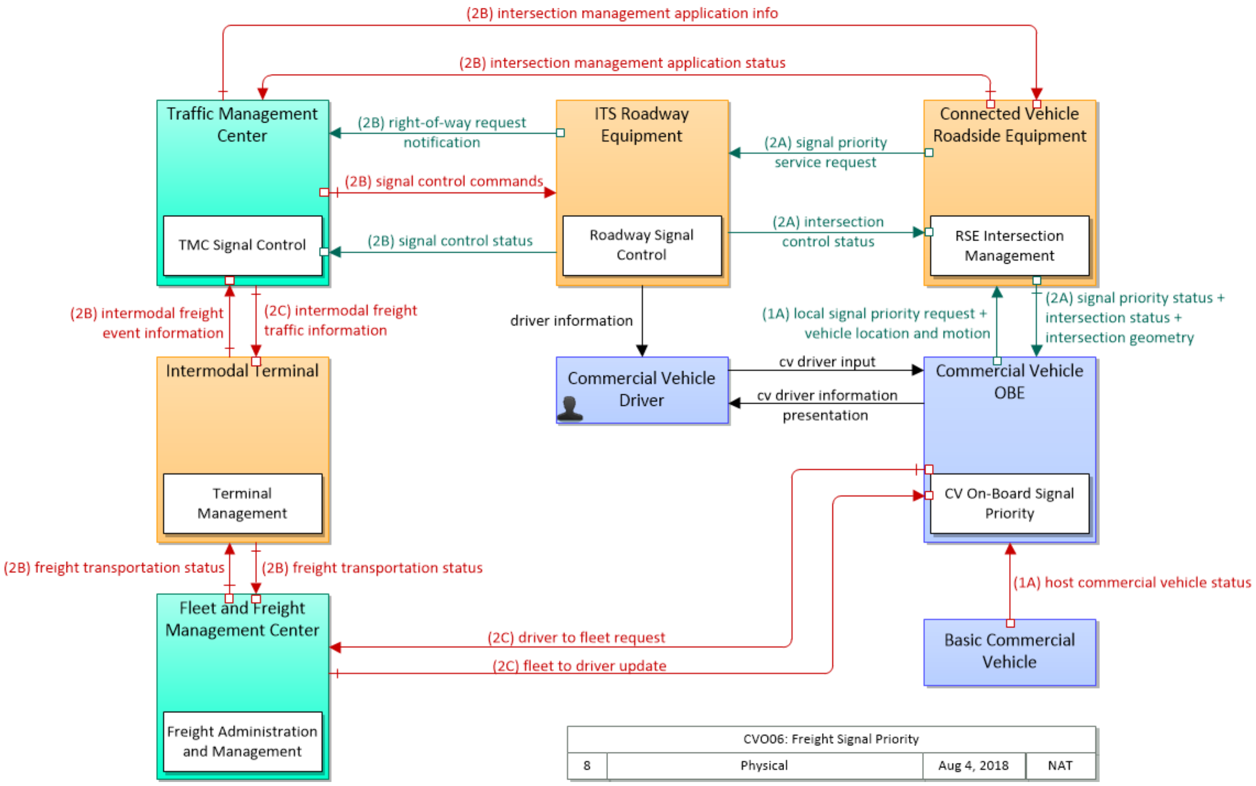


Figure 3-3. CVO06 Freight Signal Priority in Arc-IT

Figure 3-4 shows the TSP in ARC-IT. As with the FSP, it can be seen that it allows both distributed and central priority. The vehicle-to-roadside communication can be accomplished using both CV-based technology to roadside CV units or through other communication means to the controller cabinet. The center-to-center requests are made through transit management to transportation management center requests.

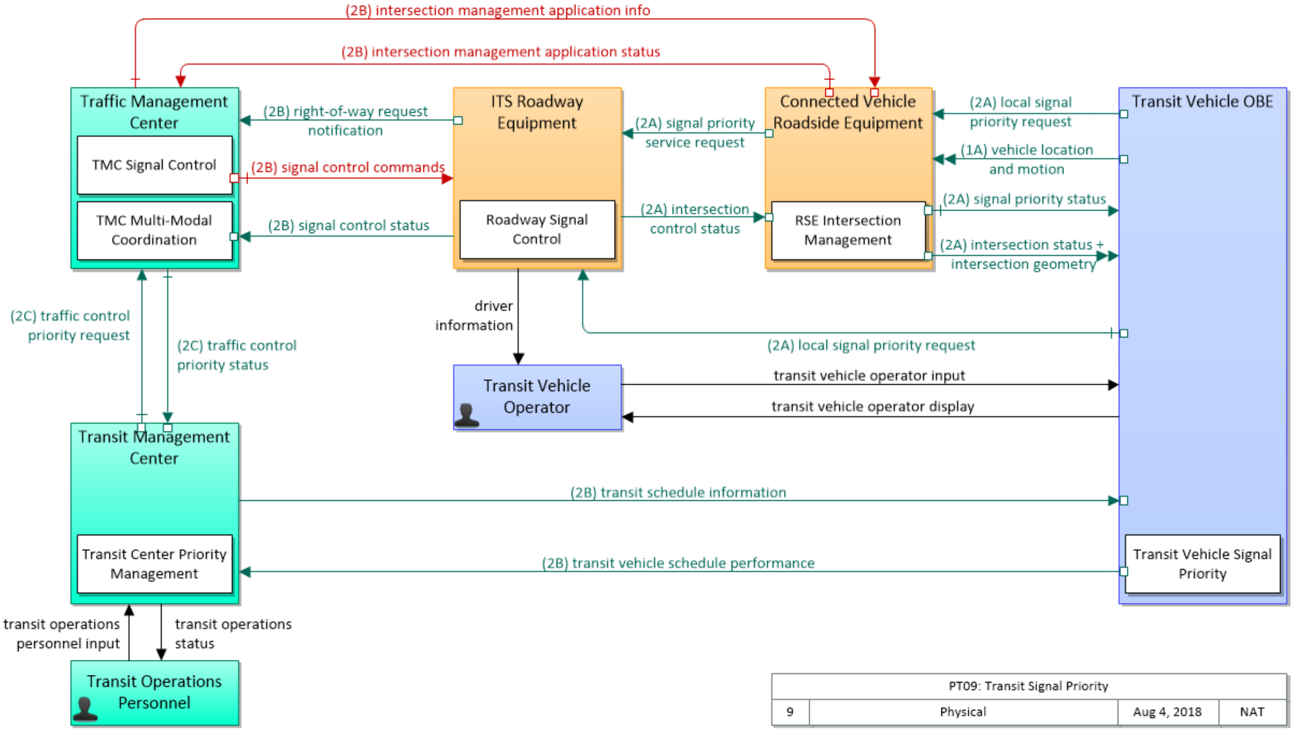


Figure 3-4. PT09 Transit Signal Priority in Arc-IT

The current version of the FDOT's Statewide and Regional ITS Architectures referred to as SITSA, is based on Version 7.0. SITSA does not adequately address CV deployment and does not have an FSP package. The FDOT plans to update ITS architecture to be based on the most recent version of ARC-IT in 2019 (Ponnaluri, 2019). It is interesting to note that the architecture for FDOT Districts 4 and 6 only includes TSP service package for Miami-Dade County, shown in Figure 3-5, and only accommodates the center-to-center priority, which is the preferred option by Miami-Dade County. No TSP service package is included for FDOT District 4. Figure 3-6 shows the Emergency Routing presented in the architecture and shows that, for fire truck preemption, it can accommodate both central and distributed preemption. It is known that in FDOT District 4, Broward County prefers the distributed architecture for preemption while in District 6, Miami-Dade County prefers the central configuration. This will be further explored in this study.

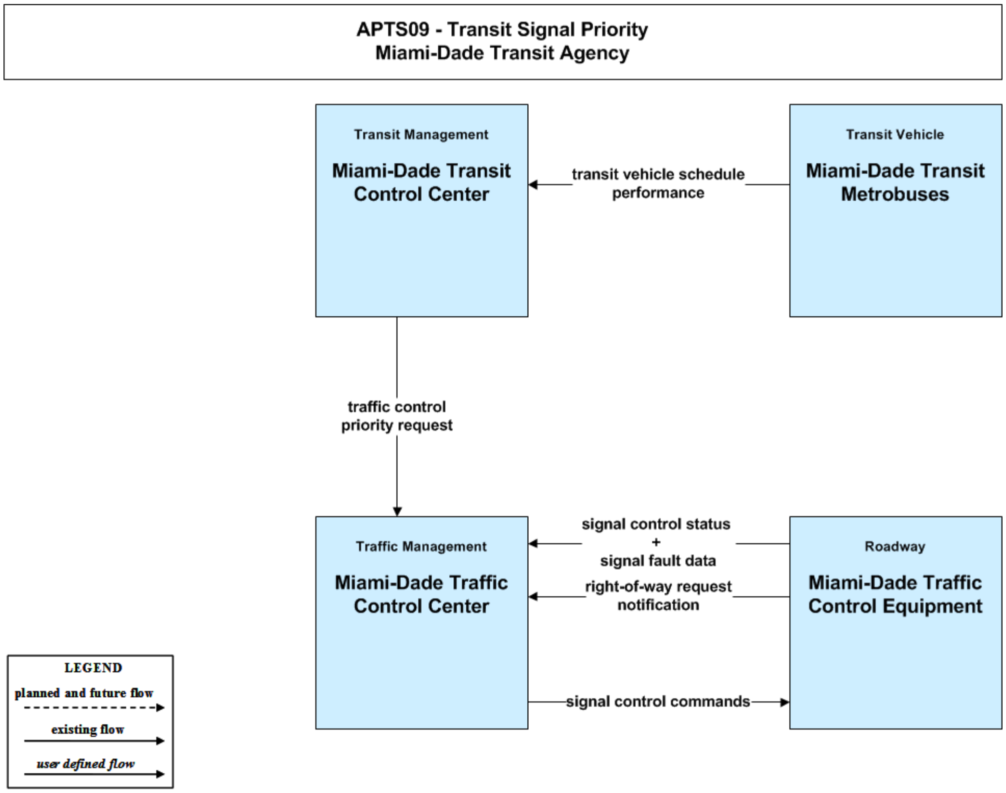


Figure 3-5. APTS09 Miami-Dade Transit Signal Priority in SITSA

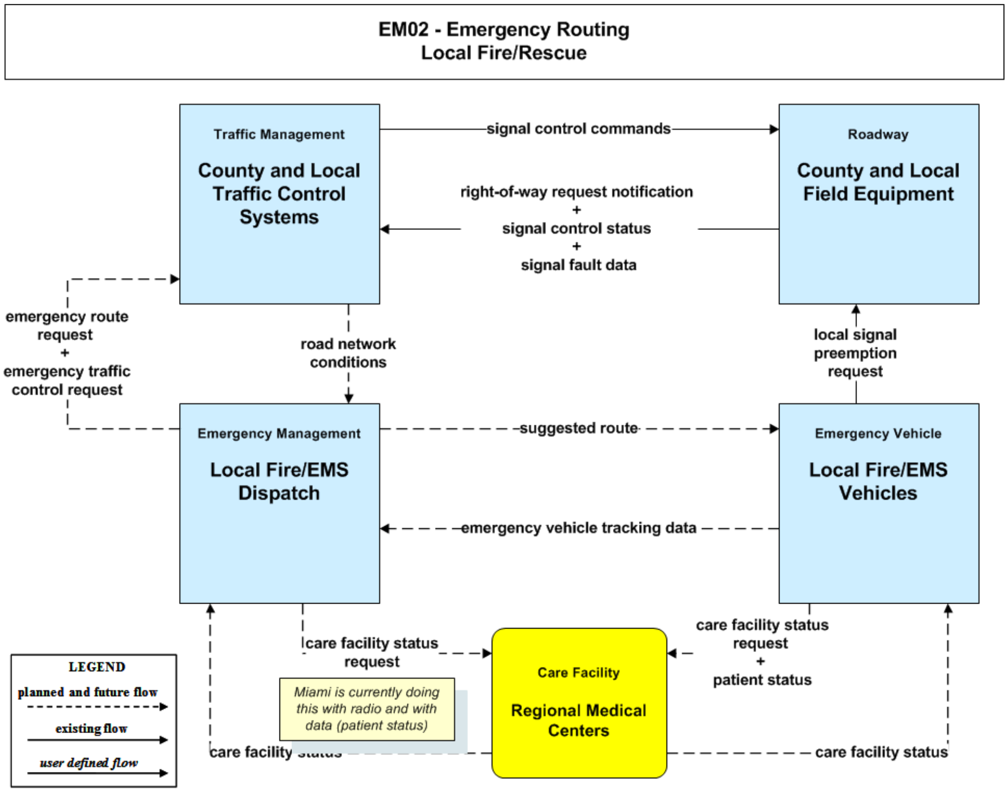


Figure 3-6. EM02 South Florida Emergency Routing Local Fire and Rescue in SITSA

3.3 Stakeholders

The following is a list of stakeholders that needs to be involved in the project activities.

i. Florida Department of Transportation (FDOT) including Transportation System Management and Operations (TSM&O), Planning, Public Transportation, and Freight Departments
ii. County and City Traffic Engineering, Signal Control/Public Works, Public Transportation, and Information Technology Departments
iii. Transportation Planning Organizations (TPO) and Metropolitan Planning Organizations (MPO)
iv. Commercial vehicle companies
v. Fleet and Freight management
vi. Intermodal terminal management
vii. Emergency management (Fire and rescue, police)

3.4 Existing Situation

The literature review confirmed that TSP is increasingly being adopted around the nation with applications ranging from small towns to big cities. Variations of transit signal priorities have been implemented around the nation including Florida. The implemented TSP systems include active and passive systems, central or distributed, different strategies (green extension and early green; and to a lesser degree actuated transit phase, phase insertion, phase rotation), and unconditional or conditional priorities. Research has been conducted on the associated technical and institutional issues and guidance have been given regarding the conditions under which the TSP can be justified from general traffic and transit points of view.

Automatic Vehicle Identification (AVI) technology, as well as Automatic Vehicle Location (AVL) based on GPS, have been used to detect approaching transit vehicles and various wireless communication techniques have been utilized for vehicle-to-roadside and vehicle-to-center communications. In this regard, it should be mentioned that in Florida, there have been agencies like Miami-Dade County that prefer the central type of TSP. Other agencies like Broward County and Palm Beach County prefer the distributed (local) type of control, as explained in the previous section. Thus, any developed TSP/FSP concept should account for both types of architectures.

Research has been done on the optimization of the TSP strategies, for example, to resolve conflicting transit signal priority requests. The priority level of a TSP request was set in one study reviewed in the literature review based on the bus travel delay, transit route level, and transit mode. In another study, it was prioritized based on in-bus passenger delay and passenger waiting delay at the next bus stops as the indexes to measure the priority level, aiming to reduce schedule deviation and enhance the reliability of bus service.

Unlike TSP, the FSP implementation has been very limited, although there has been some research on the subject as described in the literature review. In addition, until recently there has been limited research regarding the combination of FSP and TSP, possibly combined with preemption, in which a rail-road crossing or emergency vehicle preemption request can override a priority request. With some existing controllers, TSP requests are served one at a time on a first-come, first-served basis and multiple requests at the same time cannot be guaranteed. However, this is changing with some of the ATC and 2070 available from signal vendors. Thus, the exact capabilities of the existing controllers need to be understood.

A significant advancement with the provision of signal timing services to a multimodal mixture of traffic has been in the development, pilot testing, and evaluation of the MMITSS application, as part of the USDOT CV program. MMITSS is a next-generation traffic signal system that provides service to all modes of transportation utilizing CV technology combined with infrastructure detection (see Figure 3-7). MMITSS consists of five different applications as below (Ahn, Rakha, & Kang, 2016):

i. I-SIG aims at maximizing the throughput of passenger vehicles and minimizing the delay of priority vehicles under saturated conditions and minimizing the total weighted delay during under-saturated conditions.
ii. TSP allows transit agencies to manage bus service by adding the capability to grant buses priority.
iii. PED-SIG integrates information from roadside or intersection sensors and new forms of data from pedestrian-carried mobile devices.
iv. PREEMPT preempts signal phases for emergency vehicles.
v. FSP provides signal priority near freight facilities based on current and projected freight movements.

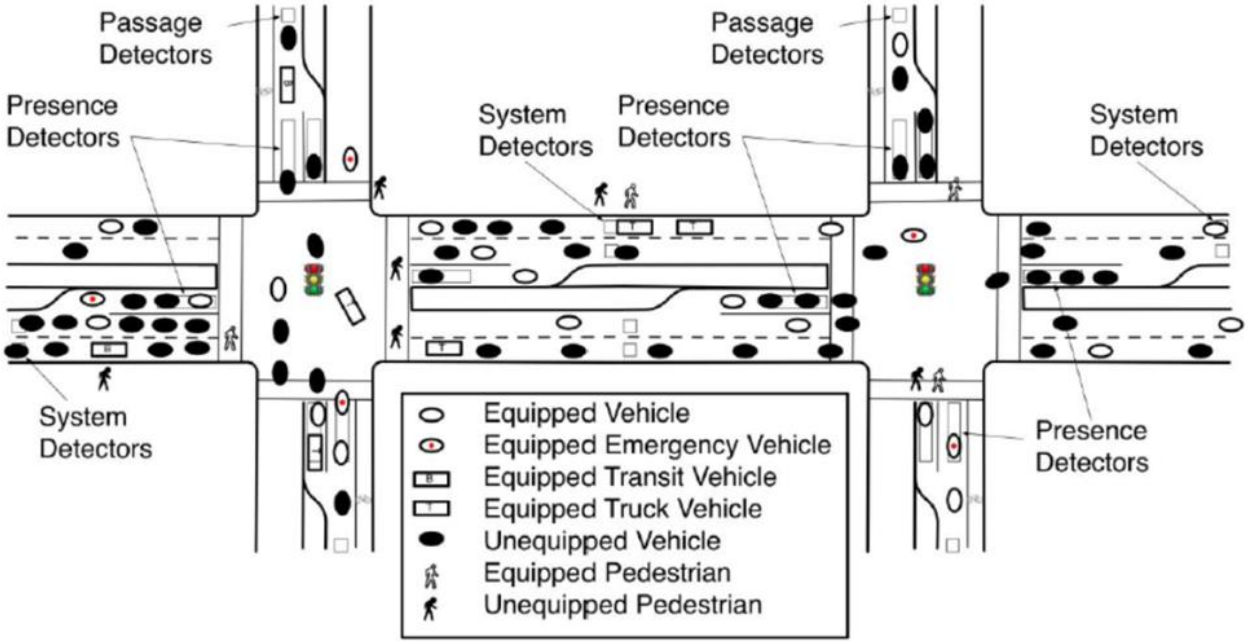


Figure 3-7. Illustration of the MMITSS Concept (Source: University of Arizona., 2015)

3.5 System Description

In multimodal priority system that combines FSP and TSP, a vehicle approaching an intersection is detected at some point upstream of the intersection at a distance that depends on the detection and wireless communication technologies. A transit priority is initiated based on active requests for priority and in some cases solely based on the detection without such request. The traffic control system will then make a decision about granting the priority depending on the priority logic. In general, the control system either applies early green and red truncation, which start the green early to reduce the probability of the vehicle stopped or delayed or holds the green until the transit vehicle clears the intersection (green extension). There are other options such as phase insertion and phase rotation, but they are much less commonly applied. Once the bus or truck is found or estimated to leave the stop line, the controller resumes the normal signal timing.

The provided system will consider and provide priority for qualified classes of vehicles that request priority. Depending on the amount of information available to the system, the provision of the priority will be based on the vehicle mode, vehicle operation parameters (static and dynamically measured), position, speed, traffic conditions, and possible weather conditions. Granting the priority will also consider a local policy that identifies the importance of some vehicles over others.

Multiple signal priority requests for vehicles of different types (transit and freight) should be managed and served according to a priority scheme. The allocation of priority levels and the conditions under which the priority is guaranteed should be determined based on a previous analysis of the corridor, measured and target performance of the different modes, and stakeholder priorities and agreements. The different levels of priority can be assigned for vehicles of different modes but also for vehicles of the same travel mode (e.g., different bus lanes or trucks with different acceleration/deceleration performance). This can be also changed based on time of day, traffic conditions, and weather conditions. Of course, railroad and emergency vehicle preemption when applied at an intersection will have a higher priority than both the TSP and FSP.

Conditional TSP can be implemented based on schedule adherence or the number of passengers. As with TSP, the granted priority to a freight vehicle in FSP can consider the specific characteristics of the truck such as the required stopping distance of the truck, the impact on traffic due to slow acceleration, and even the type of shipment. The traffic operations, freight, and transit agencies will work together to identify the relative priority of general traffic, freight, and transit. The prioritization with respect to trucks can use truck size, truck weight, vehicle dynamics, different types of shipment, origin, destination, time-of-day, weather, and other factors to assign the appropriate level of priority. The FSP concept may also be used in conjunction with the identification of a freight corridor to encourage trucks to use the corridor to improve the safety and operations of other corridors.

The priority requests can be made at the central level through center-to-center communication such as between the traffic management center with the transit management center and/or the freight management center/Intermodal terminal. It can also be made using a distributed (local) priority architecture. With this distributed concept, non-equipped vehicles can be classified based on point detectors and equipped vehicles can be identified using an AVI technology such as infrared (IR) or Radio Frequency Identification (RFID), detected and classified using infrastructure sensors, and/or tracked by the system using AVL/GPS technology. Communication to the roadside can be achieved using various technologies such as 980 MHz, 2.4 GHz, DSRC 5.9 GHz connected vehicle technology, and cellular communications. There are various implementation scenarios that will be outlined, providing the opportunity to implement the FSSP and TSP under a variety of frameworks, environments, and objectives.

As stated in the previous section, limited experience exists with the actual planning, design, implementation, and operations of FSP. An added complexity is when the FSP will have to be operated in conjunction with TSP. As stated, many existing controllers serve requests one at a time on a first-come and cannot serve multiple requests at the same time. Prioritization of the requests is also an issue that needs to be considered. The application and harmonization of the concurrent TSP and FSP requests and the prioritization of the requests are major considerations in this project.

It should be mentioned that although other communication technologies can be used for the purpose of FSP/TSP, the use of CV based FSP and TSP applications have an advantage in that such applications allow utilizing the deployment platform for many other CV-based mobility and safety applications. CV applications will require the Road Side Equipment (RSE) and On-Board Equipment (OBE). Exchange of information between the roadside and the vehicle will include Basic Safety Messages (BSM), Mobile Application Part (MAP) messages, and Signal Phasing and Timing (SPaT) messages, all of which are important for effective TSP and FSP operations. An equipped vehicle will receive the MAP and SPaT data and broadcast BSM data and based on the received information combined with other information send requests for service to the roadside equipment. With this scenario, The RSE will communicate with the traffic signal controller using the National Transportation Communications for ITS Protocol standards (NTCIP) 1202 and 1211 for signal control and prioritization. This will allow the RSE to request priority based on communications with the vehicle OBE.

3.6 Implementation Scenarios

There are various configurations and associated scenarios of implementing the FSP, each of which has a different level ability to deliver the system functionalities in the overview presented in the previous section. In particular, the abilities of these implementation scenarios to satisfy the prioritization of TSP and FSP requests and conditional priority vary.

3.6.1 Scenario 1: Provision of Distributed Priority

As described earlier in this concept of operations, the distributed or local priority application is based on vehicle-to-roadside equipment communications and all decisions are made at the intersection level. This option requires additional equipment onboard the vehicles and, on the roadside, and thus additional capital and maintenance costs. The following subsection describes four implementation scenarios of the distributed priority that may be considered for FSP and TSP implementation.

3.6.1.1 Scenario 1-1: Distributed Priority Decisions, Based on Sensor Classification

With this option, the FSP is based on the identification of trucks using point traffic sensors that can classify trucks such as video image detectors, radar, and/or Weigh-in-Motion (WIM). This option provides the least information about the approaching truck trip and operational attributes such as acceleration/declaration abilities, schedule adherence, trip purpose, etc. WIM sensors provide more information than other types of point sensors. No active request from the truck is sent from the truck to the roadside. However, TSP can be based on active priority requests. The lack of information limits the assignment of different levels to the priority requests and the conditional priority options. However, this option has the advantage that it does not require coordination with the variety of freight and fleet administrations to ensure that OBE is installed on the trucks. One of the most constraints with unconditional priority is providing priority to a vehicle that is on time or ahead of schedule resulting in passengers missing their rides. One option is to use a hybrid scenario where the TSP is granted based on onboard equipment identification and the freight priority is granted based on point detectors.

Saunier et al. (Saunier, Sayed, & Lim, 2009) developed a prototype truck detection and tracking system using video sensors. The study pointed out that the video sensors should be able to detect, identify, and track heavy trucks traveling within a corridor. A concern of the study was false alarms due to classification errors. Thus, the development team paid special attention to minimizing the false alarms rate. Several other potential issues with video detection were highlighted in the paper including the ability to track trucks as they move on the link, impacts of environmental conditions on the detection, and the ability for multiple object tracking and classification. The research showed the ability to the developed system for a relatively high recall for trucks, from 78% to 95%, with a false alarm rate below 0.5%. The vendors of currently available video image and radar technologies should be contacted to determine their product ability to classify trucks for FSP purposes.

Sunkari et al. (Sunkari, Charara, & Urbanik, Reducing Truck Stops at High-Speed Isolated Traffic Signals, 2000) used a loop-based traffic classifier that requires a pair of loops in each lane to identify trucks and determine their individual speeds for FSP purposes. Figure 3-8 shows the loops installed at a distance of 550 feet upstream from the intersection. This distance was calculated based on the approach speed and loops positioned to provide the appropriate dilemma zone treatment. Figure 3-9 shows the configuration of using a loop-based classifier for FSP.

Figure 3-8. Installed Loop Detector (Source: Sunkari et al., 2000)

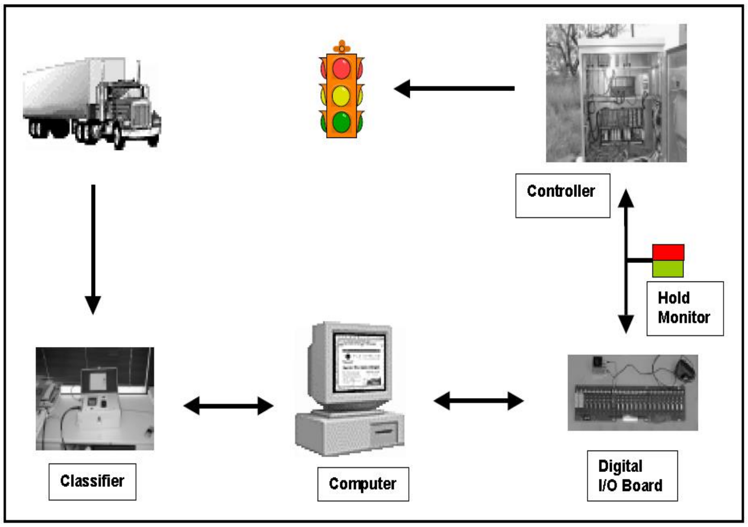


Figure 3-9. Utilization of Loop-based Classifier for FSP (Source: Sunkari et al., 2000)

3.6.1.2 Scenario 1-2: Priority Decisions Based on AVI/AVL Technology, Fully Made at Controller Cabinet

With this option, the transit vehicle communicates its identification (if AVI technology like IR or RFID is used) or location (if AVL/GPS is used) to the controller cabinet. However, with this option, the decisions about granting priority are made fully at the cabinet. This type of system can compare simultaneous priority and preemption requests to make the decisions of granting priority. A disadvantage is that not all needed information about the vehicles requesting the priority for the specific trip is available to the decision process at the roadside. Such information resides in the vehicle and is not available to the controller. Conditional priority based on stored information in the control database is possible and this information can be updated daily. The information may include criteria such as truck type, bus schedule adherence, time of day, trip information, etc. The truck will have been equipped with on-board units to support the identification or tracking of trucks and possibly sending additional information to the roadside, but the on-board equipment does not have the logic to request conditional priority. However, equipped vehicles can send additional information regarding their eligibility and level of the priority to support the decisions to grant priority.

The selection of the AVI or AVL technologies to detect transit vehicles or trucks for Scenarios 1-2, 1-3, and 1-4 is an important consideration in TSP and FSP implementation. Smith et al (2005) classified the detection technologies as hard-wired loop detection, light-based (infrared) detection, sound-based detection, radio frequency-based detection, and satellite (GPS) based detection (Smith, Hemily, & Ivanovic, 2005). They pointed out that the accuracy of the detection system is impacted by various factors such as environmental conditions, surrounding objects, and detector placement. Li et al. compared different technologies including AVI loop, optical/infrared (light-based) detection, wayside or radiofrequency reader detection, GPS with radio communications, and Wi-Fi technologies. The comparison is shown in Table 3-1 (Li, et al., 2008).

Table 3-1. Comparison of TSP Detection System

System	Costs			Customize ID & Data Format?	Potential Interface with AVL, schedule?	Tested & Proven Tech?	Central or Local System Typical Applications?	Requires Line of Sight?	Possible Additional Equipment for Implementation		Range	Jurisdictions using TSP detection
	Per Intersection	Per Bus	Operating / Maintenance						Additional Bus Hardware?	Additional Intersection Hardware?		
Smart Loops	$2,000, depends on local contractor	$250	Low (cost of loop)	No	Maybe	Yes	Both	No	Transmitter	Would likely need additional loops at each intersection (check-in/check-out)	Limited only by lead-in cable from loop to controller	Los Angeles; Chicago; Pittsburgh; San Mateo County, CA; Arlington Heights, IL
Optical	$3,500 for card and rack in cabinet $ 6,500 for site setup and installation	$3,000	$2,000 (emitter replacement) Not probable	No	Yes	Yes	Local	Yes	Optical Emitters	Optical detectors, phase selector for controller cabinet	2,500 feet under ideal conditions	Portland, OR; San Francisco; Tacoma; Kennewick, WA; San Jose; Calgary; Houston; Sacramento; Philadelphia; St. Cloud, MN; Salt Lake City; Alameda & Contra Costs Counties (CA)
Wayside or RF based	$35,000 - $40,000 includes mast arm poles for readers	$50 - $600	$50 (tag replacement), $1,000/year	Yes	Yes	Yes	Both	No	None	Roadside reader	Limited only by connection between wayside reader and controller, some readers may be able to detect up to a block away	King County, WA
GPS	$7,500	$5,000	No data available	Yes	Maybe	No	Both	No	GPS/ radio units	Radio receiver, phase selector	2,500 feet with no obstructions	Broward County, FL (emergency vehicle preemption only)
Wi-Fi	$5,000	$5,000 or less	Low	Yes	Yes	Yes	Both	No (may depend on antenna)	Wireless transmitter	Wireless receiver, bridging equipment	1 Mile +/- (Can be increased with additional access points)	Los Angeles County

Most existing TSP uses either AVI-based system or AVL-based detection. With the AVL-based detection, a beacon at the intersection receives messages from infrared (IR) radar or radiofrequency emitter installed on the vehicle. The messages can include additional information such as vehicle ID, vehicle classification, and vehicle priority level. GPS-based AVL systems can track vehicle movement and improves the ability to predict the arrival and departure of the vehicle at the intersection. Thus, the GPS-based approach has become a favorite approach to detection.

The AVI loops or “smart” loops can classify transit vehicles from general traffic using AVI technology that has a coded transmitter attached to the underside of the priority vehicle. The transmitter provides an antenna-based vehicle detection system integrated into a loop detector.

3.6.1.3 Scenario 1-3: Priority Decisions Fully Made at the Approaching Bus

With this option, the priority decision and associated level are made fully at the approaching truck or transit vehicle based on criteria such as fright shipment, truck schedule, truck weight, schedule adherence, ridership, etc. The advantage of this option is that more real-time information about the vehicle can be considered since all this information is available in the vehicle. However, there is a major disadvantage of this option in that it cannot consider other priority requests from other vehicles with different levels. In addition, it may not be able to consider real-time traffic conditions and signal timing in the decision. Thus, this option is not recommended in this study since it cannot accommodate setting different levels of priority.

Infrared light-based detection is among the widely used technology (see Figure 3-10). It includes an emitter on the vehicles, detectors mounted at or near the intersection, and a phase selector in the controller cabinet that implements the request for priority or preemption. This technology requires a line of sight between the emitter and detector. There may also be latency in receiving requests from the emitter and limited accuracy of detection range. The data transfer is also limited to an identification code. Thus, this technology is less preferred.

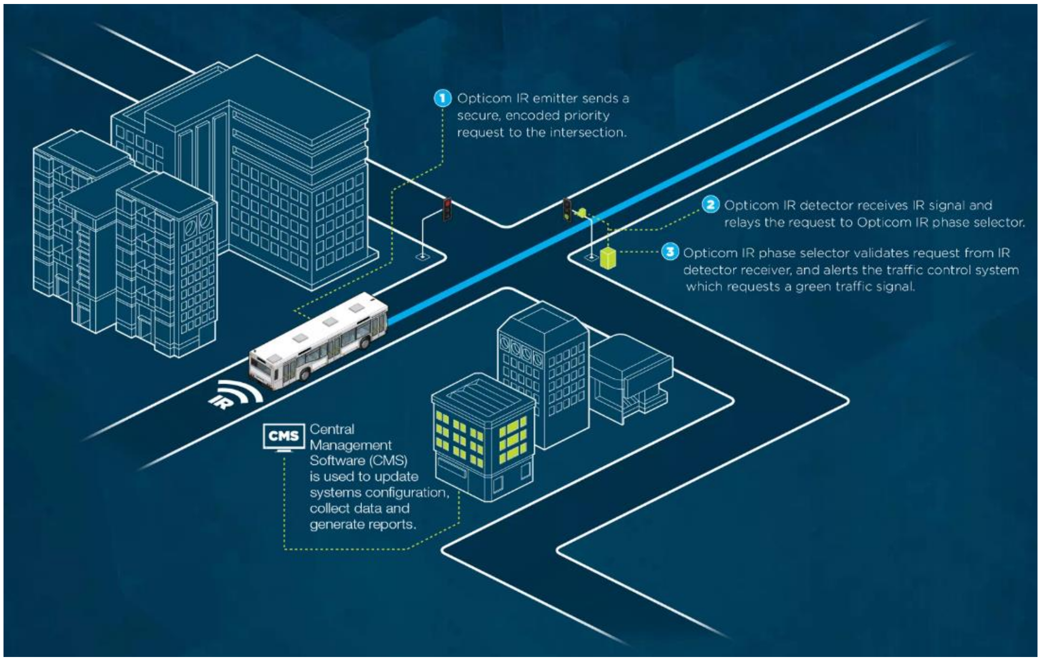


Figure 3-10. Opticom Infrared-based TSP (Source: https://www.gtt.com/)

The GPS-based communication system (Figure 3-11) uses on-board GPS receivers to determine vehicle position, direction, and speed. Communication from the vehicle to the signal controller utilizes radio communications. With this system, line of sight and visibility are not required for TSP detection and allows transmission of a large amount of data using wireless communications including automatic passenger counts and door open. It can also detect the vehicles leaving the intersection (checking out) to allow fast return to normal operations. The technology may suffer from the "urban canyon" effect with tall buildings preventing adequate TSP operations.

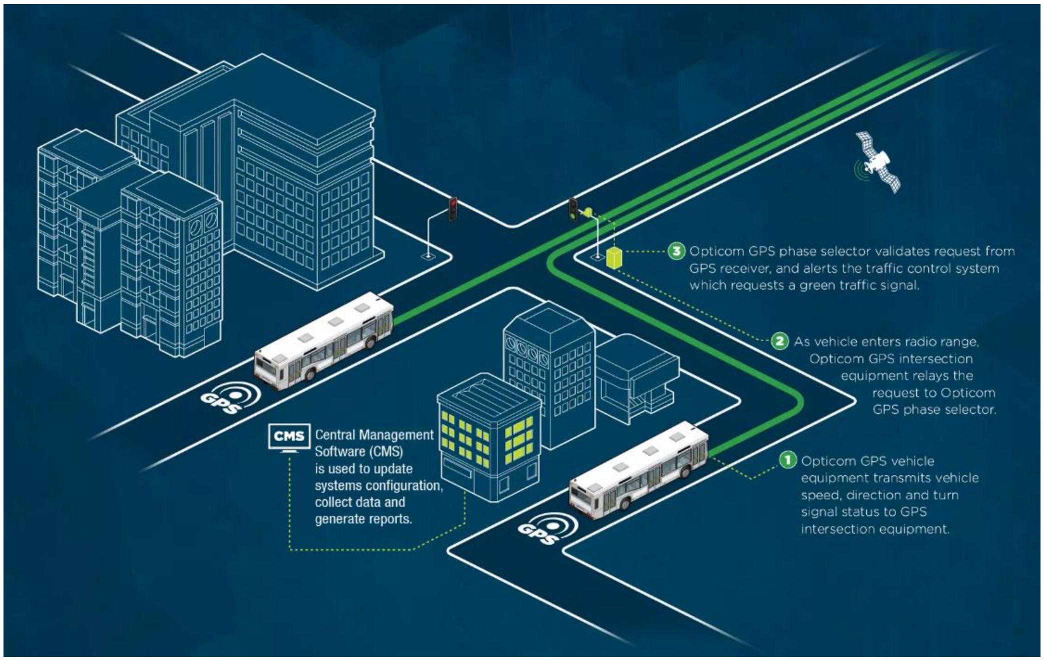


Figure 3-11. Opticom GPS-based TSP (Source: https://www.gtt.com/)

3.6.1.4 Scenario 1-4: Priority Decisions, Made at the Vehicle and Cabinet

This option considered a hybrid of the two options mentioned above. The transit vehicle only transmits input to the signal control system when it needs the priority and the hardware in the controller cabinet generates the request for priority, in a similar manner to Senario1-1. In this configuration, granting priority decisions are made at both the vehicle and the controller cabinet. Thus, it has the advantages of both scenarios 1-1 and 1-2. However, a limitation still exists is that the controller does not have access to some real-time information in the vehicle that can allow the priority application to better weight requests from multiple trucks and transit vehicles. In addition, the vehicle does not have access to the controller phasing and timing when making the decision to request priority. Such information can be used to determine the ability of the vehicle to break or to pass in yellow when it is in the dilemma zone. As stated earlier, some controllers also still cannot deal with multiple requests for priority and usually grant priority in a "first-in, first-out" fashion regardless of relative need.

3.6.1.5 Scenario 1-5: Advanced Priority Decisions, Made at the Vehicle and Cabinet Utilizing Connected Vehicle (CV) Technologies

This option is an extension of option 1-4 and utilizes connected vehicle technologies to exchange detailed real-time information between the vehicle and the CV allowing much more informed decisions regarding granting priorities considering signal timing and traffic conditions and in the presence of multiple calls with different needs for priority, as envisioned in the MMITSS application. An OBE on a vehicle in the communications range of the RSE begins to receive MAP and SPaT messages from the RSE and the RSE receives the BSM from the vehicle. The OBE determines the need and level of priority based on the safety and mobility impacts of not receiving the green as the vehicle approaches the intersection since the vehicle has access to the real-time signal phase and timing status. Based on this assessment, the OBE sends a priority request to the RSE with the priority level. The RSE makes decisions about the priority timing based on traffic conditions and the level of priority requested by the truck. Other advantages of this option are the ability to use CV roadside equipment for other safety and mobility applications and the support of the capability maturity of the agency with respect to the CV. The disadvantage is that this technology is new, and agencies have limited experience with it. This is expected to increase the cost of the implementation particularly as SPaT and MAP messages are transmitted from the infrastructure to the vehicles.

3.6.2 Scenario 2: Provision of Central Priority

As stated in the previous section, the distributed priority scenario requires additional equipment onboard the vehicles and on the roadside. Some agencies prefer a central type of priority that does not require additional infrastructure equipment. Depending on the requirement, no additional on-board devices may be needed if there is already an AVL system. Information such as vehicle location, speed, and schedule adherence can be transmitted. However, there may be latency in receiving requests from buses per their polling rate. To address this issue, priority messages should be given higher status. Real-time communication between the traffic, transit, fleet, and freight management centers will be required using industry standards.

3.6.2.1 Scenario 2-1: Priority Decisions, Made at Fleet Management Center

With this scenario, the decision about granting priority is made at the transit or freight management centers based on the real-time tracking of their vehicles utilizing AVL technologies like GPS. The requests are forwarded through center-to-center communications to the Traffic Management Center (TMC) central software that communicates the priority request to the local controllers. The central system can weigh inputs from multiple vehicles in the fleet that they are managing but not vehicles from other fleets. Thus, this option cannot handle simultaneous FSP and TSP. In addition, additional detailed real-time information from the vehicles and traffic conditions are not available to the decision-making process. An issue with all central-based system that needs to be examined is the resolution at which the transit vehicle locations are sampled by the AVL system versus the requirements. Thus, additional on-board equipment or communications may need to be considered for the vehicles.

3.6.2.2 Scenario 2-2: Priority Decisions, Made at Fleet Management Center and Traffic Control System

This is an extension of Scenario 1 since it also requires the fleet management center to make a decision to send a request to the traffic management center. However, the traffic management center software or the controller cabinet equipment will make the final decision of granting the priority based on the consideration of priority requests from vehicles that belong to other fleets (e.g., different transit agencies or truck fleets) and based on traffic conditions.

3.6.2.3 Scenario 2-3: Priority Decisions, Made at the Vehicle, Fleet Management Center and Traffic Control System

With this option, the first layer of the decision-making process is made at the individual vehicle level based on information on-board the vehicle. The priority request and associated level are then sent to the fleet management center for the second layer of decisions and then to the traffic management center for the third layer of decision. A variation of this option is that the vehicles of some of the fleets send the requests and associated information directly to software located at the traffic management center. This last variation was the option selected for implementation as part of the planning for a CV pilot project in Miami (Automating Florida’s Freight) that did not go to the implementation stage. Scenario 2-3 can take advantage of CV data in making the decisions by receiving SPaT and MAP messages in a similar fashion to Scenario 1-5.

Yet, another extension of this option is what is referred to as “Coordinated Freight Signal Priority along an Arterial,” which has been mentioned as a possible option with the CV-based MMITSS application. As with the basic FSP scenario, each of the equipped trucks determines the eligibility for priority and sends a request for priority. In this case, the TMC collects the requests for priority from connected RSEs, estimates the stop patterns for individual trucks, and provides green bands for trucks on a section of the arterial. Coordinated FSP control timing plans will be optimized on the section-to-section basis to best facilitate trucks’ movements along the arterial. The TSP application has been implemented in Utah and is being implemented and tested in New York CV pilot and lessons learned from that implementation can be used.

3.7 System Impacts

The provision of FSP and coordinating it with TSP can provide significant impacts that justify the changes recommended in this CONOPs. The slow accelerations from stops of trucks, particularly those with low power to weight ratio can have significant impacts on traffic capacity and time. Thus, reducing the stops of these trucks will have significant benefits. The required long distance to stop of trucks means longer dilemma zones for trucks and thus a high potential for crashes when the signals are changed to yellow. Green extensions can prevent these crashes. Truck stops can also result in increased pavement deteriorations. Reducing the idling of trucks at traffic signals can also impact air quality. From freight management and operator point of view, the impacts of traffic signals on mobility and reliability of travel time will have an impact on the cost of the transportation of goods and thus FSP can provide associated economic benefits. The TSP benefits in decreasing travel time and improving the reliability of transit vehicles are also well documented. This increased efficiency can even reduce the number of needed buses.

Hadi et al. based on an extensive review of TSP benefits estimated that the reduction in bus delay per intersection can range from 15 to 30 percent depending on the red time that the bus gets, which is a function of the congestion level in the system for the period under investigation. For cross-street traffic, the delay was estimated to increase by 6 percent during the peak periods and by 0 percent during the off-peak periods. In addition to reducing the person-hour of delay at the signalized intersection, the reduction in travel time of buses due to TSP can have a secondary benefit of decreasing the number of required buses for the same bus frequency (Hadi, Xiao, Ozen, & Alvarez, 2008).

A comprehensive TCRP report from 2010 on TSP provides a set of benefits ranges that may be experienced by an agency deploying TSP based on case studies from a few dozen cities. Transit travel time savings experienced were between 2 and 18 percent, with Los Angeles and Chicago observing 7.5 and 15 percent reduction, respectively. Overall, the implementing agencies indicated that the bus delay was reduced between 15 and 80 percent. Figure 3-12 shows ranges of benefits from selected entries in the ITS Knowledge Resource database at http://www.itsknowledgeresources.its.dot.gov/. Benefits of TSP systems include travel time savings, reduced delay for buses at intersections, and reduced emissions.

The target of the CV-based FSP and TSP presented in the MMITSS Concept of Operations document (University of Arizona, University of California PATH Program, Savari Networks, Inc., SCSC, Econolite, Kapsch, and Volvo Technology, 2012) are 27% for the average delay and 33% for variability in travel time. An assessment conducted for the USDOT indicated that the CV-based signal priority operations can improve connected bus travel times by 8.2 percent and connected truck travel times by 39.7 percent (Hatcher, et al., 2017).

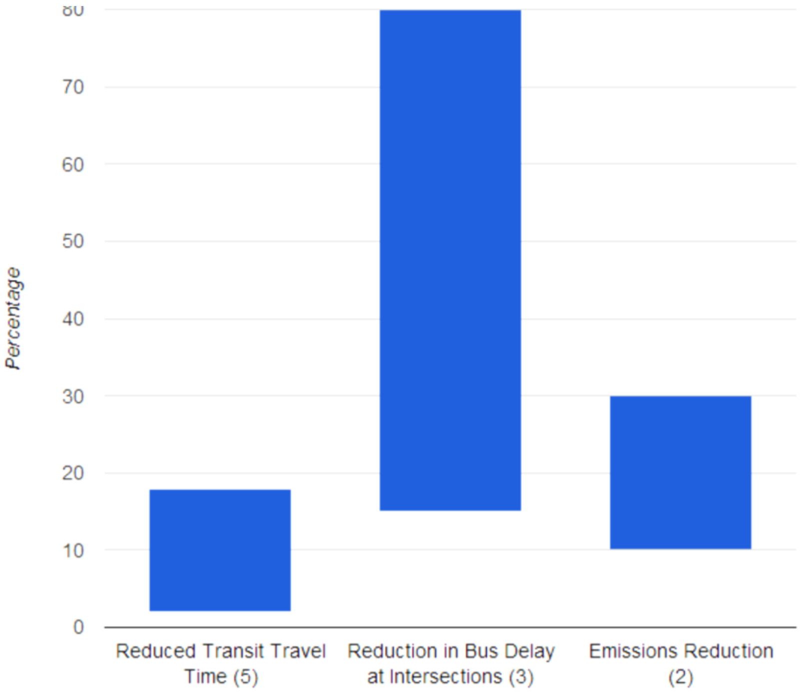


Figure 3-12. Benefits of Transit Signal Priority Systems

3.8 Constraints and Risks

There are a number of issues that have to be considered when planning and implementing FSP. Obviously, the main concern of traffic agencies is to ensure optimal operations for general traffic. Frequent FSP, sometimes combined with TSP and emergency vehicle preemption can result in some impacts on the cross street and left-turn movements. Thus, the operational scenarios of FSP will have to be assessed to assess these impacts if any.

The decision on a scheme to assign priorities to approach freight and transit vehicles should also be done with inputs from all stakeholders. Such a scheme should consider the impacts on general traffic, freight traffic, and transit. Moreover, a clear policy on prioritization needs to be established. The priorities may be different by location and time of day. Six of the eight central and distributed implementation scenarios can accommodate the simultaneous FSP and TSP with different priority levels to different degrees. Careful examination of these scenarios, associated technologies, performance, cost, and agency preference are essential.

An important aspect of the selection of the detection and communication technologies is the distance at which the transit and freight vehicles are detected. It is preferred that the detection be at a distance from the signal allowing better granting of priority. The preferred technology for TSP should also consider nearside bus stops and also should detect the vehicle leaving the stop line (referred to as checking-out).

The impact of a near-side transit stop on TSP should be carefully considered. If the TSP grants early green while the bus is boarding/alighting passengers, this service will be wasted. Relocating transit stops can be expensive. Thus, the TSP should account for this issue by having OBE to detect the opening and closing of transit vehicle doors before making a TSP call to the traffic controller.

4 Methodology

In this chapter, the developed methodology is thoroughly presented. The first part of the methodology includes a discussion of the case study selected for implementing the strategies and evaluating their impacts on the traffic networks, the process followed for the development of the microsimulation model and its calibration and validation on the PTV VISSIM platform, priority scenarios. The second section includes the preparation of guidelines involving the simulation network, calibration process, developed model, and finally the proposed guideline.

4.1 Evaluation of FSP and TSP in Urban Corridors

The scope of the project is to improve freight mobility, sustain good transit services and ensure no deterioration of the congested traffic conditions of the overall network. The implementation of the recommended priority strategies aims to achieve that goal. The process for efficiently developing the methodology of the study is first to explain in detail the problem. A suitable tool for resolving the already explained problem is identified through the literature review and the case study for implementing this tool is selected. Then, the method followed for solving the problem along with the results is analyzed. The flowchart of the developed methodology is presented in Figure 4-1 below.

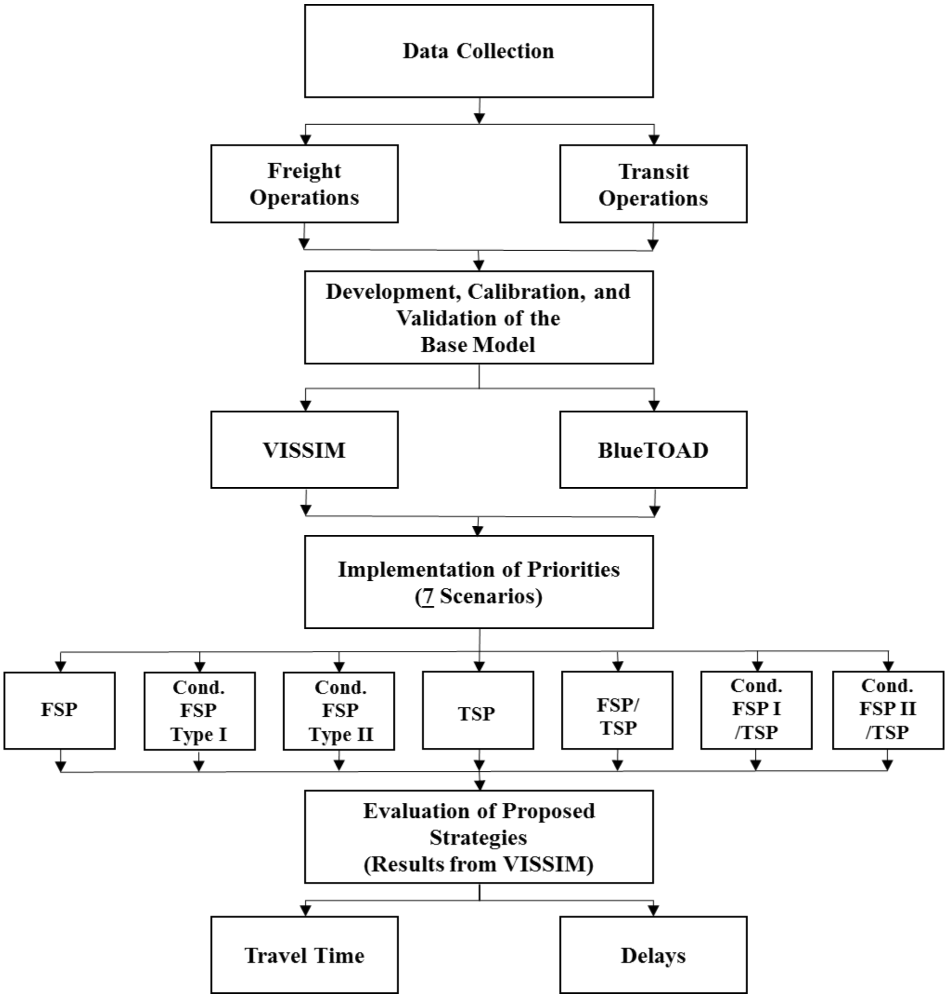


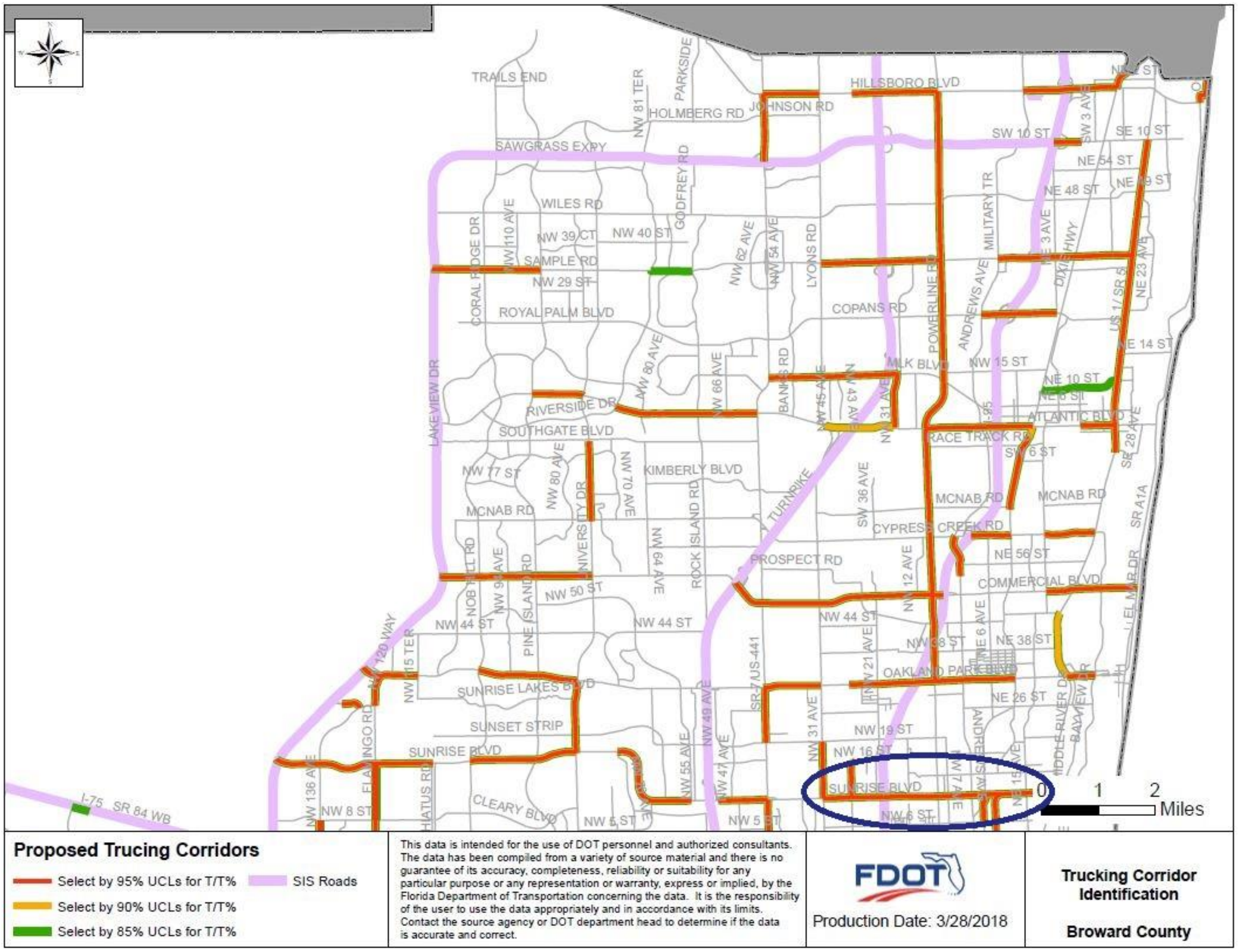
Figure 4-1. Methodology Flowchart

4.1.1 Case Study

The simultaneous implementation of the FSP and TSP strategies aims to relieve the congested conditions caused by trucks. Thus, for evaluating the efficiency of these two applications, the case study should be located on a highly congested corridor that facilitates increased truck and transit volumes at the same time.

In the state of Florida, there are areas that are facing augmented levels of congestion close to freight facilities, for example, close to ports and airports. One of the most congested counties in Southeast Florida is Broward County including the corridors that are close to the Fort Lauderdale – Hollywood International Airport and the Port of Everglades.

The above conclusion was reached after analyzing numerous Geographic Information System (GIS) maps provided by the FDOT. The GIS maps included the percentage of freight presence along with the corridor segments for each County in the State of Florida. By comparing the provided maps, Broward County was selected for further investigation. Figure 4-2 below is a GIS map presenting all the corridor segments on Broward County and the percentage of the freight movements observed on them. This map was utilized for identifying the most suitable corridor segments for implementing the FSP and TSP technologies regarding the freight movements.



This data is intended for the use of DOT personnel and authorized consultants. The data has been compiled from a variety of source material and there is no guarantee of its accuracy, completeness, reliability or suitability for any particular purpose or any representation or warranty, express or implied, by the Florida Department of Transportation concerning the data. It is the responsibility of the user to use the data appropriately and in accordance with its limits. Contact the source agency or DOT department head to determine if the data is accurate and correct.

Figure 4-2. Trucking Corridor Identification - Broward County (Source: FDOT)

The problematic traffic conditions in the areas close to the ports appear to be affected by the increased volumes of trucks around these areas that are responsible for moving the cargo from or to the port and to or from the airport and the distribution centers that are located in the west part of Florida. Figure 4-3 below shows the geographic location of Broward County on the State of Florida.

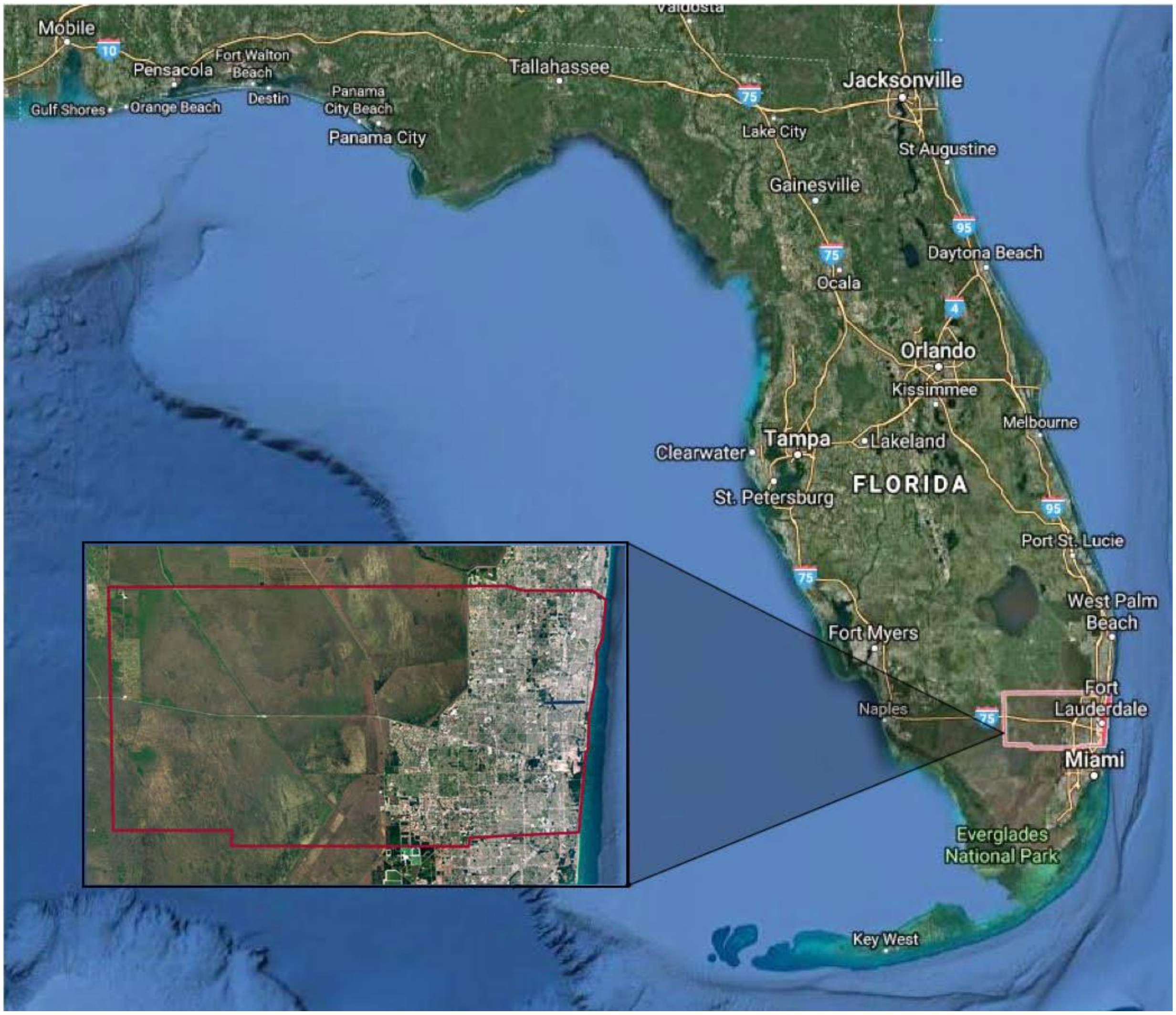


Figure 4-3: Location of Broward County on the State of Florida (Source: Google Maps)

4.1.1.1 Sunrise Boulevard

The case study selected for the implementation of the FSP and TSP strategies is a congested multimodal corridor in the city of Fort Lauderdale, in Broward County. State Road 838 (SR 838), or Sunrise Boulevard, is a 10.2 miles corridor that extends from east to west crossing the cities of Plantation and Fort Lauderdale in central Broward County. The limit of the corridor on the west is with the Sawgrass Expressway (SR 869) and in the east with North Ocean Boulevard (SR A1A).

The most important intersections that are crossing Sunrise Boulevard are the State Road 817 (University Drive), State Road 91 (Florida's Turnpike), State Road 7 (US 441), State Road 9 (I-95), State Road 845 (Powerline), State Road 811 (NE 4th Avenue), US 1, and Sunrise Boulevard Bridge over the Atlantic Inter-coastal Waterway and State Road A1A. The geographic location of Sunrise Boulevard on Broward County is presented in Figure 4-4.

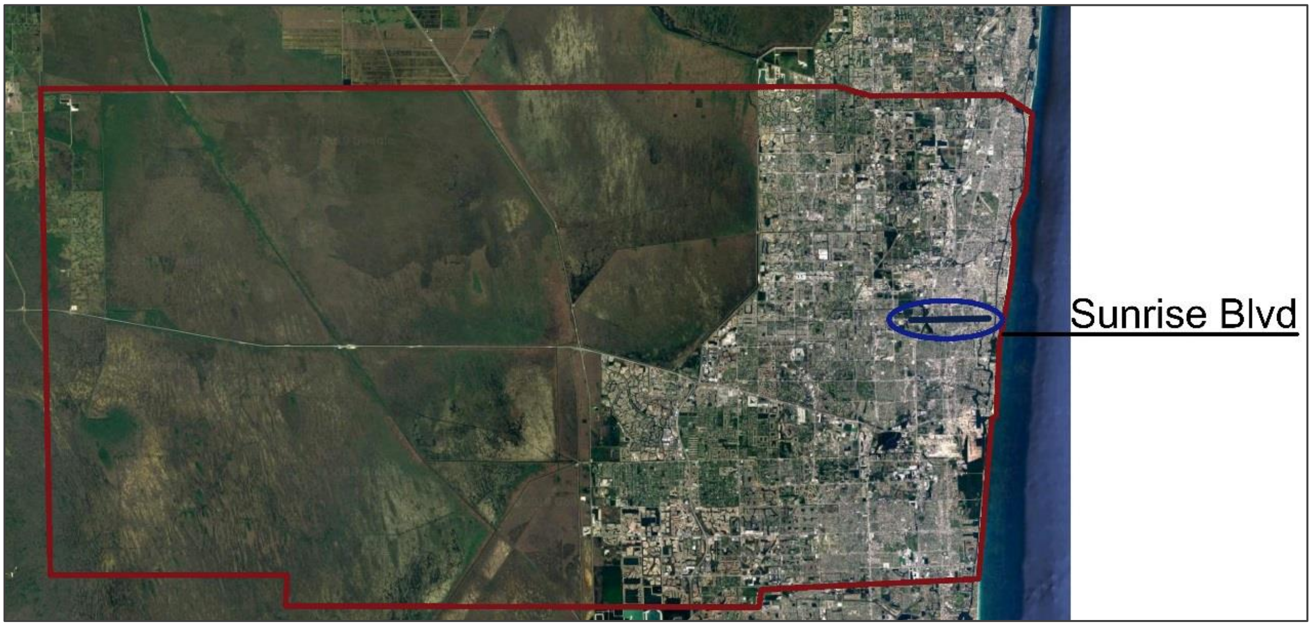


Figure 4-4: Geographic Location of Sunrise Boulevard (Source: Google Maps)

For this study, the limits of Sunrise Boulevard, which is considered as the studied corridor, are from NW 31st Avenue until North Federal Highway. This corridor is 4.4 miles long and consists of 22 signalized intersections, with two of these intersections to serve only pedestrian movements. The operations of the signalized intersections along the corridor are coordinated. Both eastbound and westbound directions consist of three lanes, while in a short segment near the interstate I-95, the number of lanes increases to four lanes per direction. Figure 4-5 provides the location of all the signalized intersections studied for this research project.

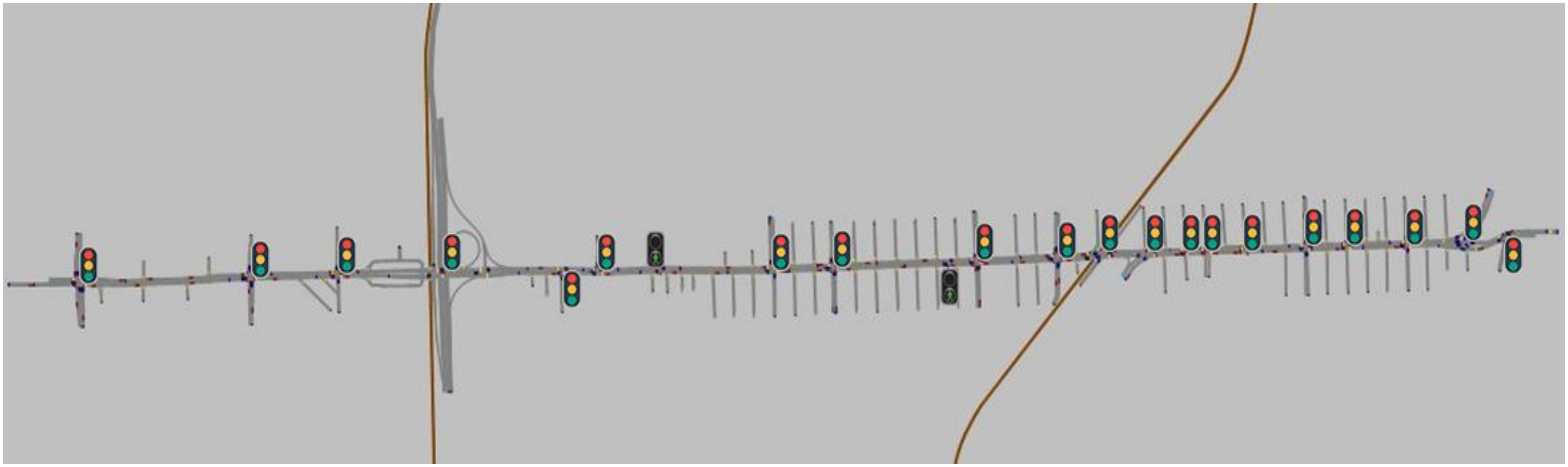


Figure 4-5: Segment of Sunrise Boulevard Studied

4.1.2 Freight Operations

The freight movements along Sunrise Boulevard corridor are relatively heavy throughout the day. The main reason for high truck volumes is the connection this corridor provides between the Port of Everglades and the distribution centers in Broward County. The Port of Everglades operates 24 hours and is considered the biggest container port in Florida, with the highest number of freight movements. A portion of the port's cargo is distributed by train, but the number of freight trucks is also high. Most trucks are directed towards the middle part of Florida, where most of the warehouses and distribution centers are located. Thus, Sunrise Boulevard, along with its parallel roads, facilitates a high number of truck movements that are higher than a normal truck volume for an urban area.

In addition, the location of the Fort Lauderdale – Hollywood International Airport in Broward County is a determinant factor in justifying the existence of high truck volumes around the area. The airport is managing a high number of cargos daily and the distribution of the products from and to the airport is mainly based on the operations of trucks. This concludes the surrounding area and arterials connected to the airport are facing daily heavy traffic caused by the freight vehicles movements, necessary though for the efficient operations of freight transportation.

4.1.3 Transit Operations

Broward County Transit (BCT) oversees operating the transit movements for Broward County area. The agency provides fixed route bus, express, and community shuttles and paratransit services in Broward County. They also connect the county with the Miami-Dade and Palm Beach Counties. Along Sunrise Boulevard corridor, there are 5 bus lines operating in each direction and 10 bus lines are crossing the corridor.

The bus lines included in the case study are 5 that are operating along the segment corridor. On weekdays, the studied buses' headways vary from 20-35 minutes, depending on the time of the day. Figure 4-6 shows the system map of the studied transit lines in Broward County.

The bus lines included in the study are the following:

i. Route 10, Broward Central Terminal to Camino Real and Dixie Highway

ii. Route 14, Broward Central Terminal to Hillsboro Boulevard via Powerline

iii. Route 20, Broward Central Terminal to Northeast 3rd Avenue and Sample Road

iv. Route 31, Broward Central Terminal to Hillsboro Boulevard and Lyons Road via Northwest 31st Avenue and Lyons Road

v. Route 36, from Sawgrass Mills Mall to Sunrise Boulevard and A1A via Sunrise Boulevard

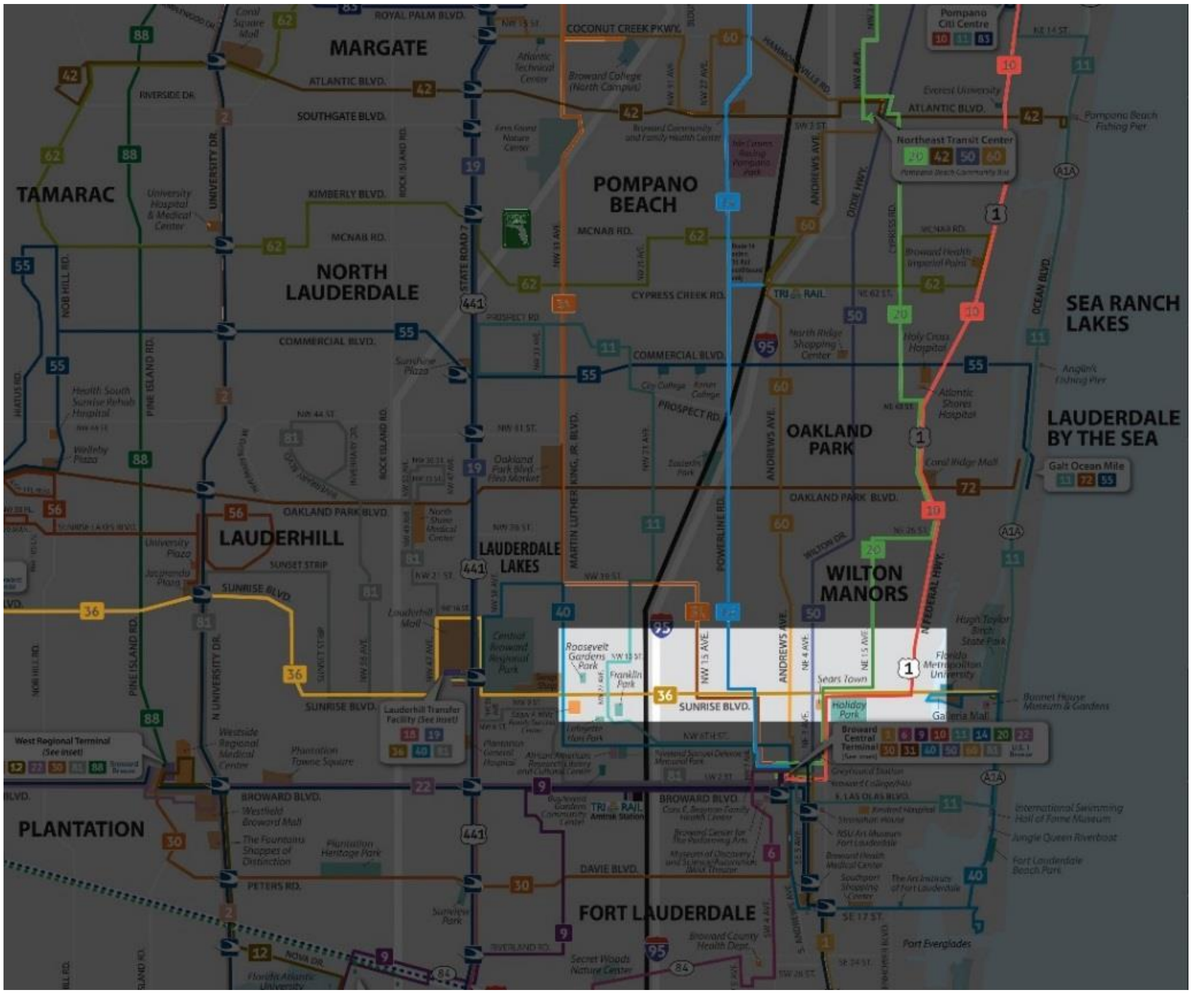


Figure 4-6: Bus Lines Included on the Case Study (Source: Broward County Transit)

4.1.4 Microsimulation Model

In this section, the description of the development of the microsimulation model is presented. The topics that will be discussed are the utilized data, simulation characteristics, calibration and validation procedures, base case design, and the FSP-TSP scenario designs. The test procedure and results are discussed in the next chapter.

4.1.4.1 Microsimulation Software

PTV VISSIM is a standard multi-modal traffic flow simulation software package developed by PTV Group in Germany. It was firstly developed in 1992 and today it is one of the world's leading software packages providing simulation technology to support the planning and optimization of the movement of people and goods. PTV VISSIM is a simulation platform that allows users to simulate real traffic conditions. Through this software, the users can map a network and model different geometries that will present a realistic and detailed overview regarding the traffic flow and its impacts.

In addition, PTV VISSIM allows the microscopic, mesoscopic, or even a combination of both in a hybrid simulation. It is designed to include motorized private transport, goods transport, rail, and road-related public transport, pedestrians and cyclists. This provides to the experts the opportunity to analyze the interaction of different transport modes in one model, compare the junction geometries, and analyze public transport priority schemes or the effects of different signal patterns.

One major advantage of the PTV VISSIM is its flexibility regarding the geometry of the model from simple intersections to ones that are more complex or the application of numerous traffic patterns and different characteristics of road users. Also, the software provides the ability to the user to use the generic COM interface for interacting with external applications.

4.1.4.2 Model Development

The first step before starting to develop the model utilizing the simulation platform was to gather the necessary data for the geometry of the corridor, the traffic operations, and the traffic control system. The data related to the geometry of the corridor were collected from aerial photos, on-site field observations and with the use of Google maps.

The traffic operational data included traffic volumes for the main and the side roads, turning movement counts, individual speeds for different transport modes, lane usage, and signal plans for each signalized intersection during the day were obtained from Broward County. The data related to the transit operations along Sunrise Boulevard were collected based on field observations and from the Website of Broward County's transit system. Figure 4-7 presents a sample of the turning movement counts data for a weekday for all four directions of the signalized intersection of Sunrise Boulevard and NW 9th Avenue.

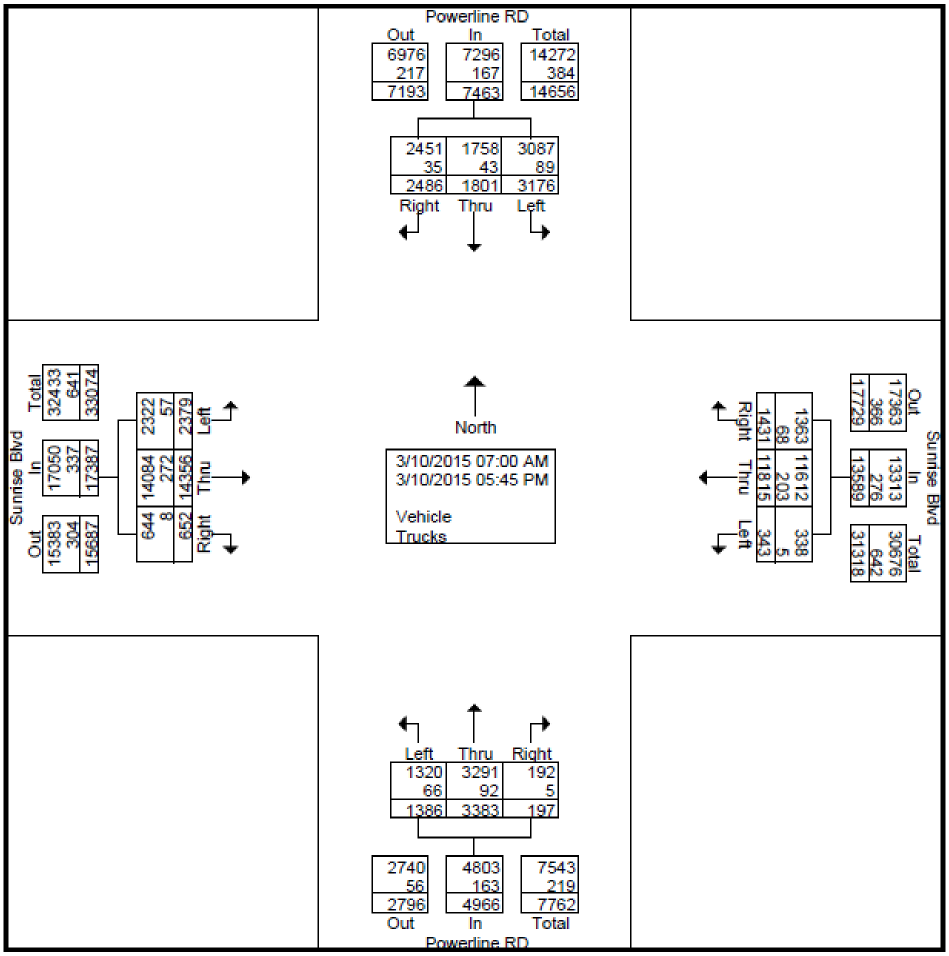


Figure 4-7. Turning Movement Counts for Sunrise Boulevard and NW 9th Avenue (Source: FDOT)

Furthermore, a VISSIM model of Sunrise Boulevard was provided by the FDOT for the A.M. peak hour. The model was used as an initial starting point for the effort in this study and then adjusted to the case study's limits and its calibration and validation were readjusted to imitate the reality. The most current data provided by the state agencies were also updated in the model.

In addition, the focus of the project was the freight mobility improvements, thus further attention was given to replicate the freight characteristics of the model as realistically as possible. The calibration process considered the truck lengths and their weight, power, acceleration, and deceleration distributions. The trucks' speed distribution, the following distance and the lane and lateral change were some additional variables that were adapted to efficiently imitate the real truck traffic conditions. The proper values for all the truck characteristics that were modified in the model were extracted from the Highway Capacity Manual (HCM) (Highway Capacity Manual: A Guide for Multi-Modal Mobility Analysis, 2016), FHWA website (Federal Highway Administration , n.d.), National Cooperative Highway Research Programs (NCHRP) (National Cooperative Highway Research Program, 2003), and the Florida Department of Highway Safety and Motor Vehicles (FLHSMV) (Florida Department of Highway Safety and Motor Vehicles, 2016).

All the characteristics of trucks were organized on 9 individual vehicle classes by the FHWA. Each FHWA vehicle class corresponds to specific types of trucks with specific dimensions that have different average weight, length, power, and weight to power ratio. The types of trucks represented by the FHWA vehicle class are presented in Table 4-1.

Table 4-1. Federal Highway Administration (FHWA) Vehicle Classification

FHWA Vehicle Class	Vehicle Classification
5	2-Axle, Single Unit Trucks
6	3-Axle, Single Unit Trucks
7	4-Axle, Single Unit Trucks
8	2-Axle Tractor W / 1 or 2-Axle Trailer / 3-Axle Tractor
9	3-Axle Tractor / 2-Axle Trailer
10	3-Axle Tractor / 3-Axle Trailer
11	5-Axle Multi-trailer
12	6-Axle Multi-trailer

Figure 4-8 presents the image of each individual truck vehicle class along with the rest of vehicle classes existing in all traffic networks.

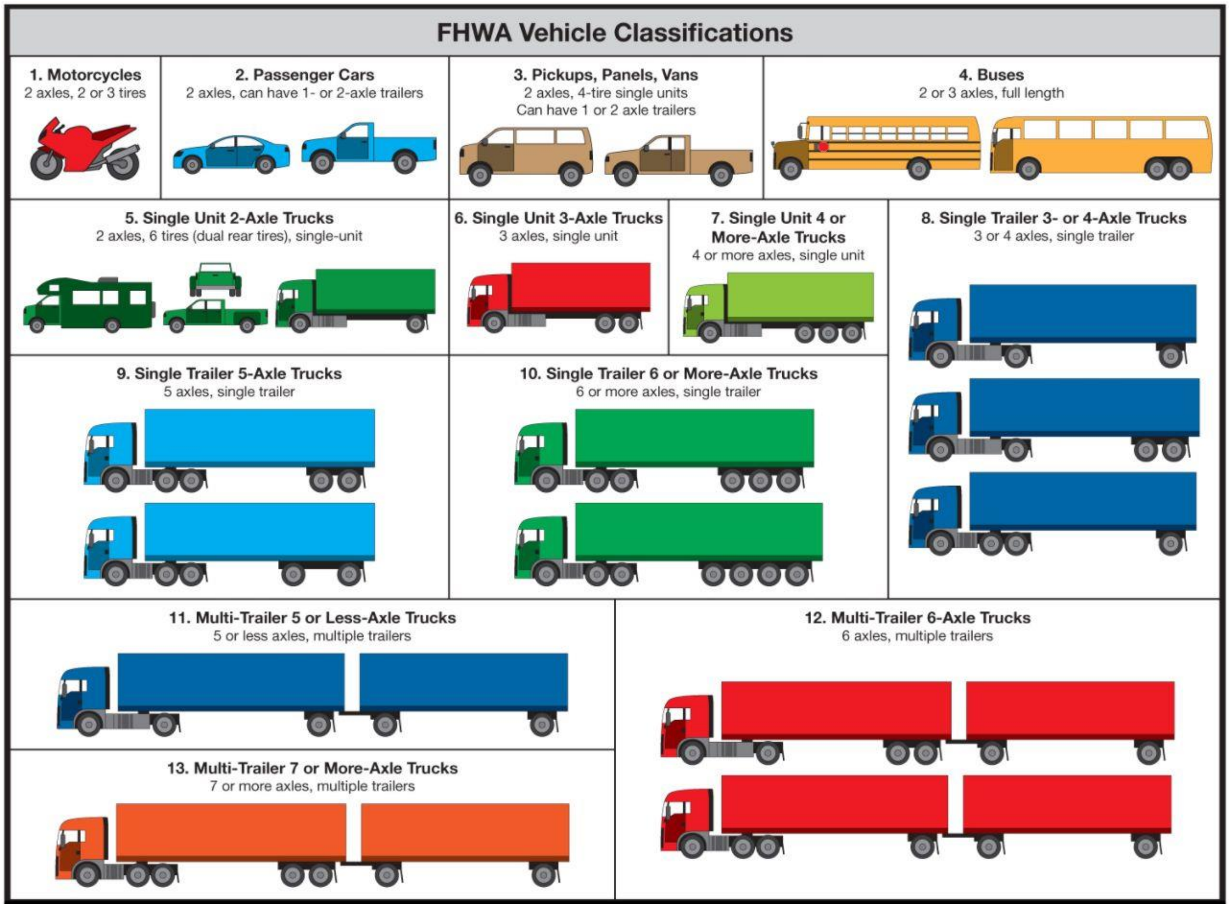
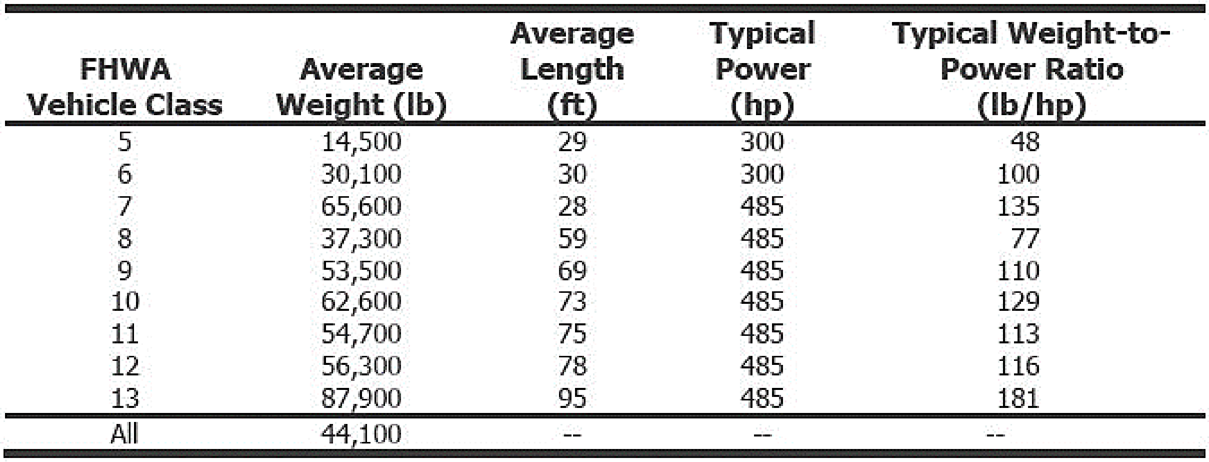


Figure 4-8: Vehicle Classification (Source: FHWA)

The trucks' characteristics for each type of truck were gathered and distributed into the individual FHWA vehicle classifications by the Federal Highway Administration. The variables gathered were the average weight, average length, power and weight to power ration and they are listed in Table 4-2 below.

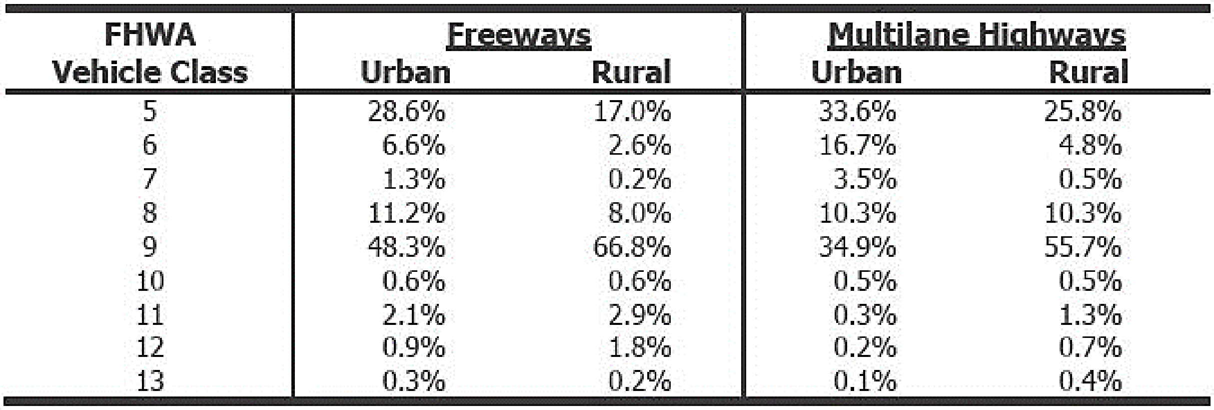
Table 4-2: Characteristics of Trucks by FHWA Vehicle Class - Florida (Source: FHWA)



FHWA Vehicle Class	Average Weight (lb)	Average Length (ft)	Typical Power (hp)	Typical Weight-to-Power Ratio (lb/hp)
5	14,500	29	300	48
6	30,100	30	300	100
7	65,600	28	485	135
8	37,300	59	485	77
9	53,500	69	485	110
10	62,600	73	485	129
11	54,700	75	485	113
12	56,300	78	485	116
13	87,900	95	485	181
All	44,100	--	--	--

Finally, the percentage of trucks that are moving along an arterial corridor, depending on the different truck FHWA vehicle classes, were included in the model. Table 4-3 presents the trucks' percentages calculated by the Federal Highway Administration (FHWA) for the State of Florida. The percentages differ depending on the geometry and purpose of the road (freeways and highways) and on the location of the study (urban or rural area). In this case study, the multilane highway for urban areas was the most suitable selection for representing the traffic network on Sunrise Boulevard.

Table 4-3: Percentage of Trucks by FHWA Vehicle Class - Florida (Source: FHWA)



FHWA Vehicle Class	Freeways		Multilane Highways	
	Urban	Rural	Urban	Rural
5	28.6%	17.0%	33.6%	25.8%
6	6.6%	2.6%	16.7%	4.8%
7	1.3%	0.2%	3.5%	0.5%
8	11.2%	8.0%	10.3%	10.3%
9	48.3%	66.8%	34.9%	55.7%
10	0.6%	0.6%	0.5%	0.5%
11	2.1%	2.9%	0.3%	1.3%
12	0.9%	1.8%	0.2%	0.7%
13	0.3%	0.2%	0.1%	0.4%

In the current research project, the vehicle classes were organized into 5 different categories based on their length and characteristics and then they were added in the microsimulation model along with all their characteristics previously analyzed. The categorization was done considering the low percentage of the two last vehicle classes, the similarity on the characteristic of some classes, and for conveniently handling the model. The new truck categories are presented in Table 4-4 below.

Table 4-4: Truck Categories Implemented in the Microsimulation Model

Truck Categories	FHWA Vehicle Classes
HGV1	5
HGV2	6
HGV3	8
HGV4	9
HGV5	7, 10, 11, 12, 13

4.1.5 Calibration – Validation

A significant component of the microsimulation model is the calibration and validation process. According to the FHWA guide (Federal Highway Administration, 2017), calibration is defined as the adjustment of computer simulation model parameters to accurately reflect prevailing conditions of the roadway network. The most common calibration parameters of microscopic simulation models are driver lane changing aggressiveness, car-following behavior, lane change gap acceptance, route choice, vehicle speed distributions, and vehicle acceleration distributions.

Validation is defined as the process of comparing the simulated model results with field measurements in order to determine the accuracy of the simulation model. The most commonly used validation parameter is travel time, speed, queues and/or delays. After the completion of the calibration and validation procedures, the model is considered ready for use, since it replicates the real traffic conditions of the network. More specifically, the users at that point can include their own scenarios and implement them on the model depending on the objective of their research.

In the current project, the first phase of the calibration – validation procedure focused on adjusting the characteristics of the automobile, mostly the driving behavior parameters, acceleration, and deceleration distribution and speed distribution. At that point, the validation of the model was based on travel-time data estimated based on Bluetooth reader measurements.

The utilized Bluetooth reader product was the Bluetooth Travel-time Origin and Destination (BlueTOAD), developed to measure the vehicle's travel time with the use of non-intrusive roadside technology. The BlueTOAD system aims to detect anonymous Bluetooth signals broadcast from mobile devices to determine accurate travel times and speeds and calculates travel times and speeds in real-time to provide route management capabilities. Figure 4-9 presents the two most commonly used types of the BlueTOAD systems.

Figure 4-9: Types of the BlueTOAD System (Source: www.trafficcast.com)

Usually, the BlueTOAD system is located along a corridor in a predefined way, in order to measure the travel time from the middle of a signalized intersection until the middle of the following intersection. Thus, the location of the vehicle travel time measurements in the microsimulation model was selected based on the BlueTOAD locations on the corridor.

Finally, the field data collected by the BlueTOAD system were compared with the travel time measurements resulted resulting from the microsimulation model. After matching the model results with the field data measurements by readjusting the truck and vehicles' variables mentioned above, the procedure was completed. The calibration – validation process was finalized, and the base model was completed, replicating the current traffic conditions of Sunrise Boulevard.

4.1.6 Development of Priority Strategies

Once the simulation model was successfully calibrated and validated based on the procedure and data presented in the previous section, different priority scenarios were developed and implemented. The two most utilized ways for implementing the Active Freight and Transit Signal Priority strategies are through green extension and red truncation (early green), as stated earlier.

The green extension strategy extends the duration of the green light for the movement assigned to be favored to be able to cross the signalized intersection. Contrarily, the red truncation strategy appears when the light is red for the approaching priority vehicle, so the strategy shortens the duration of the green time for the rest of the phases, aiming to provide the green light by the time that priority vehicle will reach the intersection. In order to implement the priority strategies in the simulation model, it was necessary to make numerous adjustments to the signal controller such as cycle length, signal timings, and adding detection systems for sensing the approach of the priority vehicle and to activate the appropriate strategy.

4.1.6.1 Detection System

In the simulation study, the technology utilized for detecting the buses and the trucks were point detectors for the check-in and check-out of the priority vehicles. However, in the real world, the check-in and check-out can be accomplished using any other technology as reviewed earlier in this document. In the model, the detectors were placed along Sunrise Boulevard before and after the traffic signals of each signalized intersection. The check-in detectors were activated when the truck or the bus passed above them, and they were placed before the intersection for sending the message that a priority vehicle was arriving at the intersection. The check-out detectors were placed exactly after the signal stop bar in order to assure that the truck or bus has crossed the intersection.

A sensitivity test of the microsimulation model was conducted aiming to identify the optimal location for the check-in detectors. For the truck movements, the average speed was around 30 mph. The needed time for the truck to reach the intersection on green regardless of the priority strategy (early green or green extension) was calculated to be approximately fifteen seconds. The optimal location of detectors was around 660 feet (30 mph*1.47*15sec) upstream of the stop bar of the intersection.

The procedure for the buses was the same, but the speed, in that case, was set to around 25-30 mph. The location of detectors was around 500 feet (25-30mph*1.47*15sec) from the upstream stop bar of the intersection. In case there was a bus stop between the location of the detector and the signal head, the transit detectors were in the vicinity of the bus stop and the travel time for reaching the upstream stop bar of the intersection was adjusted accordingly. Figure 4-10 is a capture from the PTV VISSIM model, showing the location of the check-in and check-out detectors near an intersection for the TSP strategy, as described in this section.

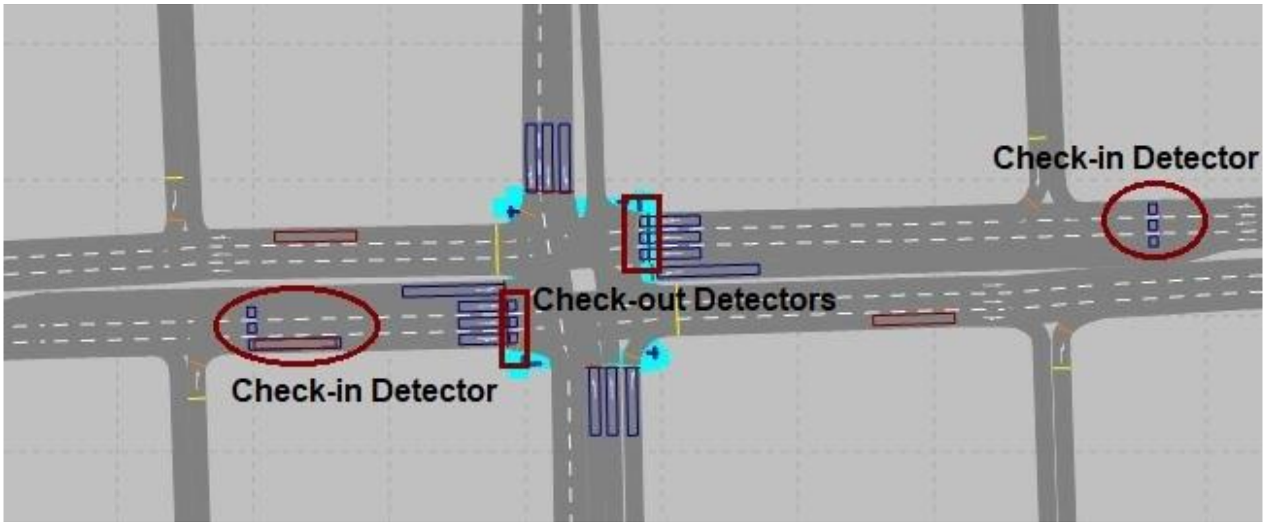


Figure 4-10: Check-in and Check-out Detectors on PTV VISSIM Microsimulation Model

4.1.6.2 Signal Timing Adjustments

Apart from the detection system needed to be installed in the model in order to sense the movements of the priority vehicles, numerous adjustments were necessary to the signal controller in the model. The current study used Ring Barrier Controllers (RBC) for coordinating the signal phases and patterns.

On the RBC file, there was a separate section for the user to add the necessary data for implementing a priority strategy. A new transit or freight signal group that operates in the priority mode was created in the RBC. When this priority signal group was enabled, the signal controller reorganized the duration of the phases and adjusted the operations of the signal groups in order to provide to that priority signal group a green light as soon as the transit or freight vehicle approached the intersection.

While the priority signal group was enabled, the conflict movements were usually abbreviated based on various parameters. After the termination of the priority signal group, the signal controller was in the recovery process. Then the signal controller returned all the signal groups to their original coordinated operations. Figure 4-11 provides an example of a maximum priority extension for coordinated signals along with the recovery process. The figure presents the operation of the signal groups in a normal cycle and then how the priority signal group affects the duration of the rest of the groups, before returning to its initial coordination.

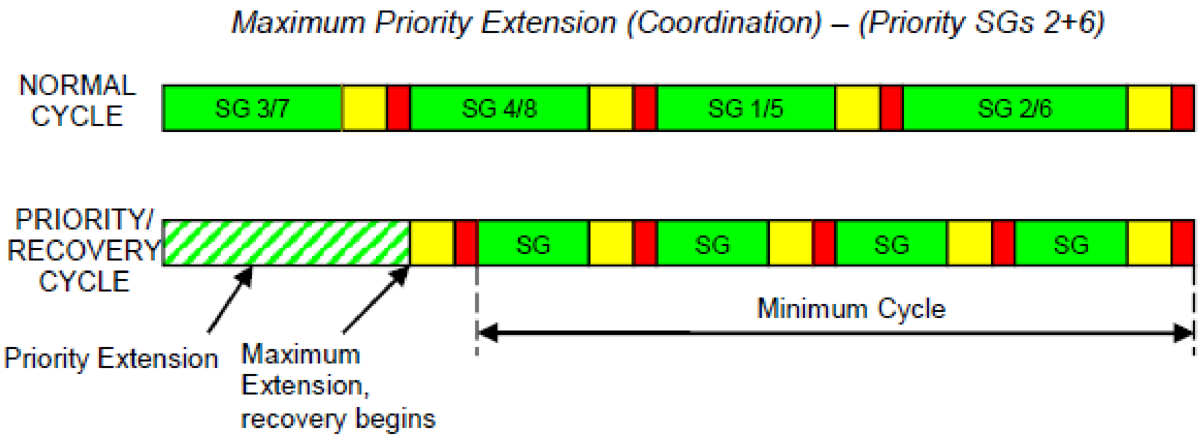


Figure 4-11: Maximum Priority Extension – Coordination (Source: RBC Manual – PTV VISSIM)

In addition, in order to create a new priority signal group, numerous necessary steps needed to be followed. Each movement of the priority signal group was attached to the corresponding initial signal group, called parent signal group since they were the ones that needed to be the timing for the priority to time. The configuration of the priority signal group and the parent group are presented in Figure 4-12.

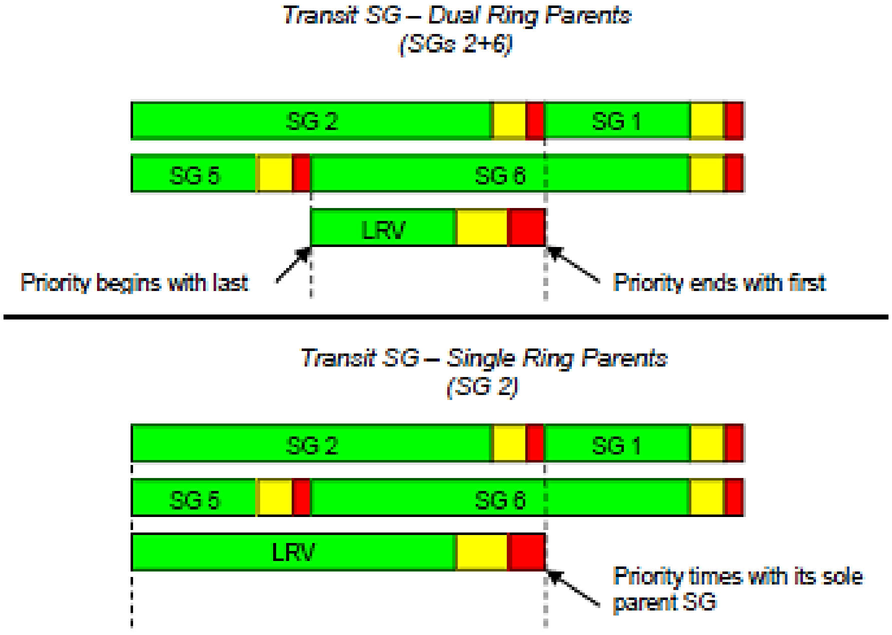


Figure 4-12: Priority Signal Group and Parent Signal Group Configuration (Source: RBC Manual – PTV VISSIM)

Regarding the conflict signal groups, their timing would not begin until the priority has completed timing its clearance intervals. The signal groups that needed to omit during the priority operations were added during the procedure of the development of the priority signal group.

In general, numerous parameters are included on the RBC file aiming to assist the successful operations of the priority requests, but they are not all mandatory to be adjusted on every research project. In that case, the additional parameters that needed to be adjusted on the RBC file for successfully implementing the priority strategies were the Travel Time and the Travel Time Slack.

The travel time referred to the estimated time that the priority vehicle needed in order to arrive at the intersection starting from the detection point. This value provided to the signal controller the ability to adjust the remaining phases for accommodating the priority call. The travel time slack was developed to include the uncertainty of the arrival time of the priority vehicle to the intersection. The value of the travel time slack was added to the travel time parameter. In Figure 4-13, it is visible the physical hypostasis of travel time and the travel time slack parameters as applied on the phases of the cycle.

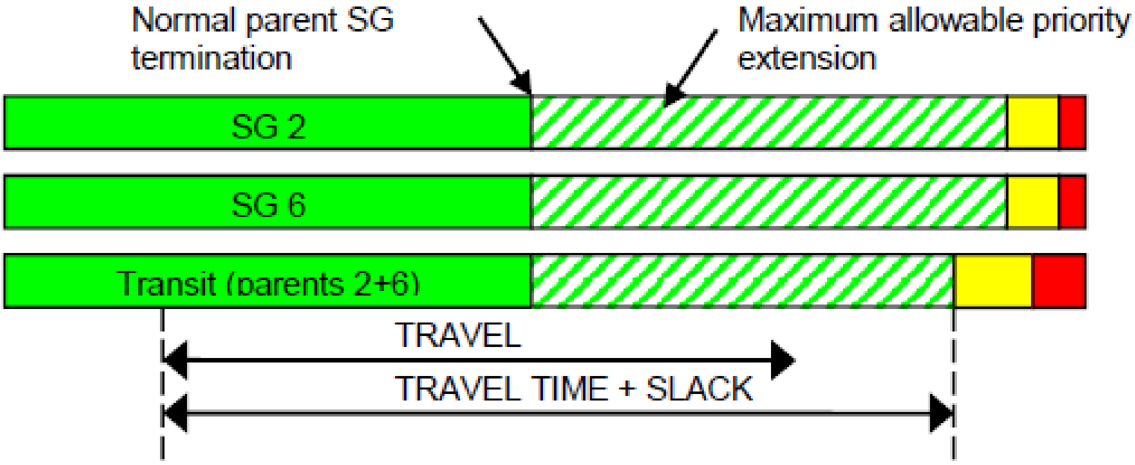
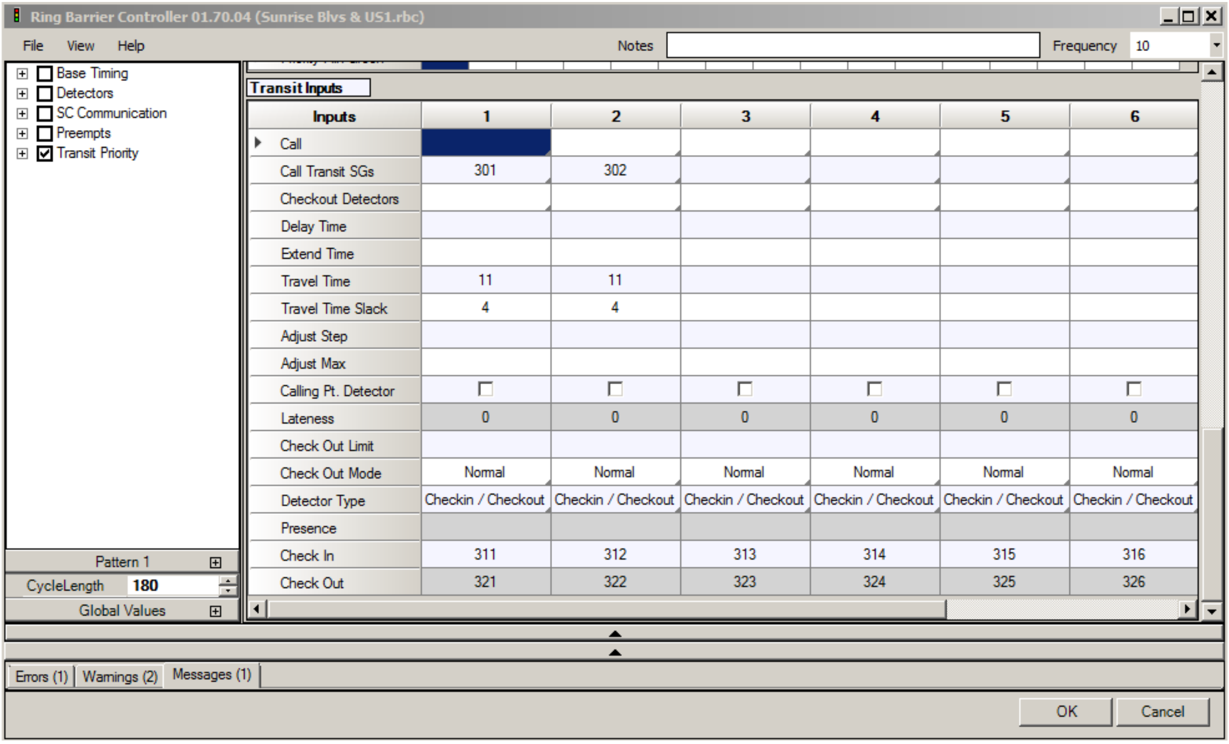


Figure 4-13: Travel Time and Travel Time Slack (Source: Manual RBC – PTV VISSIM)

Finally, the Check-in and Check-out detectors were assigned to a specific priority movement, in order to send the request for priority to the signal controller and then ensure that the priority vehicle has crossed the intersection. Figure 4-14 shows the travel time, travel time slack parameters and the detectors on the RBC file.



Frequency 10

- ☐ Base Timing
- ☐ Detectors
- ☐ SC Communication
- ☐ Preempts
- ☑ Transit Priority

CycleLength 180

Inputs	1	2	3	4	5	6
Call						
Call Transit SGs	301	302				
Checkout Detectors						
Delay Time						
Extend Time						
Travel Time	11	11				
Travel Time Slack	4	4				
Adjust Step						
Adjust Max						
Calling Pt. Detector	☐	☐	☐	☐	☐	☐
Lateness	0	0	0	0	0	0
Check Out Limit						
Check Out Mode	Normal	Normal	Normal	Normal	Normal	Normal
Detector Type	Checkin / Checkout	Checkin / Checkout	Checkin / Checkout	Checkin / Checkout	Checkin / Checkout	Checkin / Checkout
Presence						
Check In	311	312	313	314	315	316
Check Out	321	322	323	324	325	326

Figure 4-14: Priority Parameters on the RBC File from the PTV VISSIM Software

4.1.7 Priority Scenarios

4.1.7.1 Base Scenario

The base scenario was the basic scenario created in this study, which provided an emulation of the current traffic conditions of the network. The base model aimed to provide a general idea of the operation of the corridor and the interaction and impact of trucks and buses to the rest of the vehicles. In addition, it was important to examine the most problematic and congested signalized intersections that affect the smooth operations of vehicles and identify the reasons that caused these conditions.

The model was considered the most crucial of all the models developed on the project since the development of the rest of the scenarios was based on it. The extended focus was given to successfully imitate the field conditions by analyzing the calibration and validation procedures. The efficiency of the priority scenarios was also based on the comparison of the base model with each scenario individually.

Thus, the identification of the black spots of the current traffic conditions through the observation of the base scenario was significant for the process of analyzing the results of the priorities. The running period for this model was one hour with a warmup period of 15 minutes and it replicated the morning peak hour. Figure 4-15 is a caption of the base model extracted from the PTV VISSIM software.

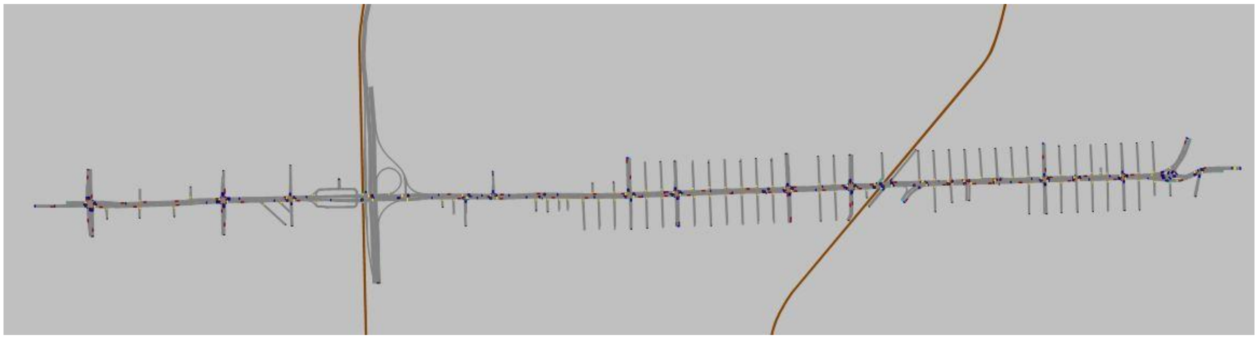


Figure 4-15: Base Model from the PTV VISSIM Software

4.1.7.2 SCENARIO I – Freight Signal Priority

The first step before implementing simultaneously the FSP and TSP strategies was to implement each strategy individually, in order to evaluate their impact on the corridor and try to provide smoother traffic conditions. The first scenario focused on the successful implementation of the Freight Signal Priority strategy, aiming to improve freight mobility along Sunrise Boulevard. The truck priority was applied in the microsimulation model, as described earlier. The procedure followed for implementing the FSP scenario was identical to the commonly used procedure of the TSP strategies.

The check-in detectors were adjusted to detect only the truck movements. They were placed before each signalized intersection, further from the intersection, depending on the allowed speed before each signalized intersection and the dynamics of the freight vehicles. After the truck detection, a message was sent to the simulated signal controller of the intersection they were approaching. Once the simulated signal controller received the priority request from the check-in detector, then the process of readjusting the signal phases begun in order to allow the truck to cross the intersection without stopping. The signal controller has been set to provide priority to trucks according to specific variables related to the priority strategy of the freight movements.

Thus, the first scenario was developed to prioritize the freight movements and to examine the impacts of the FSP on the performance of the trucks and the general traffic. The duration of the simulation run was set to for one hour with a warmup period of 15 minutes to replicate the morning peak hour. The results were compared with the base model and the rest of the scenarios aiming to identify the effects of FSP technology.

4.1.7.3 SCENARIO II – Conditional Freight Signal Priority Type I

The increased demand for cargo has resulted in an increase in the number of freight vehicles in urban areas. The case study was primarily selected due to the high truck volumes on the corridor. The unconditional prioritization of the freight movements along the studied corridor might have a negative effect on the other directions of travel, due to the increased duration of the green time allocated to the truck movements. Thus, the implementation of the Freight Signal Priority only under specific conditions (providing conditional priority) could possibly benefit the freight movements without damaging the operations on the minor directions.

The first category of trucks, HGV1, that includes vehicle class 5, consists of motor caravans, dual-purpose vehicles with 13 or more seats, camping and recreational vehicles, motor homes, etc. The vehicle class 5 holds almost 40% of the trucks as seen in Table 4-3, so it represents a high percentage of the trucks operating on the traffic network. On the other hand, these types of trucks are not normally considered when thinking about FSP.

Thus, the second scenario of the project is an extension of the first scenario but excluding the first category of trucks from the priority strategy. Most specifically, the priority was denied for the first category of trucks and the detection system in the simulation was readjusted to detect the calls from the rest of the truck categories. No alteration was needed for the parameters of the Ring Barrier Controllers used in Scenario I.

The implementation of the Conditional Freight Signal Priority Type I aimed to prioritize the freight movements that are related to the freight operations, excluding any type of trucks that are not related to commercial purposes. The simulation duration was the same as in Scenario I and the results aim to detect the impact of the conditional FSP under specific conditions.

4.1.7.4 SCENARIO III – Conditional Freight Signal Priority Type II

The third scenario followed the logic of Scenarios I and II. The difference is the introduction of the exclusion of an additional truck category from the priority strategy. More specifically, Scenario III is used to assess the impact of the FSP strategy by excluding truck categories 1 and 2 (HGV1 and HGV2).

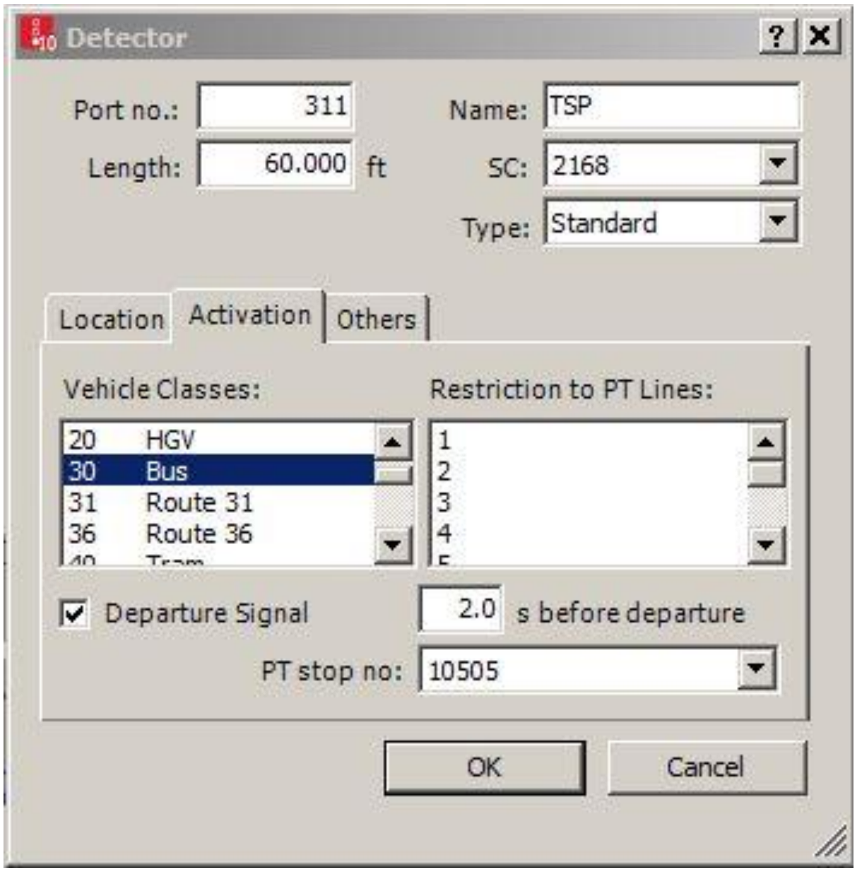
As mentioned previously, the HGV1 category that referred to as to vehicle classification 5 consists mostly of noncommercial trucks, while the HGV2 category consists of a low number of trucks with length like the HGV1 category. Thus, in Scenario III, the detection system was readjusted to ignore the calls of the first two categories of trucks. Regarding the parameters of the Ring Barrier Controllers, no alteration was needed.

The implementation of the Conditional Freight Signal Priority Type II aimed to favor the freight movements that are related to the freight operations, excluding any type of truck that is not related to commercial purposes and the trucks with the smaller length. The simulation duration was the same as in Scenario I and the results aim to assess the impact of the FSP under specific conditions.

4.1.7.5 SCENARIO IV – Transit Signal Priority

Scenario IV included the application of the TSP strategy along Sunrise Boulevard, providing priority only to the buses that travel on Sunrise Boulevard and not to the ones that cross the Boulevard. The goal of the study was to provide priority to the buses along the main corridor only and examine how this would affect the operations of the main road and the side roads as well.

The check-in detectors were placed before each signalized intersection, based on the speed and characteristics of the buses, apart from the cases that a bus stop was in the near-side close to the intersection. In that case, the check-in detector was placed in the vicinity of the bus stop. Both detectors were set to be activated only when the buses crossed over them and the detectors sent directly a message to the signal controller of the intersection that they related to. In the case that the detector was placed at a bus stop, the detection signal was sent to the signal controller 2 seconds before the bus departing from the bus stop. Figure 4-16 presents the arrangement of the parameters of the check-in detector that is placed at a bus stop close to an intersection.



Port no.: 311

Name: TSP

Length: 60.000 ft

SC: 2168

Type: Standard

Vehicle Classes:

20	HGV
30	Bus
31	Route 31
36	Route 36

Restriction to PT Lines:

1
2
3
4

☑ Departure Signal 2.0 s before departure

PT stop no: 10505

Figure 4-16: Detector Set-up for the TSP Strategy on a Bus Stop

Regarding the variables related to the signal controller for the signalized intersections, the changes were minor. Specifically, the values of the time extension, the travel time, and the travel time slack were adjusted to the distance of the detectors and the bus dynamics.

Thus, the fourth scenario of this study prioritized the buses utilizing the TSP strategy. After the completion of all the necessary readjustments, the model was set to run for one hour with a warmup period of 15 minutes to replicate the morning peak hour. The results extracted from this model were compared with the base model and the rest of the scenarios aiming to identify the effects of the TSP technology on the network.

4.1.7.6 SCENARIO V - Freight & Transit Signal Priorities

After successfully implementing each individual priority strategy along Sunrise Boulevard, the next step included the implementation of the combination of the TSP and FSP strategies. The fifth scenario described the simultaneous prioritization of the freight and transit movements along Boulevard.

Regarding the detection system for the two priorities, two approaches were investigated. The first option analyzed the utilization of two separate check-in detectors, one for detecting the transit vehicles and the second one for the freight vehicles, while maintaining the check-out detectors. The second option proposed the use of a common detection system for both check-in and check-out calls. After running tests and analyzing the results of the two approaches, the second option was selected, as the most efficient one.

Thus, the check-in and check-out detectors were adjusted to sense both buses and trucks' movements and send a signal to the signal controller for requesting priority to those movements. On some locations in the microsimulation model, the bus stop location was very close to the intersection. Consequently, the check-in detectors for the transit and the freight vehicles were separated for those cases. If the check-in detector for the trucks was placed on such a close distance to the signalized intersection, the priority request would not be provided successfully. Figure 4-17 shows an example of the utilization of two separate check-in detectors for the priority strategies, extracted for the model.

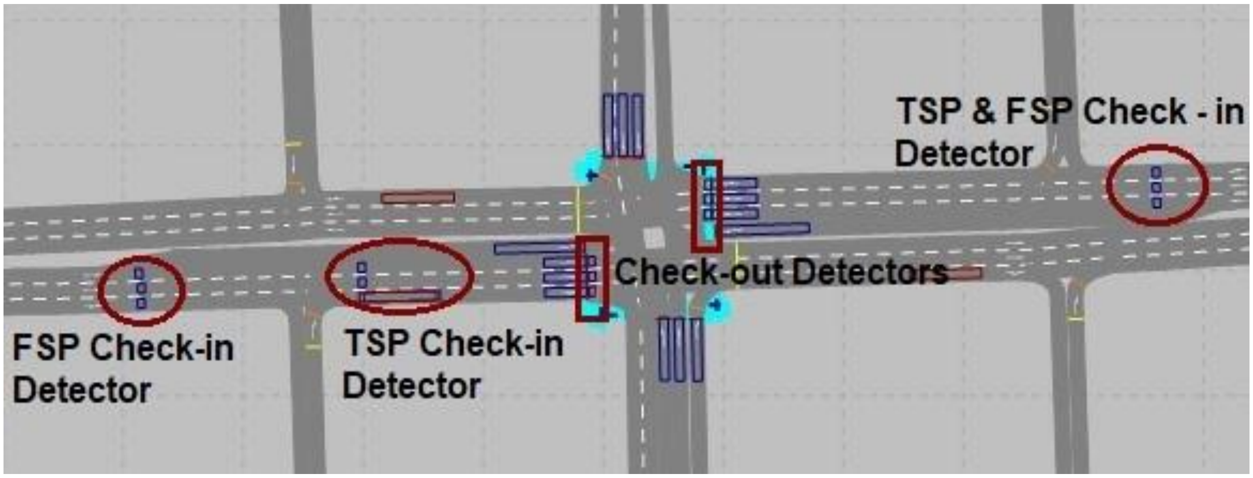


Figure 4-17: FSP and TSP Detector on the PTV VISSIM Model

For Scenario V, the parameters of the Ring Barrier Controllers were consistent and included the same values as in Scenario II. The duration of the microsimulation process was one hour with a warmup period of fifteen minutes to replicate the morning peak hour. The results extracted from that simulation were compared firstly with the base scenario and secondly with all the previously developed scenarios. The purpose of the result analysis was to examine the differences between the various scenarios and their impacts on each transport mode individually and the overall performance of the network.

4.1.7.7 SCENARIO VI – Conditional Freight Signal Priority Type I & Transit Signal Priority

The implementation of conditional Freight Signal Priority and unconditional Transit Signal Priority was the sixth scenario developed for the current project. The transit movements operating along Sunrise Boulevard were not that extensive, so the TSP was implemented without any specific condition. The application of the FSP strategy was based on the dimensions of the trucks, as in Scenario II.

Specifically, the first category of the trucks, HGV1 that includes vehicle Class 5 was excluded from the prioritization procedure, since it consists of a low percentage of commercial trucks. The detection system was adjusted to sense both buses and trucks and send a signal to the signal controller for requesting priority to those movements. However, in this case, the detectors were enabled only for the trucks of categories 2 to 5. Regarding the detectors for the bus stops that were close to the intersections, the check-in detectors for the transit and the freight vehicles were again separated.

Moreover, no alternation was necessary on the parameters of the Ring Barrier Controllers, so the values from the previous scenario were used. The duration of the microsimulation process was one hour with a warmup period of 15 minutes and replicating the morning peak hour. The results of the microsimulation were compared with all the previously developed scenarios, aiming to identify the scenario with the optimal results and the variables that affect mostly the efficient application of the priority strategies.

4.1.7.8 SCENARIO VII – Conditional Freight Signal Priority Type II & Transit Signal Priority

The final scenario of the project focused on the implementation of an additional type of conditional Freight Signal Priority and unconditional Transit Signal Priority. The current scenario was based on the conditional FSP strategy followed in scenario III.

The scenario VI excluded the detection of the truck categories 1 and 2 from the detection system of the priority vehicles. The parameters on the Ring Barrier Controller remained the same as in the previous scenario. The microsimulation model’s duration was one hour with a warmup period of fifteen minutes and replicating the morning peak hour, while the results were compared with all the already existing scenarios.

4.1.8 Measures of Effectiveness

This section describes the measures of effectiveness used to quantify the performance of the alternative strategies/scenarios examined in this study. The current research study focused on assessing the impacts on the travel time of all vehicles, the transit, and freight vehicles, as well as the delays of these vehicles. The study also assesses the green time durations. In addition, the effect on the overall networks' operations and on the delays on the street side movements was a significant part of this study.

The travel time expresses the period needed for transporting from point A to point B. It depends on the distance between the two points and the vehicle's speed. According to the FHWA (Dowling , 2007), travel time has been widely used in long-range planning studies at regional or corridor level to evaluate traveler benefits of alternative improvements. Also, it has been used to evaluate the traveler benefits of signal timing improvements for an individual facility.

In this study, the travel time has been assessed through the microsimulation model for all investigated scenarios. The measurement was achieved by dividing the corridor into segments. Specifically, the travel time has been measured from the middle of a signalized intersection until the middle of the consecutive signalized intersection. This division into shorter segments provides a better understanding of the operations of each portion of the corridor. The identification of any issue is easier when the case study is separated into individual segments.

The vehicle delay considers the period that a vehicle is waiting on a complete stop in order to cross an intersection. The measurement of the vehicle delay begins counting from the moment that a vehicle stops completely until the moment it starts accelerating again. Based on the FHWA (Dowling , 2007), the vehicle delay is a parameter used for evaluating the alternatives in long-range planning studies at regional or corridor level and the benefits of signal timing improvements for individual intersection or facility, for comparing different degrees of congestion and for estimating the fuel consumption and air quality impacts.

Delay could be considered as a part of the travel time, since it expresses a part of the travel time that obstructs the vehicles' movements, such as the stopped time during congestion. The delay has the same disadvantage as the travel time since it includes some incomplete trips on its measurements. The vehicle delays for the overall corridor has been calculated as the travel time measurements. The individual delays for each corridor segment were extracted from the model in order to calculate the overall delays on Sunrise Boulevard.

Finally, the green time duration was selected as another measure for evaluating the effectiveness of the different priority strategies. The average duration of the green time for all the signalized intersections of the eastbound and westbound approaches was calculated through the microsimulation model. The comparison of the variation on the green time duration along the main directions due to the implementation priority strategies was evaluated for analyzing the effects of the priorities on the operations of the signal phases.

4.2 Guideline for Implementing FSP and TSP in Urban Corridors

The guidelines developed in this study are based on the results from simulation modeling that estimate the impacts of signal priority. In this effort, the different vehicle classes are modeled, and their performance is calibrated to estimate the impacts of TSP, FSP, and the combination of the two. Particular consideration was given to the properly modeled acceleration/deceleration characteristics of freight vehicles that have a considerable effect on traffic congestion. It is also important to estimate the priority on the travel time of each vehicle class (cars, buses, and freight), separately when estimating the impacts. These impacts were used to estimate the dollar values of the impacts considering the value of travel time of passengers and trucks and the occupancy of passenger cars and transit vehicles. This study utilized the values of travel time and occupancies estimated for Florida by Hadi et al. (Hadi, et al., 2019). Table 4-5 shows the list of these parameter values. Please note that, if an agency wants to use a different set of values, they can do so.

Table 4-5. Value of Time and Occupancy

Parameters	Value ($)
Value of Time (Person) ($\boldsymbol{\beta_{car}/\beta_{bus}}$)	15
Value of Time (Freight) ($\boldsymbol{\beta_{freight}}$)	80
Bus Occupancy ($\boldsymbol{O_{bus}}$)	50
Car Occupancy ($\boldsymbol{O_{car}}$)	1.2
Freight Occupancy ($\boldsymbol{O_{freight}}$)	1.0

Past studies showed that the TSP implementation guideline for an intersection mostly depends on intersection volume-to-capacity (v/c) ratios. However, this study has found that TSP and FSP are not only a function of the intersection v/c ratio but also significantly affected by the percentage of freight and transit.

To determine if TSP and/or FSP could be implemented on a specific intersection or not, a simulation model needs to be built for that intersection. After proper calibration, the simulation model needs to be run with different signal priority configuration. There are four different signal configurations that need to be tested: no priority, TSP only, FSP only, and both TSP & FSP. For each configuration, the simulation model is run and delay of different vehicle classes (car, bus, and freight) is recorded. Thus, the total cost of delay is calculated using Equation 1.

$$\boldsymbol{C_i = \sum_j d_j * \beta_j * O_j} \tag{1}$$

Where; C is the total cost of delay for a specific signal configuration i,

d is the delay

β is the value of travel time

O is the occupancy for vehicle type j

Values of β, and O are provided in Table 4-5 and d is calculated from the simulation output.

The benefit (B) of a specific signal configuration (i) is calculated using Equation 2.

$$\boldsymbol{B_i = C_i - C_{no\ priority}} \tag{2}$$

The signal configuration which provides the maximum benefit should be a consideration for implementation.

Each TSP/FSP project is advised to do a preliminary analysis using the simulation model to justify the signal priority applications. However, it is obvious that at certain roadway conditions TSP/FSP could not provide any further benefits to the system. Therefore, performing simulation for such conditions would be a waste of resources.

In this study, an extensive simulation effort was performed with different demand volumes, transit frequency, and freight demand to find out the conditions when TSP/FSP is recommended for further analysis. A decision tree is developed utilizing the simulated data to determine three possible alternatives for TSP/FSP implementation:

i. Recommended,
ii. Not Recommended, and
iii. Simulation-Required.

If the intersections traffic data does not meet certain conditions, then TSP/FSP is not recommended by the guideline and no simulation needs to be performed for further analysis. Recommended implies that the intersection is suitable for TSP/FSP implementation. There are also certain conditions when it is difficult to recommend a specific guideline for implementation. Therefore, in such cases, this study recommends performing details simulation to determine the applicability of TSP and/or FSP.

4.2.1 Simulation Network

In order to develop the decision tree, simulation data has been generated with different parameters and signal configuration settings. A simple isolated signalized intersection has been considered for the analysis. Figure 4-18 shows the configuration of the intersection. It has three lanes in the east-west direction (Major direction) and two lanes in the north-south direction (Minor direction).

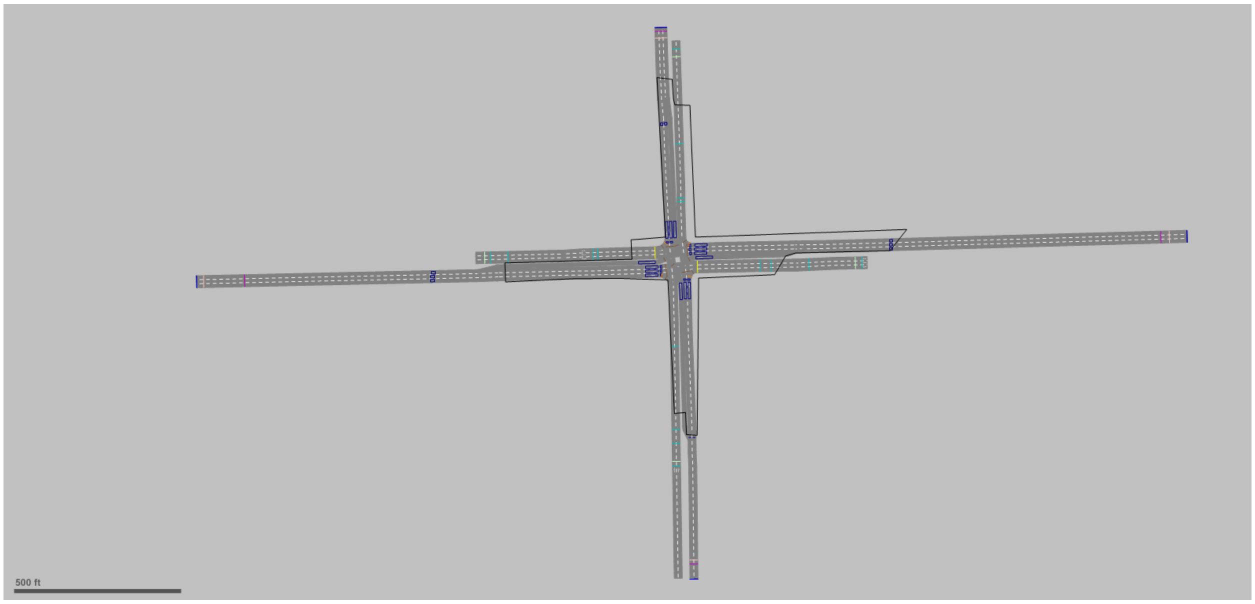


Figure 4-18. Simulation Network

A COM program has been written in Python language to test the TSP and/or FSP with different parameter combinations and signal configurations. Table 4-6 summaries the parameter that has been used for simulation.

Table 4-6. Different Simulation Parameters Set

Parameter Name	Major Road	Minor Road
V/C	1.0, 0.8, 0.6, 0.5	1, 0.8, 0.6
Freight Percentage	5%, 10%, 20%	5%, 10%, 20%
Transit Frequency per hour	3, 6, 12	3, 6, 12

All the possible combinations from Table 4-6 were simulated in VISSIM. For each combination of different parameters, the simulation is run for 10 different signal configurations:

i. Major Road TSP,
ii. Major Road FSP,
iii. Major road TSP + FSP,
iv. Minor road TSP,
v. Minor road FSP,
vi. Minor road TSP + FSP,
vii. Major + Minor road TSP,
viii. Major + Minor road FSP,
ix. Major + Minor road TSP + FSP, and
x. No signal Priority.

Based on the configurations described above the simulation was run over 9,720 different parameters set and signal priority settings. For each configuration, the simulation was run multiple times (5 times) to incorporate stochasticity. The average delay for all those five runs was considered for the cost calculations.

4.2.2 Freight Calibration Process

Apart from the traditional calibration process of a microsimulation model, it is recommended to calibrate some of the microscopic characteristics of the heavy vehicles. Length, weight, power and acceleration/deceleration characteristics are major parameters of heavy vehicles that need to be calibrated before running the simulation model. The acceleration/deceleration characteristics of a truck largely depend on the weight and power of the trucks. HCM summarizes average weight, length, and power along with the percentage of trucks of each FHWA vehicle class from data collected in Florida (see Table 4-7 and Table 4-8). Those two tables are combined together, and a summary is presented in Table 4-9.

Table 4-7. Characteristics and Percentage of Trucks by FHWA Vehicle Class

FHWA Vehicle Class	Average Weight (lb)	Average Length (ft)	Typical Power (hp)	Typical Weight-to-power Ratio (lb/hp)	Freeway		Multilane Highway	
					Urban (%)	Rural (%)	Urban (%)	Rural (%)
5	14,500	29	300	48	28.6	17.0	33.6	25.8
6	30,100	30	300	100	6.6	2.6	16.7	4.8
7	65,600	28	485	135	1.3	0.2	3.5	0.5
8	37,300	59	485	77	11.2	8.0	10.3	10.3
9	53,500	69	485	110	48.3	66.8	34.9	55.7
10	62,600	73	485	129	0.6	0.6	0.5	0.5
11	54,700	75	485	113	2.1	2.9	0.3	1.3
12	56,300	78	485	116	0.9	1.8	0.2	0.7
13	87,900	95	485	181	0.3	0.2	0.1	0.4

Table 4-7 shows the vehicle composition at different types of roadways. It also shows that heavy vehicle fleets are mostly composed of FHWA vehicle classes 5, 6, 8 and 9 which represents around 95% of the heavy vehicles. The rest 5% is composed of FHWA vehicle classes 7, 10, 11, 12, and 13. In addition, those later 5 classes have the same power (485 hp) and higher weight (greater than 54,700 Ib); resulting in a higher power to weight ratio (greater than 110 lb/hp). In this study, these

5 FHWA classes are combined into one class and represent it as HGV5. The details of the re-defined classes are shown in Table 4-8.

Table 4-8. HGV Vehicle Classes

HGV sub Category	FHWA Vehicle Class	Freeway		Multilane Highway		Length	Average Weight (lb)	Typical Power (hp)	Typical Weight-to-power Ratio (lb/hp)
		Urban (%)	Rural (%)	Urban (%)	Rural (%)				
HGV1	5	28.6	17	33.6	25.8	29	14,500	300	48
HGV2	6	6.6	2.6	16.7	4.8	30	30100	300	100
HGV3	8	11.2	8	10.3	10.3	59	37,300	485	77
HGV4	9	48.3	66.8	34.9	55.7	59	53500	485	110
HGV5	7, 10, 11,12,13	5.2	5.7	4.6	3.4	See Table 4-9	See Table 4-9	485	-

Table 4-9. Distribution of Weight for HGV 5

FHWA Vehicle Class	**Weight**	**Average Percentage Calculated from Table 4-8**	**Cumulative Percentage**	**Length**
7	65,600	29	29	28
10	62,600	12	41	73
11	54,700	35	76	75
12	56,300	19	95	78
13	87,900	5	100	95

Table 4-8 shows that this study has utilized five different classes of freight vehicles to simulate the actual field condition. In VISSIM, five different heavy vehicle types are defined to represent those five classes. Vehicle length, weight, and power distribution are calibrated for each vehicle class. For HGV1, HCV2, HGV3, HGV4 those are fixed value however for HGV5 those values are a distribution from Table 4-9. The vehicle weight and power distribution will limit the maximum acceleration/deceleration characteristics of a certain vehicle class. However, the desired acceleration/ deceleration still needs to be calibrated based on field data. Therefore, the acceleration and deceleration are calibrated for each vehicle class based on literature value.

Washburn and Ozkul developed acceleration profiles for different types of heavy vehicles based on data collected on Florida highways (Washburn & Ozkul, 2013). They have tested three different methodologies to generate the acceleration profile and recommended that the methodology developed by Al Kaisy et al. (Al-Kaisy, Jung, & Rakha, 2005), produce more reasonable acceleration profile. This study has utilized the same results to implement into VISSIM.

Table 4-10 summarizes the values. Please note that HGV1 and HGV2 have the same acceleration characteristics as both are single-unit trucks and have unique acceleration characteristics as shown by Washburn and Ozkul, (Washburn & Ozkul, 2013). However, they are kept in a different class in VISSIM (HGV1 and HGV2) as they have different weight to power ratio which will limit their maximum acceleration property.

Table 4-10. Heavy Vehicle Acceleration Characteristics

Speed	HGV1	HGV2	HGV3	HGV4	HGV5
0	3.4	3.4	3.7	3.4	3.4
10	3.3	3.3	3.3	3	3
20	2.8	2.8	2.8	2.5	2.5
30	2.7	2.7	2.7	2.4	2.4
40	2.5	2.5	2.5	2.3	2.3
50	2.4	2.4	2.4	2.2	2.2
60	2.3	2.3	2.3	1.5	1.5
70	1.9	1.9	2	1	1.2
80	1.5	1.5	1.5	0.8	0.8
90	1	1	1	0.5	0.5
100	0.6	0.6	0.6	0.3	0.3
110	0.2	0.2	0.3	0	0
120	0	0	0	0	0

4.2.3 Model Development

The main objective of this study is to prepare a guideline for TSP and/or FSP implementation. Based on the simulation data, different data mining techniques have been tested to develop a prediction model for signal priority implementation. This study has found the classification tree is the most suitable technique to determine the implementation possibilities.

Hourly traffic volume, bus frequencies, and freight percentage of major and minor directions are the direct input data of the model. However, several other derived features are also included to generate a more accurate prediction model. Finally, the following variables that are found significant by the models:

i. The proportion of major to minor road hourly volume (MajorMinor_Volume_proportion).
ii. Hourly truck volume per lane for the major direction (Truck_Volume_Major).
iii. Hourly truck volume per lane for the minor direction (Truck_Volume_Minor).
iv. The proportion of major to minor road hourly truck volume (MajorMinor_truck_proportion).
v. The proportion of major to minor road hourly bus volume (MajorMinor_bus_proportion).
vi. Volume to the capacity ratio for the major road (vc_major).
vii. Volume to the capacity ratio for the minor road (vc_minor).

This study has generated different models based on different signal priority strategies. Either the major or the minor direction could be selected for the TSP/FSP implementation. For each direction, the signal priority could be designed for either transit or freight or both. This study developed separate guidelines for each of those six conditions. Please note that if the agency decided to consider both directions for TSP and FSP implementation then it is suggested to perform a simulation analysis to determine the best signal priority strategies. This study has found that more than 94% of the simulation test cases priority on minor direction provides better system benefits when both directions are in consideration. This is expected as minor direction usually experiences higher delay than major direction and providing priority in such direction results a higher benefit.

The scikit-learn package developed for python is utilized in this study to generate the decision tree. The decision tree classifier function of the scikit-learn package fits a decision tree based on the observed data. The following parameter of decision tree classifier function is modified in this study: criterion, min_impurity_decrease, and max_depth. Criteria determined what function will be used to measure the quality of the split. In this study, entropy (information gain) is considered as the criterion. Min_impurity_decrease is the minimum entropy threshold to split a node. Max_depth is the depth of the tree. The manual adjustment found that min_impurity_decrease of 0.001 and Max_depth of 2 for major and 3 for minor provides a satisfactory result. As this model will be used as planning stages, therefore the model should be general and applicable for a wide range of traffic conditions. Therefore, keeping the maximum depth of the model as lower as possible could enhance its generality.

As mentioned in the methodology section, the model will predict three different possibilities for TSP/FSP implementation: recommended, not recommended, and simulation required. If the model generates a leaf with less than 10% impurity, then the class is determined either Recommended or not recommended. A leaf with more than 10% impurity, it is labeled as a further simulation is required.

80% of the whole dataset is used to develop the model. The rest 20% of the data is kept for model testing. The test data is used to find out the accuracy of the model prediction. The test results show that the misclassification rates for the “recommended” and “not recommended” classes are less than 5%. Figure 4-19 to Figure 4-23 represents the different models developed in this study and Table 4-11 presents the test results. For TSP implementation in the minor direction, no model could be fitted with the data. Therefore, for this configuration, it is always recommended to perform the simulation analysis.

Table 4-11. Model Test Results

Model Name	Misclassification Rate
TSP+FSP Major	1%
TSP Major	1%
FSP Major	0%
TSP +FSP Minor	3%
FSP Minor	0%

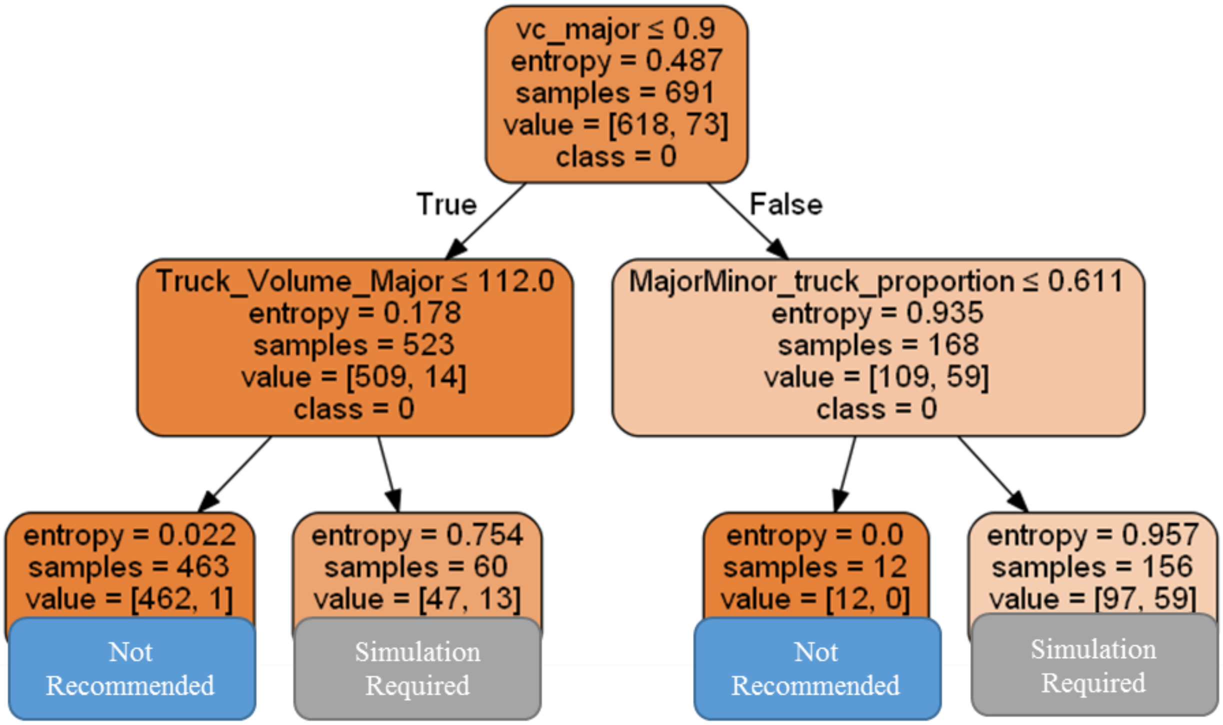


Figure 4-19. Decision Tree for TSP and FSP Implementation for Major Road

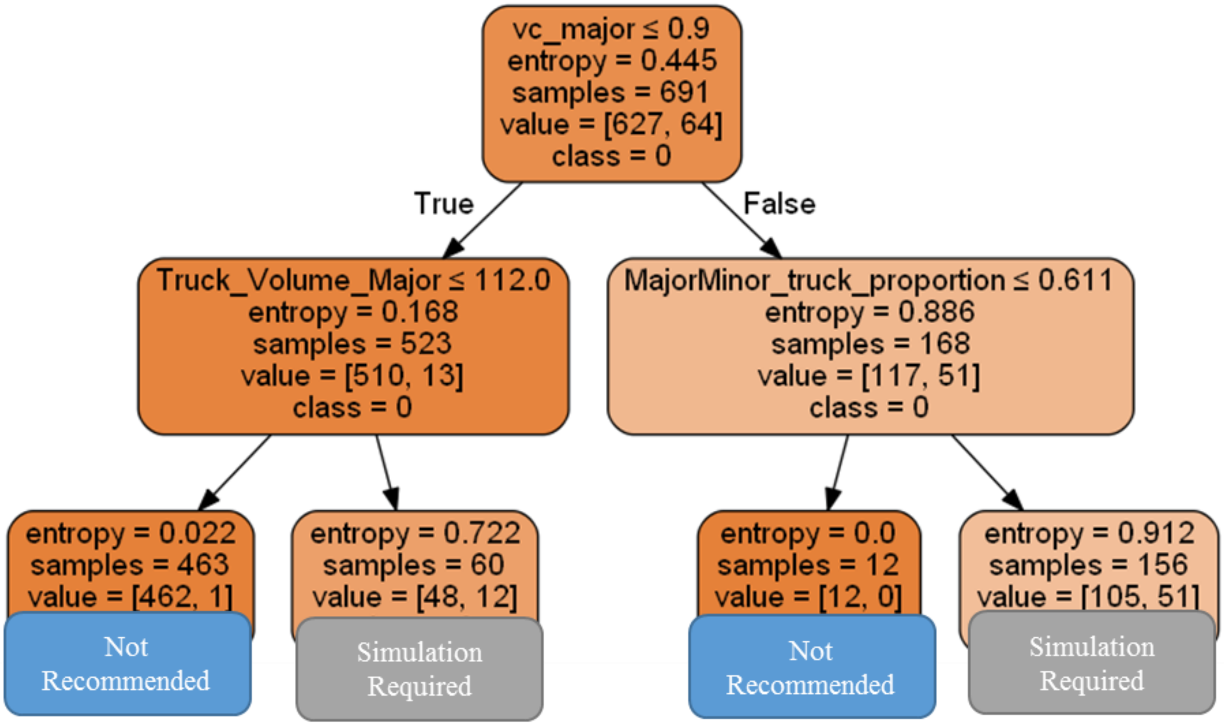


Figure 4-20. Decision Tree for TSP Implementation for Major Road

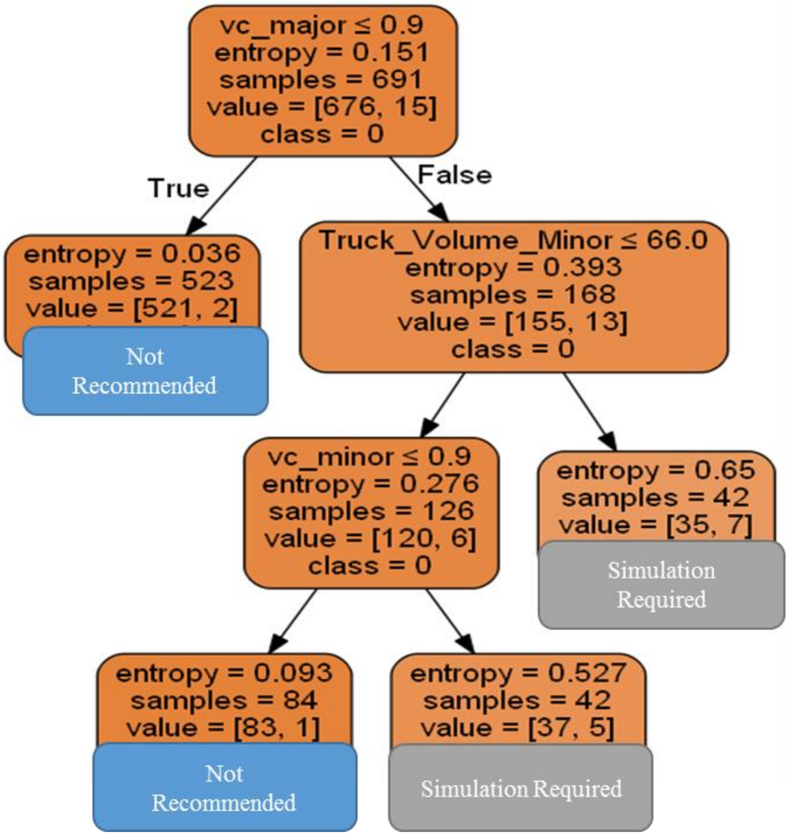


Figure 4-21. Decision Tree for FSP Implementation for Major Road

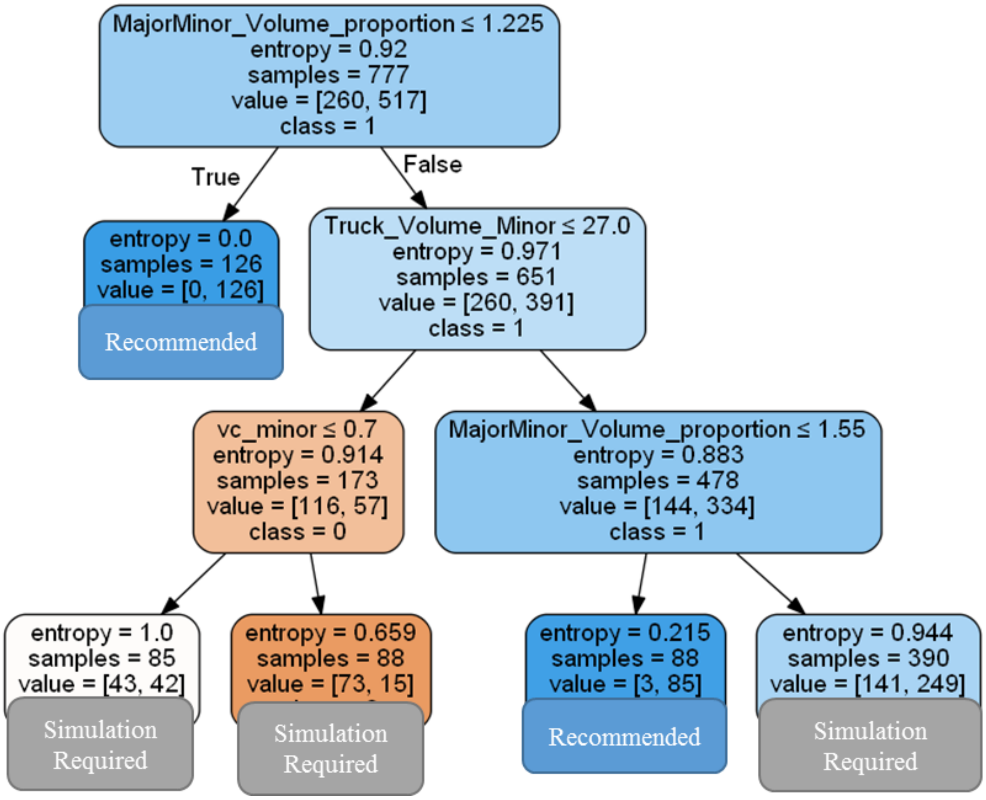


Figure 4-22. Decision Tree for TSP and FSP implementation for Minor Road

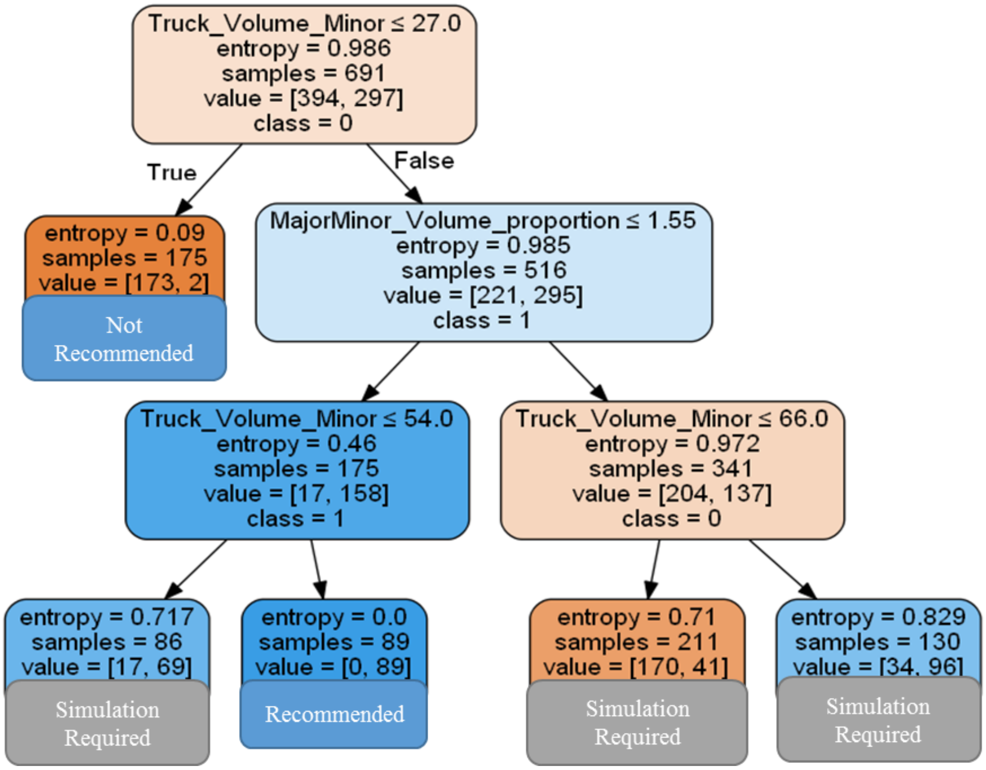


Figure 4-23. Decision Tree for FSP Implementation for Minor Road

4.2.4 Proposed Guideline

Based on the literature review and the simulation performed by this study a comprehensive guideline is developed for TSP/FSP implementation. The developed guideline is applicable for those projects where freight signal is considered, and freight delay plays an important role in the corridor benefit analysis.

A checklist is shown in Table 4-12 based on the literature review to decide whether TSP or FSP should be considered for a specific corridor or not.

Table 4-12. TSP/FSP Checklist

TSP	FSP
1. Express Bus Service 2. Bus stop location at Far side or midblock. If not, then planning to relocate the bus stop locations 3. Agencies want to reduce transit delay and increase the reliability.	1. Important truck route 2. Uphill/downhill 3. Safety issues 4. Environmental issue 5. Agencies want to reduce freight delay and increase the reliability.

Please note that it is not necessary to pass all the checklist to implement TSP and/or FSP. However, meeting more checklist items indicates more importance of the TSP/FSP implementation. Although, it is finally the agency's decision when they prefer to consider TSP/FSP implementation.

Figure 4-24 shows the full guideline for the TSP and FSP implementation. As shown in the Figure, agencies first have to choose a corridor that they want to consider for TSP/FSP implementation. To implement a signal priority, the intersection should have slack time more than 5 seconds. Slack time is calculated subtracting all pedestrian clearance time and minimum left-turn green times from the cycle time. Therefore, five seconds threshold implies that the signal priority could be given for at least five seconds. If there is enough slack time, then TSP/FSP can be implemented on that intersection.

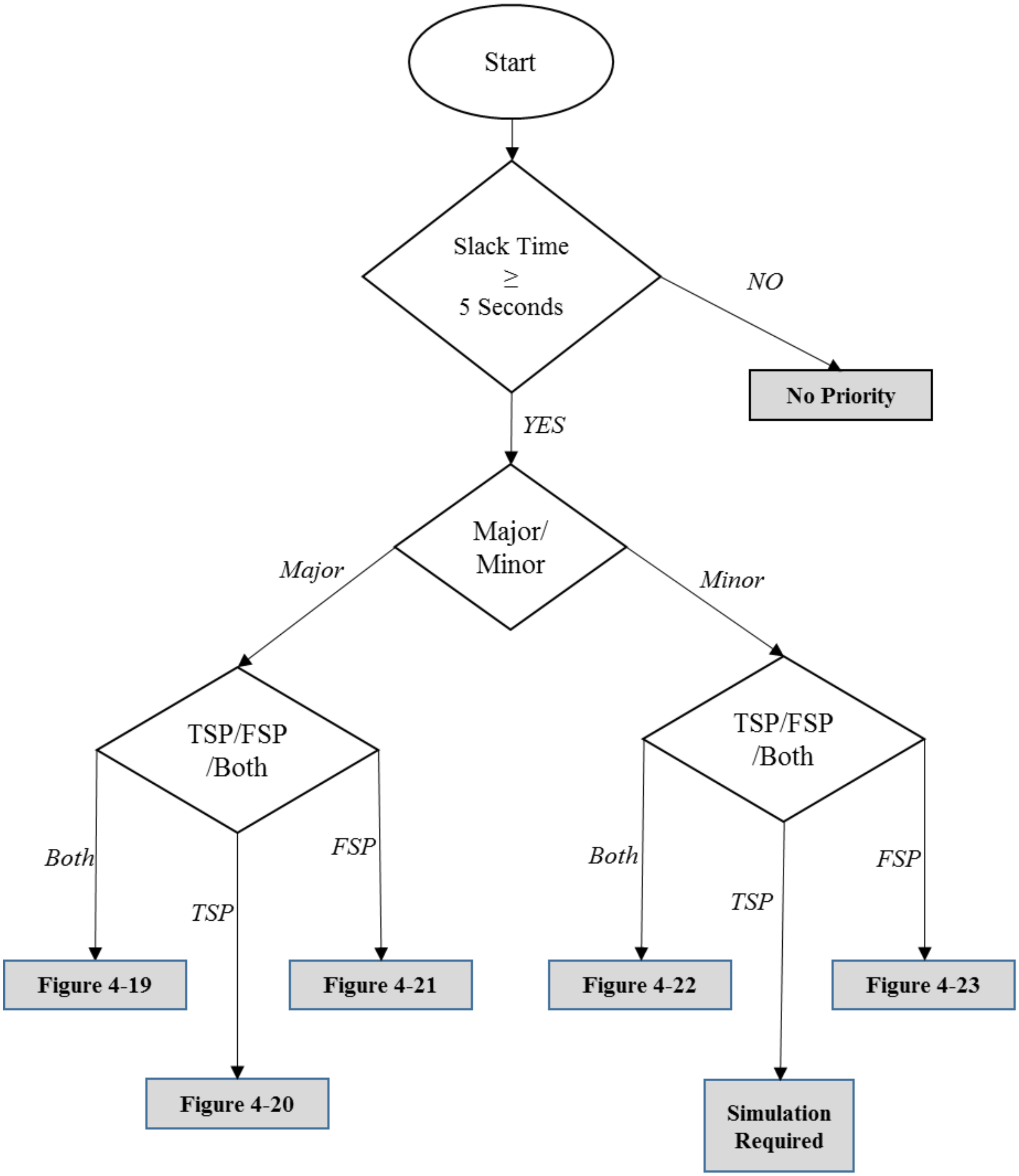


Figure 4-24. TSP and FSP Guideline

5 Results & Analysis

A detailed description of the analysis conducted based on the results from the microsimulation models is provided in this section. More specifically, the comparison of the results of the base scenario and the additional investigated scenarios that include the priority strategies are thoroughly presented. The comparison is based on the measures of effectiveness that were thoroughly presented in the previous section.

The analysis of the results aims to present the impact and the effects of implementing different priority strategies on a congested multi-modal corridor. The evaluated results are presented for each transport mode individually and for the overall traffic network. The study’s goal is to assess if the implementation of Freight and Transit Signal Priorities improves freight mobility, provide good transit services and benefits the overall congested conditions. The results of the scenarios are presented below divided by the measures of effectiveness used. The microsimulation model replicated an AM peak hour.

5.1 Travel Time Analysis

Travel time measurements extracted from the divided corridor segments along Sunrise Boulevard was the first measure of effectiveness utilized for the analysis of the results. The vehicle travel times provided a comprehensive analysis of the base traffic conditions and the different priority strategies.

In Tables 5-1 the average travel time measurements in seconds for all the transport modes for the eastbound direction (direction with the priority) are listed. The results are presented for all the different developed scenarios and for all the consecutive corridor segments. Figures 5-1 and 5-2 represent graphically the average travel time results. Figure 5-1 includes all the measurements for the unconditional priority implementations, while Figure 5-2 shows the measurements for the conditional priority strategies along with the base model.

The analysis of the corridor segments presented both positive and negative results. For most of the segments, the improvements were significant. In some cases, the differences before and after the priority implementation were minor, while in some cases they were negative. Further observations of the simulation models indicate that the negative values were usually related to the geometry of the intersections and the number of vehicles turning left from Sunrise Boulevard to the side roads. Specifically, on the NW 9th and NW 7th Avenues, the geometry of the left lane along with the increased number of vehicles waiting to turn left caused a slight increase in the travel time for that specific segment.

Comparing each priority scenario with the base model, the positive impact of all the priorities was visible. The overall travel time improvements were higher than 7% on all the scenarios. The model with the best performance was the fusion of the FSP and TSP strategies, with an increase of 16.6% on the overall travel time. Finally, the unconditional priority scenarios had higher improvements than the conditional ones, since the priority vehicles included all the truck categories.

Table 5-1. Average Travel Time (s) per Segment - All Vehicles - EB Direction

Average Travel Time (s) per Segment - All Vehicles – EB Direction									
Segment #	**Corridor Segment**	**Base Model**	**FSP**	**Cond. FSP Type I**	**Cond. FSP Type II**	**TSP**	**FSP/ TSP**	**Cond. FSP Type I / TSP**	**Cond. FSP Type II / TSP**
1	**NW 31st Ave - NW 27th Ave**	78.77	82.37	88.83	83.66	78.04	77.87	77.80	82.34
2	**NW 27th Ave - NW 24th Ave**	82.19	69.96	68.85	78.37	77.52	69.42	72.86	69.80
3	**NW 24th Ave - I-95**	48.36	45.94	46.64	47.72	50.59	45.35	47.63	47.78
4	**I-95 – NW 16th Ave**	111.52	71.36	68.15	80.50	89.10	64.44	66.83	76.76
5	**NW 16th Ave - NW 15th Ave**	32.76	30.95	30.28	30.40	30.64	27.68	29.79	31.08
6	**NW 15th Ave - NW 9th Ave**	112.57	88.69	86.11	89.03	98.11	83.59	86.27	91.21
7	**NW 9th Ave - NW 7th Ave**	26.98	29.53	36.77	26.79	31.83	29.05	31.04	29.49
8	**NW 7th Ave - Andrews Ave**	71.74	61.27	59.39	70.02	68.15	59.02	64.47	64.45
9	**Andrews Ave - NE 4th Ave**	37.38	37.24	34.24	49.43	30.00	35.22	40.15	35.47
10	**NE 4th Ave - N Flagler Dr**	45.58	30.12	32.79	31.11	44.29	31.15	36.15	34.97
11	**N Flagler Dr - N Federal Hwy (West)**	39.64	30.35	30.69	29.98	34.07	30.47	30.40	30.86
12	**N Federal Hwy (West) – NE 9th Ave**	17.22	15.22	14.52	15.74	18.14	15.40	15.60	15.40
13	**NE 9th Ave – NE 10th Ave**	6.74	6.68	6.69	6.66	6.73	6.72	6.68	6.69
14	**NE 10th Ave - NE 12th Ave**	12.73	12.34	12.41	12.33	12.63	12.39	12.26	12.37
15	**NE 12th Ave – NE 15th Ave**	40.79	34.52	39.68	39.95	40.79	31.00	39.38	38.78
16	**NE 15th Ave – NE 16th Ter**	17.72	13.53	14.19	17.70	16.96	13.57	15.47	15.81
17	**NE 16th Ter – NE 17th Way**	21.89	21.85	26.54	21.87	18.90	29.15	20.28	24.43
18	**NE 17th Way – N Federal Hwy (East)**	29.49	27.82	31.53	31.74	32.30	33.07	34.03	31.86
19	**N Federal Hwy (East) – NE 20th Ave**	19.49	16.06	16.96	16.66	17.23	17.31	16.57	16.43
SUNRISE BLVD PROJECT LIMITS		**853.58**	**725.80**	**745.25**	**779.66**	**796.01**	**711.86**	**743.66**	**755.98**

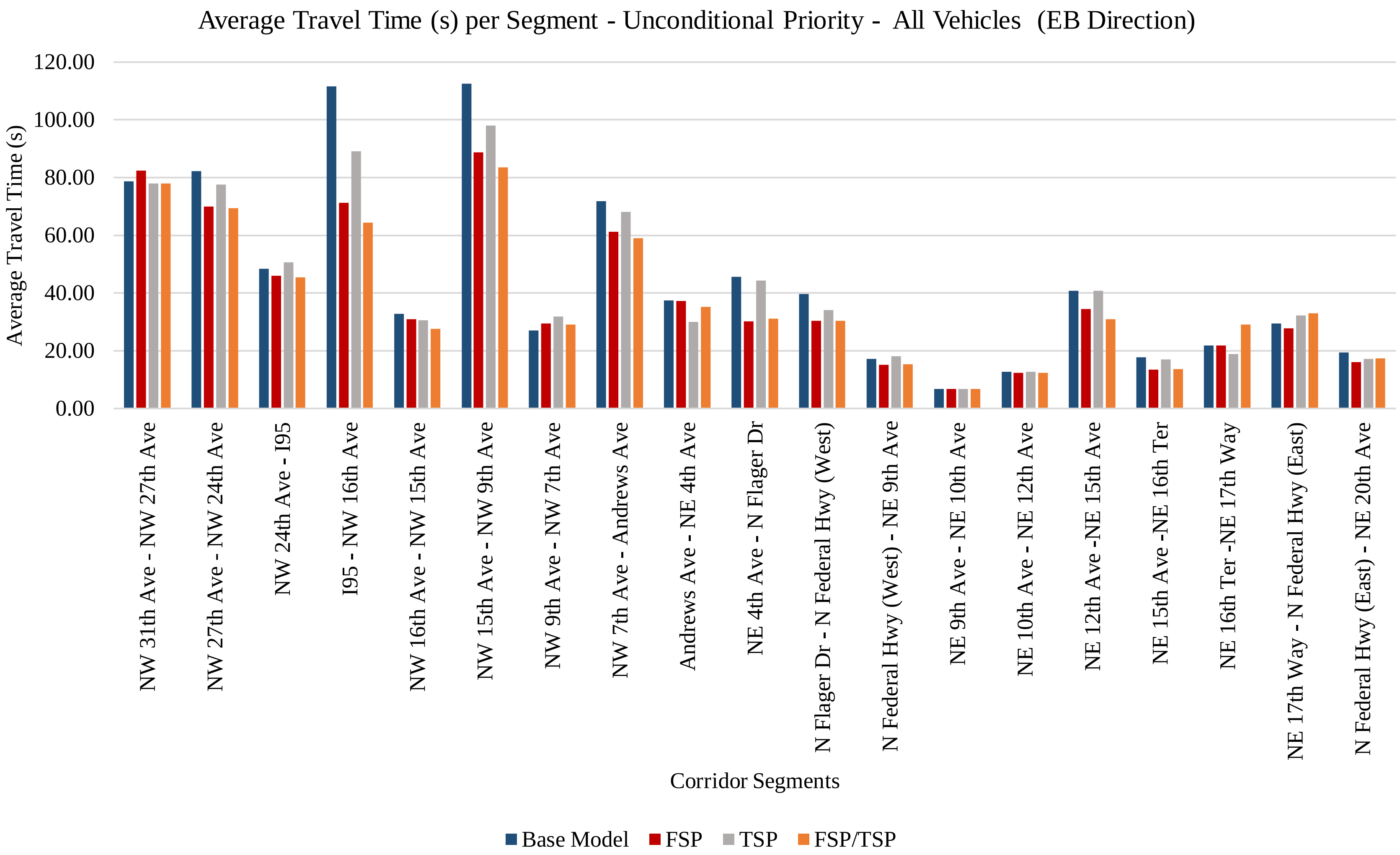


Figure 5-1: Average Travel Time (s) per Segment - Unconditional Priority - All Vehicles (EB Direction)

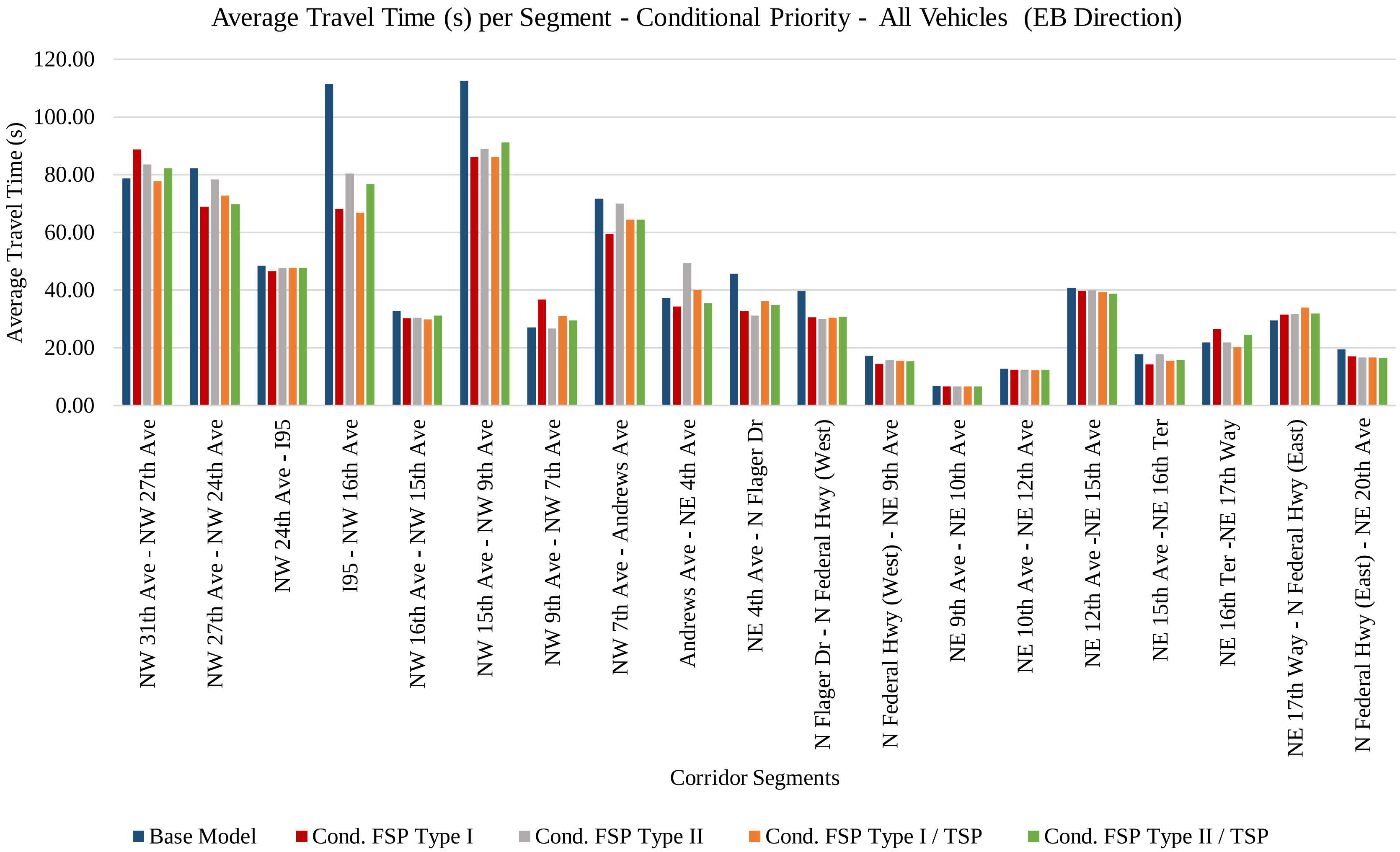


Figure 5-2: Average Travel Time (s) per Segment - Conditional Priority - All Vehicles (EB Direction)

Table 5-2 presents the average travel time measurements in seconds of the freight movements for the eastbound direction. The table includes all the scenarios for all the consecutive corridor segments. Figures 5-3 and 5-4 are a graphical representation of the average travel time results. Figure 5-3 includes all the measurements from the unconditional priority implementations, while Figure 5-4 includes the measurements from the conditional priority strategies along with the base model.

The travel time of the freight movements decreased with all implemented priority strategies for most of the corridor segments. In many segments, the improvements in travel time reached 40% in comparison with the base model. Thus, the implementation of the priority strategies was efficient, and the freight mobility was enhanced along the eastbound direction of Sunrise Boulevard. Any increase in the travel time that was identified for a few segments was due to the geometry of the road and the traffic conditions on that specific segment. For example, between the NW 9th and NW 7th Avenues, the geometry of the corridor segment was the main reason for this slight increase that was lower than 20 seconds.

The comparison of all the different models resulted that the scenarios implemented unconditional priority had higher improvements than the scenarios with conditional priority, due to the increased priority requests that the unconditional strategies need to facilitate. The lowest reduction on the average travel time was identified in the TSP scenario, that priority vehicles included only the buses, with a 5.6% saving on the travel time. The best improvement was with the FSP/TSP scenario, with a 22.2% saving on the travel time for the eastbound direction.

The results of the average travel time in seconds only for the transit vehicles for the eastbound direction are presented in Table 5-3. The table includes all the scenarios for all the consecutive corridor segments. Figures 5-5 and 5-6 represent graphically the average travel time results. Figure 5-5 includes all the measurements from the unconditional priority implementations, while Figure 5-6 represents the measurements from the conditional priority strategies.

All the priority scenarios lead to a reduction of the overall transit travel time for the eastbound direction, with the highest improvements to reach 23.94% with the Conditional FSP Type I and TSP scenario. The Scenario VI had better results than the TSP scenario that was exclusively for the transit vehicles, because scenario VI was programmed to accommodate the freight movements as well. Due to the increased number of priority requests from the trucks, the transit mobility was benefitted, and a high level of transit services was provided.

Despite the travel time savings over all the corridor segments, in some specific segments the travel time increased. This increased travel time was located on the same segment as the freight vehicles, so the problematic situation is not related to the bus's dynamics and characteristics but on the geometry of the road, and the traffic operations.

Table 5-2: Average Travel Time (s) per Segment - Freight Vehicles - EB Direction

Average Travel Time (s) per Segment – Freight Vehicles – EB Direction									
Segment #	**Corridor Segment**	**Base Model**	**FSP**	**Cond. FSP Type I**	**Cond. FSP Type II**	**TSP**	**FSP/ TSP**	**Cond. FSP Type I / TSP**	**Cond. FSP Type II / TSP**
1	**NW 31st Ave - NW 27th Ave**	76.10	76.34	82.73	88.02	76.38	74.58	74.95	77.87
2	**NW 27th Ave - NW 24th Ave**	105.23	82.51	70.97	79.00	83.26	72.36	72.40	73.22
3	**NW 24th Ave - I-95**	48.75	49.18	50.81	50.86	53.34	48.14	50.96	52.52
4	**I-95 – NW 16th Ave**	121.71	73.71	72.31	83.44	98.50	66.62	72.90	80.42
5	**NW 16th Ave - NW 15th Ave**	35.15	32.28	32.34	30.87	30.54	28.83	32.14	32.07
6	**NW 15th Ave - NW 9th Ave**	119.51	98.03	82.43	91.75	102.73	85.77	84.76	100.13
7	**NW 9th Ave - NW 7th Ave**	28.95	31.72	40.81	37.45	43.15	31.58	36.35	32.58
8	**NW 7th Ave - Andrews Ave**	76.35	60.17	56.90	74.44	76.72	59.21	67.92	67.56
9	**Andrews Ave - NE 4th Ave**	35.76	39.65	36.52	52.84	33.71	38.33	46.05	39.20
10	**NE 4th Ave - N Flagler Dr**	60.48	31.11	34.79	29.96	57.52	35.06	34.19	42.91
11	**N Flagler Dr - N Federal Hwy (West)**	45.71	34.55	37.72	33.70	37.69	33.05	29.62	32.77
12	**N Federal Hwy (West) – NE 9th Ave**	19.46	15.27	15.47	15.68	18.86	16.76	15.55	17.90
13	**NE 9th Ave – NE 10th Ave**	6.97	6.48	6.52	6.52	6.81	6.71	6.45	6.94
14	**NE 10th Ave - NE 12th Ave**	12.92	11.75	11.71	11.90	12.41	12.10	11.76	12.61
15	**NE 12th Ave – NE 15th Ave**	46.48	39.49	40.56	41.08	49.86	31.76	43.94	46.13
16	**NE 15th Ave – NE 16th Ter**	19.13	14.15	14.12	19.07	19.05	13.75	16.64	16.05
17	**NE 16th Ter – NE 17th Way**	21.15	22.49	25.17	25.90	20.00	24.52	22.31	24.25
18	**NE 17th Way – N Federal Hwy (East)**	36.78	29.46	40.96	34.51	39.54	37.39	39.78	36.66
19	**N Federal Hwy (East) – NE 20th Ave**	27.57	16.03	19.98	18.41	18.07	18.18	16.92	20.27
SUNRISE BLVD PROJECT LIMITS		**944.17**	**764.38**	**772.82**	**825.41**	**878.14**	**734.69**	**775.59**	**812.08**

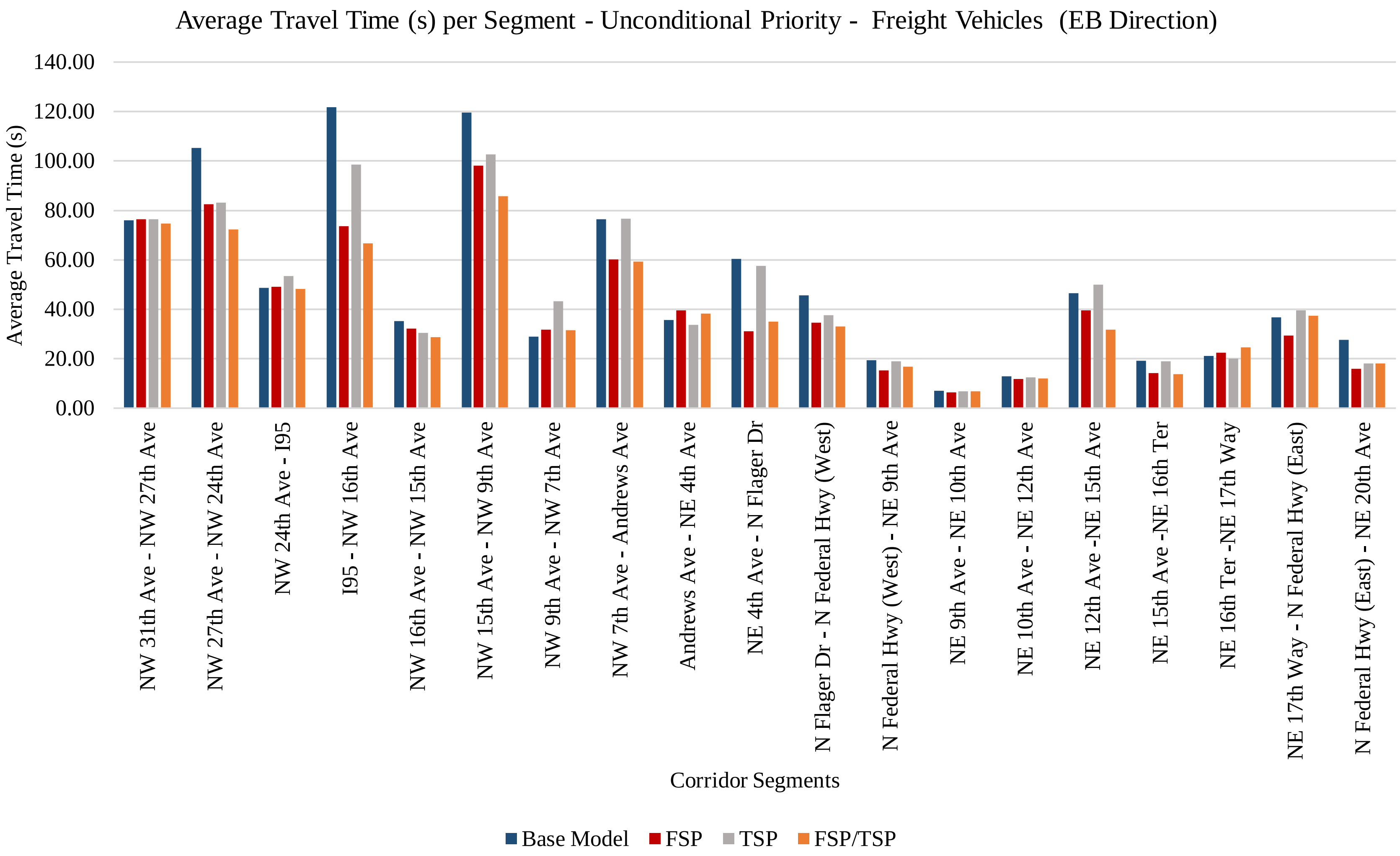


Figure 5-3: Average Travel Time (s) per Segment - Unconditional Priority - Freight Vehicles (EB Direction)

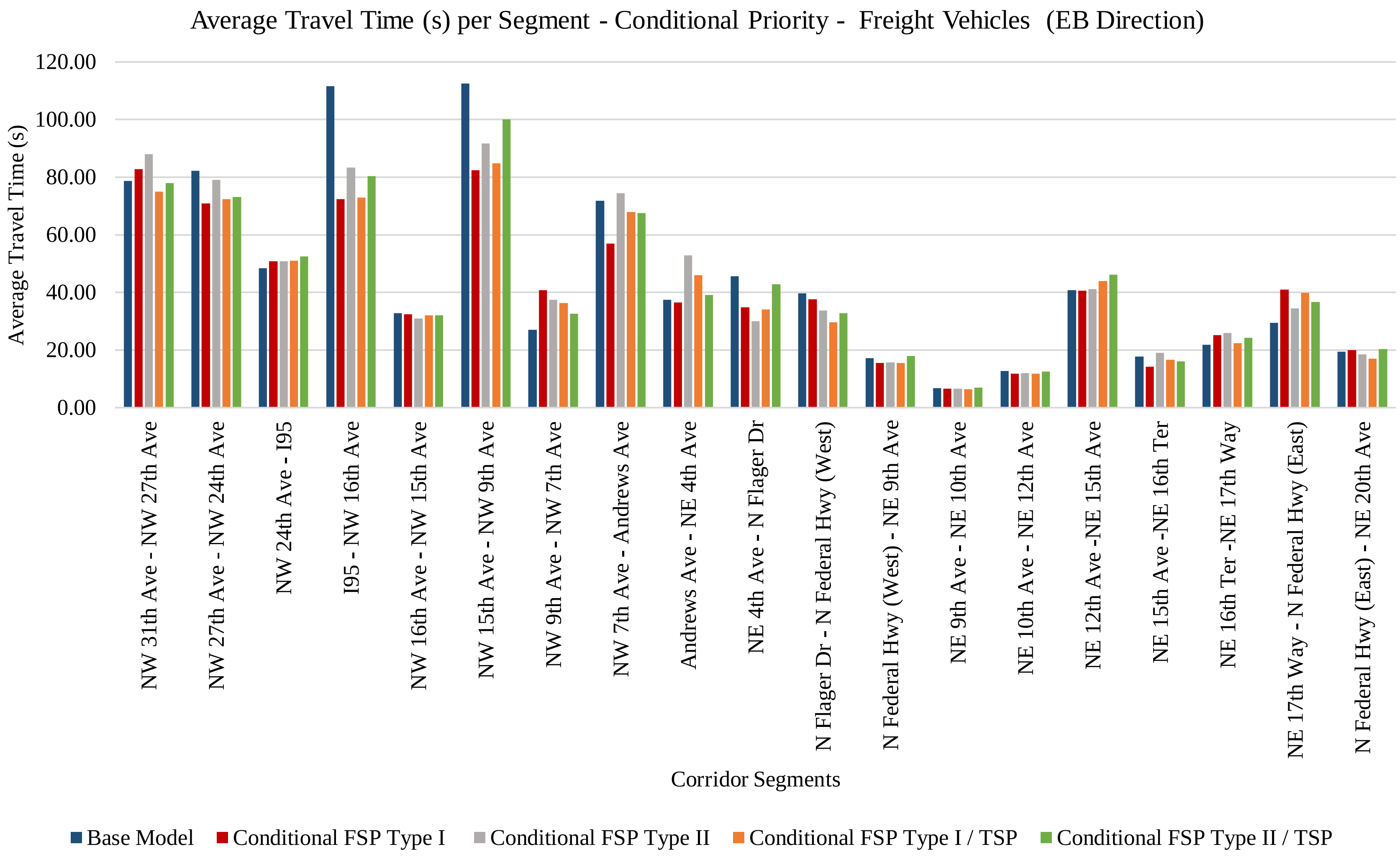


Figure 5-4: Average Travel Time (s) per Segment - Conditional Priority - Freight Vehicles (EB Direction)

Table 5-3: Average Travel Time (s) per Segment – Transit Vehicles – EB Direction

Average Travel Time (s) per Segment – Transit Vehicles – EB Direction									
Segment #	**Corridor Segment**	**Base Model**	**FSP**	**Cond. FSP Type I**	**Cond. FSP Type II**	**TSP**	**FSP/ TSP**	**Cond. FSP Type I / TSP**	**Cond. FSP Type II / TSP**
1	**NW 31st Ave - NW 27th Ave**	128.27	131.13	150.00	126.23	135.13	129.70	114.83	135.23
2	**NW 27th Ave - NW 24th Ave**	117.30	70.03	65.30	72.90	99.77	68.27	79.60	76.67
3	**NW 24th Ave - I-95**	60.37	62.47	71.10	72.30	70.50	58.20	55.53	70.30
4	**I-95 – NW 16th Ave**	137.23	96.20	89.93	104.77	93.83	80.90	66.43	67.07
5	**NW 16th Ave - NW 15th Ave**	29.67	28.10	25.63	21.33	29.27	20.70	21.20	27.03
6	**NW 15th Ave - NW 9th Ave**	167.98	131.57	163.53	157.40	151.35	119.07	101.80	147.58
7	**NW 9th Ave - NW 7th Ave**	67.76	70.55	57.88	58.10	58.20	67.48	56.40	57.40
8	**NW 7th Ave - Andrews Ave**	105.95	105.70	118.53	120.55	110.50	100.98	104.45	100.65
9	**Andrews Ave - NE 4th Ave**	128.10	89.65	92.55	100.53	85.73	63.58	80.48	63.75
10	**NE 4th Ave - N Flagler Dr**	32.95	31.73	43.78	40.58	33.90	34.83	33.85	32.23
11	**N Flagler Dr - N Federal Hwy (West)**	37.75	31.88	27.28	39.40	44.52	36.13	41.75	47.43
12	**N Federal Hwy (West) – NE 9th Ave**	28.18	31.50	26.15	23.68	29.65	27.18	24.95	25.73
13	**NE 9th Ave – NE 10th Ave**	9.28	9.10	8.79	8.48	8.87	8.67	8.93	8.37
14	**NE 10th Ave - NE 12th Ave**	41.22	40.18	40.32	41.28	39.83	40.12	41.19	39.62
15	**NE 12th Ave – NE 15th Ave**	81.19	55.09	61.54	51.91	51.63	60.56	43.10	45.06
16	**NE 15th Ave – NE 16th Ter**	29.67	26.24	28.57	27.47	28.19	27.89	28.76	29.47
17	**NE 16th Ter – NE 17th Way**	33.27	34.50	37.49	35.87	34.39	32.66	32.90	36.37
18	**NE 17th Way – N Federal Hwy (East)**	25.50	30.33	29.05	29.33	25.38	25.13	30.53	24.45
19	**N Federal Hwy (East) – NE 20th Ave**	46.30	30.53	36.45	30.90	32.05	31.90	28.18	26.75
SUNRISE BLVD PROJECT LIMITS		**1307.93**	**1106.46**	**1173.86**	**1163.00**	**1162.67**	**1033.90**	**994.86**	**1061.15**

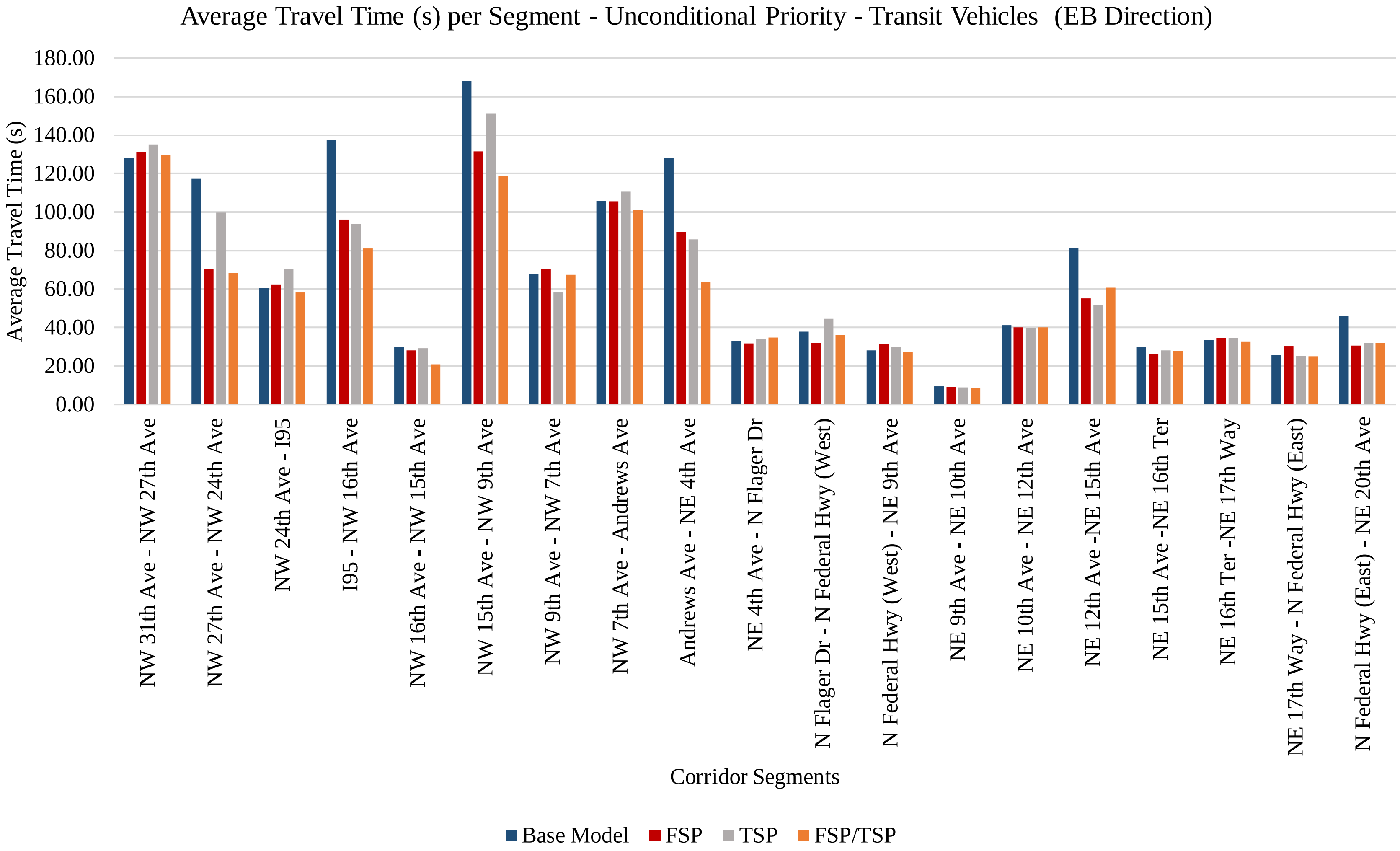


Figure 5-5: Average Travel Time (s) per Segment - Unconditional Priority - Transit Vehicles (EB Direction)

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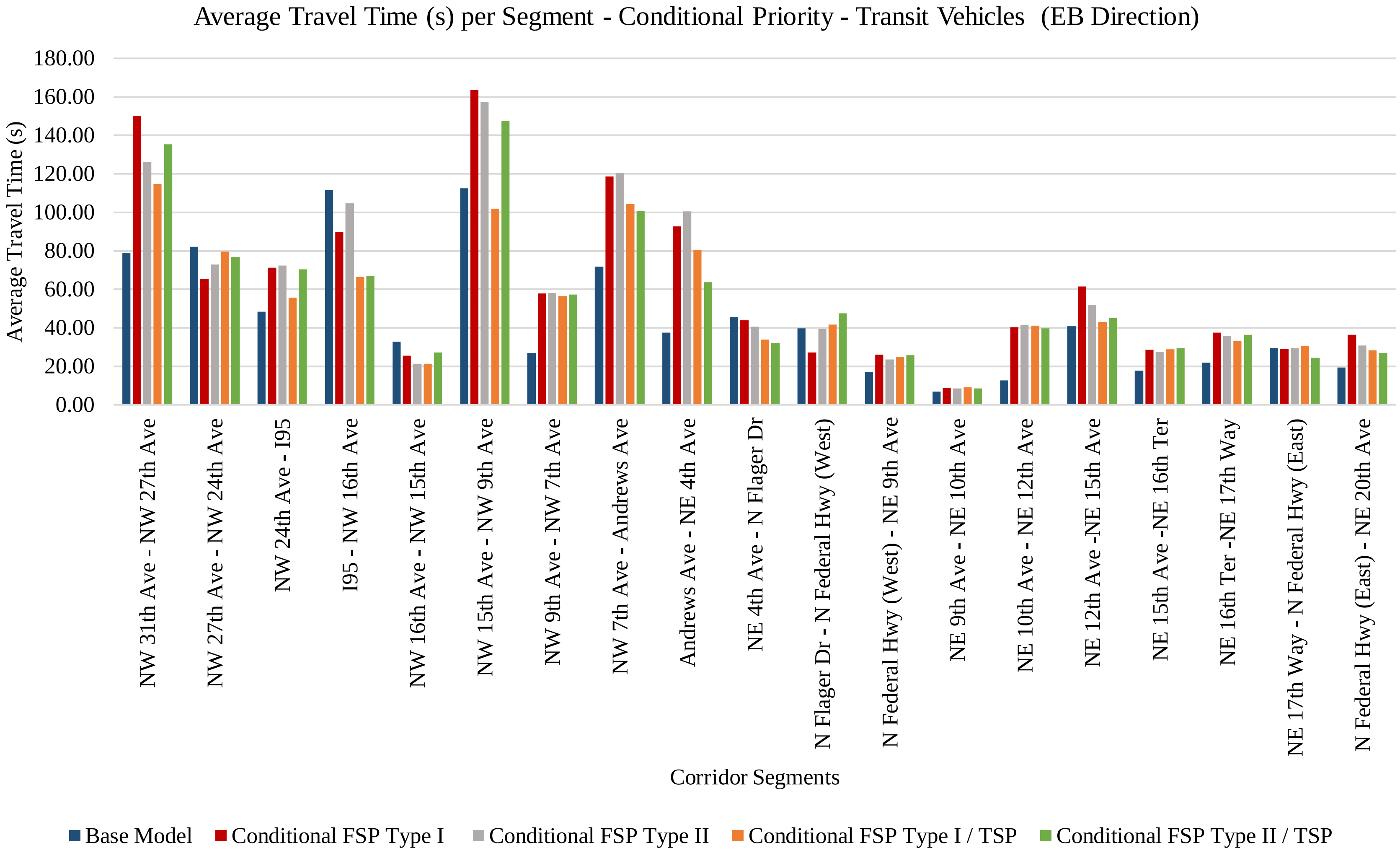

Figure 5-6: Average Travel Time (s) per Segment - Conditional Priority - Transit Vehicles (EB Direction)

The results for the westbound direction are presented next. Table 5-4 presents the average travel time measurements in seconds for all the transport modes in the westbound direction. The results are presented for all the different developed scenarios and for all the consecutive corridor segments. Figures 5-7 and 5-8 represent graphically the average travel time results. Figure 5-7 includes all the measurements from the unconditional priority implementations, while Figure 5-8 shows the measurements from the conditional priority strategies along with the base model.

The analysis of the corridor segment presented both positive and negative results. In most of the segments, the improvements were significant. In some cases, the differences due to the priority implementation were minor, while in some cases the differences were negative. The corridor segments that presented negative results were the NW 9th and NW 7th Avenues and Andrews and NE 4th Avenues. The main reason that these two segments had an increase in their travel time was the geometry of the road and the high volume of vehicles aiming to turn left to the side streets. The travel time increase in both cases was lower than 10 seconds.

The results of the analysis for each priority scenario compared to the base model indicated the positive impacts of all investigated scenarios. The overall travel time improvements were higher than 6.5% in all scenarios, except the TSP scenario with no prioritization of the trucks. The model with the highest performance was the fusion of the FSP and TSP strategies, with an increase of 14.2% on the overall travel time. The lowest improvements were again identified as the conditional priority scenarios, as also observed for the eastbound direction of Sunrise Boulevard.

In Table 5-5, the average travel time measurements in seconds for the freight vehicles for the westbound direction are listed. The results are presented for all the different developed scenarios and for all the consecutive corridor segments. Figures 5-9 and 5-10 represent graphically the average travel time results. Figure 5-9 includes all the measurements from the unconditional priority implementations, while Figure 5-10 shows the measurements from the conditional priority strategies along with the base model.

The results showed improvements in terms of the time that the trucks need to travel from the east entrance of Sunrise Boulevard, until the west exit. In most of the segments, the travel time reduction reached 47% compared with the base model. On specific segments, the travel time was consistent or minor, while on a few corridor segments it was negative. The two corridor segments that had a negative impact on the freight mobility were from NW 15th Avenue until NW 9th Avenue and from the NW 9th Avenue until the NW 7th Avenue. The increase of travel time on these segments was related to the high vehicle volumes that aimed to turn left to the side streets and the increase wasn't higher than 20 seconds.

The comparison of the priority scenarios with the base model concluded on the positive impact of all the developed scenarios. The unconditional priority strategies had higher improvements than the conditional ones and the TSP scenario was the one with the lowest reduction on the average travel time. The highest performance was identified on the FSP and FSP/TSP scenarios with an 18% savings on the trucks' travel time along Sunrise Boulevard.

Table 5-4: Average Travel Time (s) per Segment – All Vehicles – WB Direction

Average Travel Time (s) per Segment – All Vehicles – WB Direction									
Segment #	**Corridor Segment**	**Base Model**	**FSP**	**Cond. FSP Type I**	**Cond. FSP Type II**	**TSP**	**FSP/ TSP**	**Cond. FSP Type I / TSP**	**Cond. FSP Type II / TSP**
1	**NW 31st Ave - NW 27th Ave**	102.71	78.49	71.26	72.74	99.17	66.27	69.14	74.93
2	**NW 27th Ave - NW 24th Ave**	73.31	64.06	68.25	73.11	72.10	56.80	58.56	67.69
3	**NW 24th Ave - I-95**	55.86	44.23	50.63	50.06	54.58	43.85	43.65	46.95
4	**I-95 – NW 16th Ave**	53.67	49.47	52.32	53.17	51.82	49.58	50.02	52.77
5	**NW 16th Ave - NW 15th Ave**	22.83	20.02	21.05	21.43	20.32	22.46	22.13	21.46
6	**NW 15th Ave - NW 9th Ave**	78.18	70.88	76.37	73.75	78.18	71.12	70.88	73.46
7	**NW 9th Ave - NW 7th Ave**	28.99	32.96	38.23	28.87	37.46	27.44	30.94	37.85
8	**NW 7th Ave - Andrews Ave**	63.43	54.28	63.32	52.68	62.42	57.14	57.96	62.52
9	**Andrews Ave - NE 4th Ave**	40.04	37.58	42.37	43.58	36.33	40.81	43.81	40.98
10	**NE 4th Ave - N Flagler Dr**	49.61	42.47	42.25	40.53	45.58	39.42	42.01	41.07
11	**N Flagler Dr - N Federal Hwy (West)**	21.86	20.58	19.81	20.31	21.18	20.82	20.42	19.27
12	**N Federal Hwy (West) – NE 9th Ave**	14.72	13.78	14.50	14.66	14.57	14.42	13.95	13.92
13	**NE 9th Ave – NE 10th Ave**	12.11	10.08	9.89	11.44	11.55	8.36	9.73	9.42
14	**NE 10th Ave - NE 12th Ave**	12.48	11.71	11.84	11.89	12.35	11.25	11.61	11.40
15	**NE 12th Ave – NE 15th Ave**	20.37	19.60	20.08	20.00	19.99	19.47	19.47	19.94
16	**NE 15th Ave – NE 16th Ter**	40.91	38.07	36.50	39.57	37.38	37.38	40.09	40.00
17	**NE 16th Ter – NE 17th Way**	20.54	20.46	20.08	20.82	20.46	19.89	20.37	20.28
18	**NE 17th Way – N Federal Hwy (East)**	27.87	27.27	26.90	24.30	26.71	26.32	24.56	26.90
19	**N Federal Hwy (East) – NE 20th Ave**	95.25	94.59	94.49	99.20	94.48	83.22	93.52	100.08
SUNRISE BLVD PROJECT LIMITS		**834.76**	**750.59**	**780.14**	**772.12**	**816.62**	**716.03**	**742.81**	**780.89**

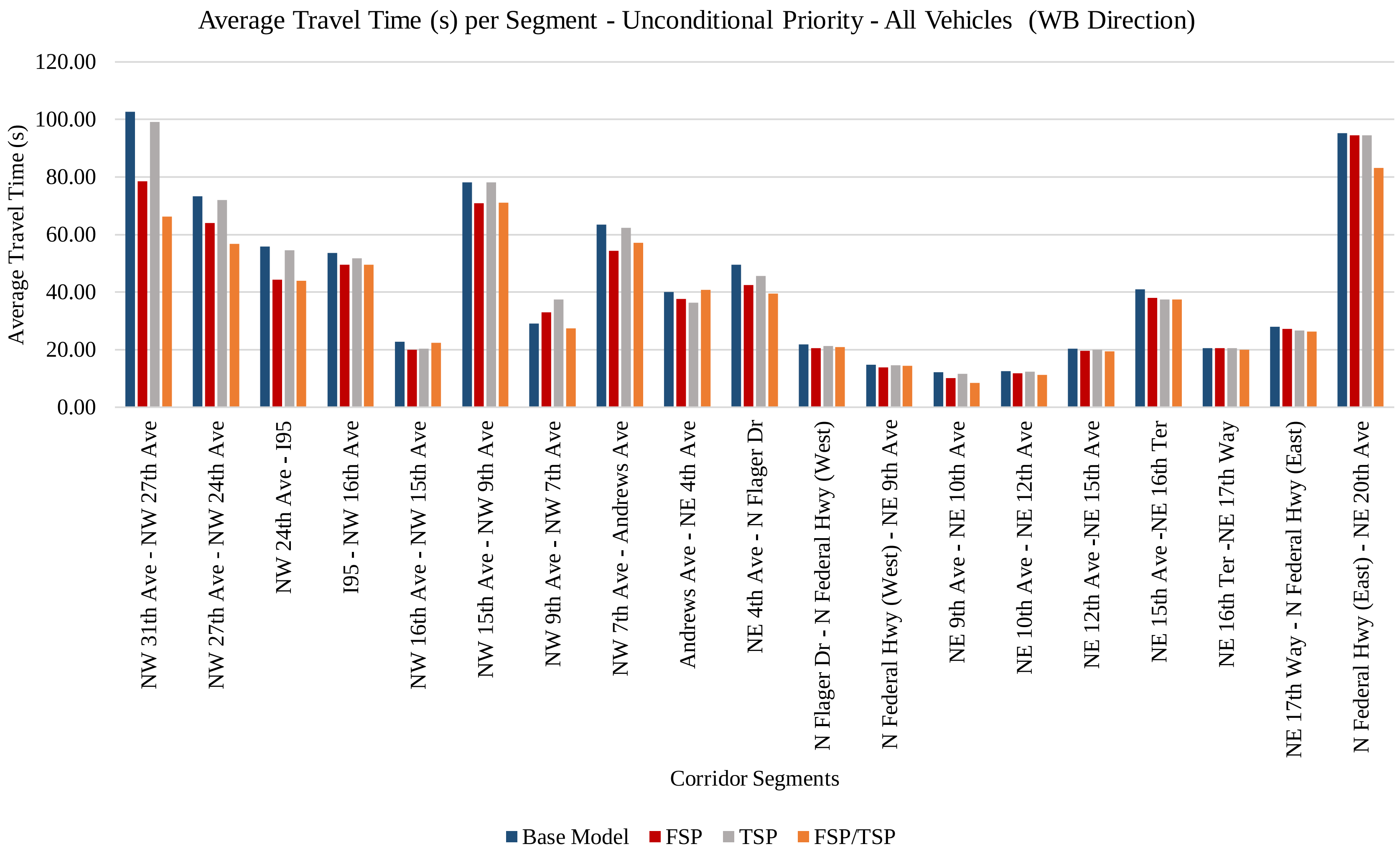

Figure 5-7: Average Travel Time (s) per Segment - Unconditional Priority - All Vehicles (WB Direction)

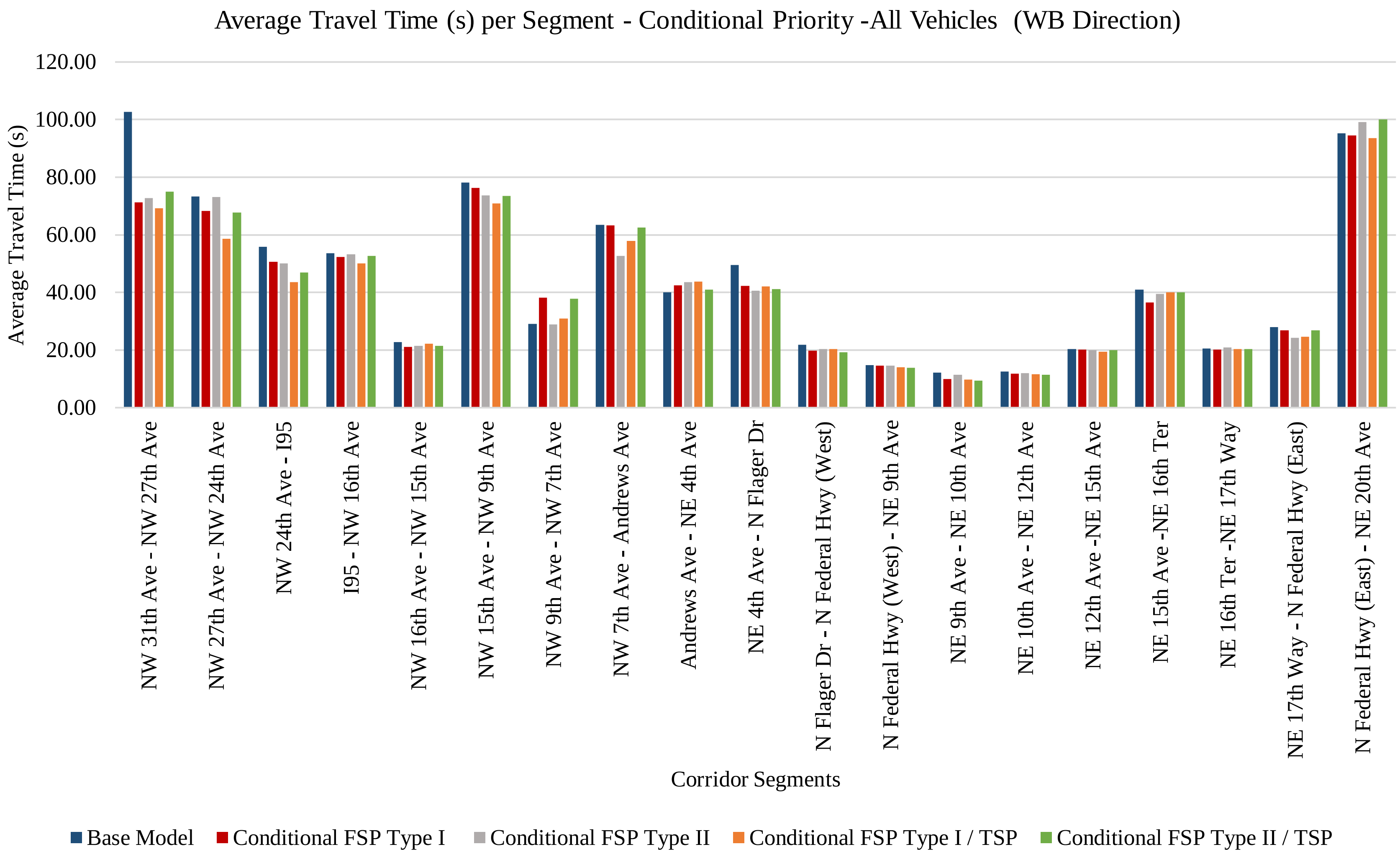

Figure 5-8: Average Travel Time (s) per Segment - Conditional Priority -All Vehicles (WB Direction)

Table 5-5: Average Travel Time (s) per Segment – Freight Vehicles – WB Direction

Average Travel Time (s) per Segment – Freight Vehicles – WB Direction									
Segment #	**Corridor Segment**	**Base Model**	**FSP**	**Cond. FSP Type I**	**Cond. FSP Type II**	**TSP**	**FSP/ TSP**	**Cond. FSP Type I / TSP**	**Cond. FSP Type II / TSP**
1	**NW 31st Ave - NW 27th Ave**	117.10	80.23	79.32	78.02	116.41	63.98	78.58	76.08
2	**NW 27th Ave - NW 24th Ave**	83.05	56.48	64.44	75.08	71.75	55.45	60.30	69.58
3	**NW 24th Ave - I-95**	57.66	45.10	57.51	49.96	57.19	42.38	45.62	52.12
4	**I-95 – NW 16th Ave**	59.77	53.51	59.47	58.63	55.06	51.77	54.54	58.71
5	**NW 16th Ave - NW 15th Ave**	24.48	17.66	20.91	22.25	22.31	22.82	23.40	21.04
6	**NW 15th Ave - NW 9th Ave**	80.43	74.90	85.19	81.38	82.43	73.27	78.39	75.03
7	**NW 9th Ave - NW 7th Ave**	36.04	34.36	40.32	31.61	47.17	32.12	39.99	36.00
8	**NW 7th Ave - Andrews Ave**	70.96	59.40	70.06	61.62	69.04	62.38	68.50	66.80
9	**Andrews Ave - NE 4th Ave**	49.81	34.29	34.25	43.06	29.53	49.54	47.14	39.21
10	**NE 4th Ave - N Flagler Dr**	48.81	36.19	46.11	40.17	48.28	42.72	39.84	41.71
11	**N Flagler Dr - N Federal Hwy (West)**	32.61	20.02	21.83	21.95	32.31	25.67	29.45	23.28
12	**N Federal Hwy (West) – NE 9th Ave**	19.82	12.38	18.57	16.86	19.02	17.52	15.44	15.91
13	**NE 9th Ave – NE 10th Ave**	16.19	10.73	11.55	13.57	15.91	8.57	10.68	10.49
14	**NE 10th Ave - NE 12th Ave**	12.79	11.63	12.21	12.49	12.28	11.45	11.99	11.69
15	**NE 12th Ave – NE 15th Ave**	20.80	19.79	20.04	20.76	20.80	20.79	20.15	20.70
16	**NE 15th Ave – NE 16th Ter**	37.19	33.75	34.50	34.03	28.53	33.69	43.40	39.70
17	**NE 16th Ter – NE 17th Way**	20.54	20.04	19.93	20.34	20.16	19.09	19.59	20.37
18	**NE 17th Way – N Federal Hwy (East)**	32.10	25.09	23.11	31.41	25.01	23.33	24.41	30.33
19	**N Federal Hwy (East) – NE 20th Ave**	116.77	116.09	80.40	108.28	111.21	106.66	87.46	124.17
SUNRISE BLVD PROJECT LIMITS		**936.92**	**761.64**	**799.72**	**821.47**	**884.40**	**763.19**	**798.86**	**832.90**

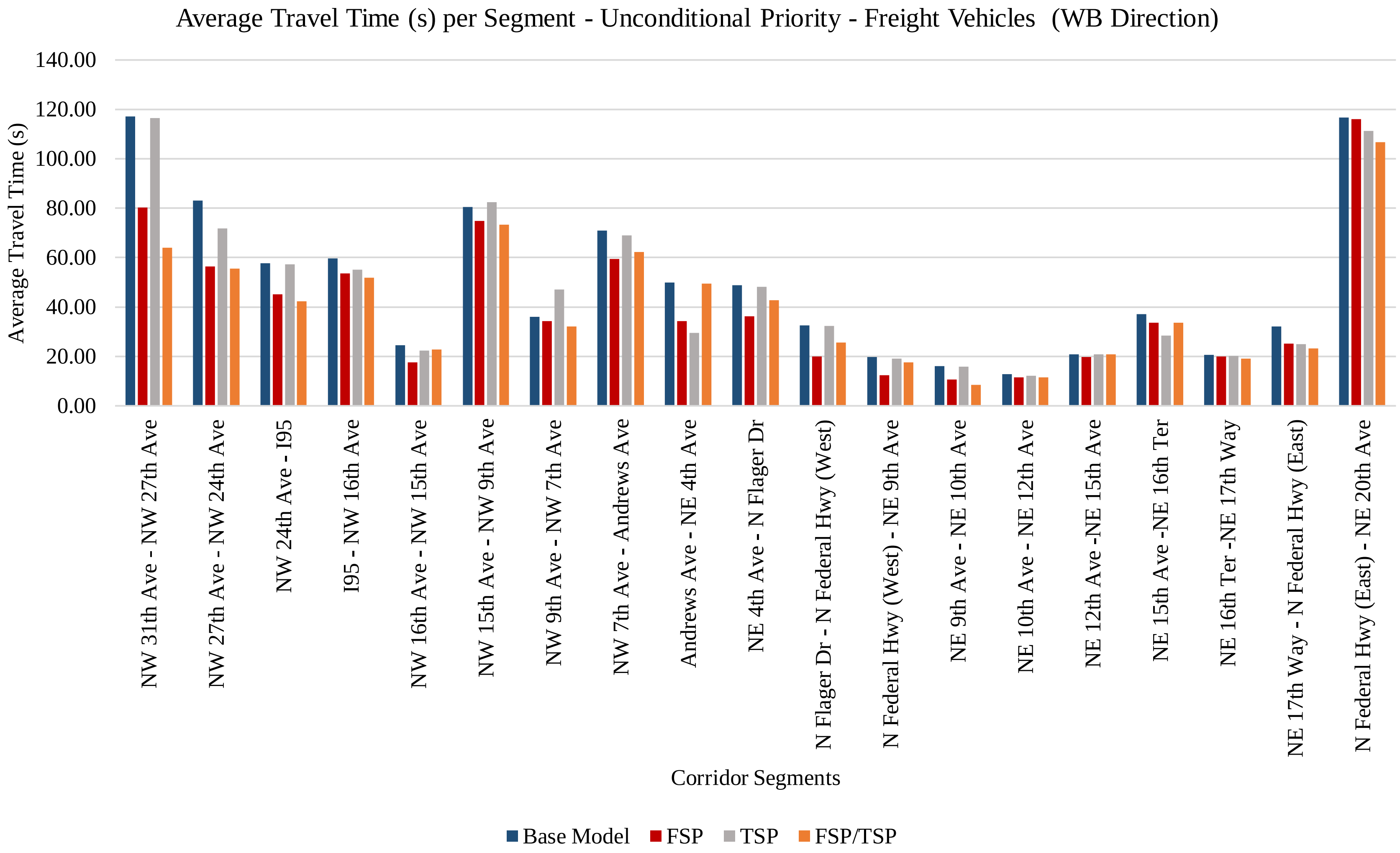

Figure 5-9: Average Travel Time (s) per Segment - Unconditional Priority - Freight Vehicles (WB Direction)

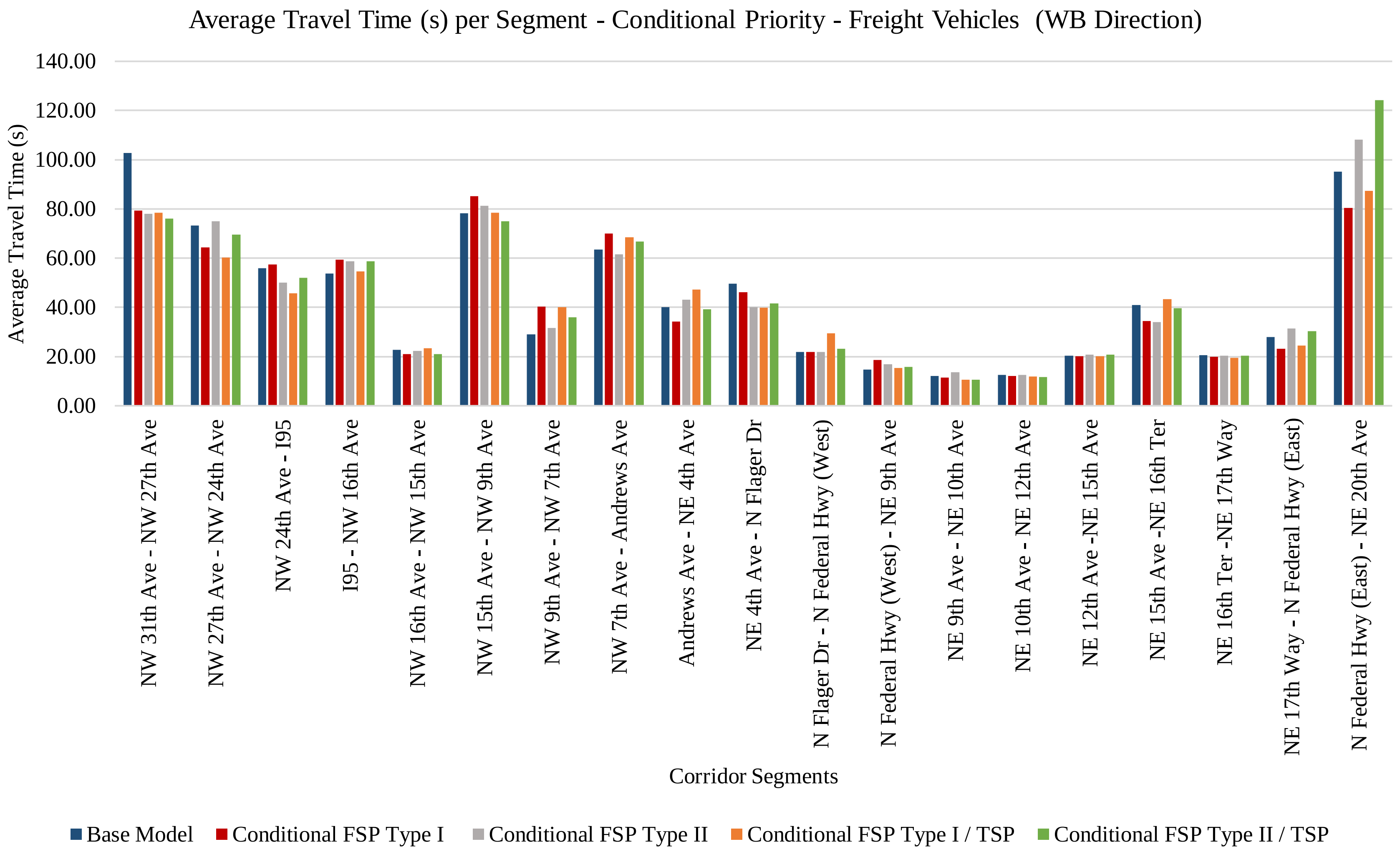

Figure 5-10: Average Travel Time (s) per Segment - Conditional Priority - Freight Vehicles (WB Direction)

The average travel time measurements in seconds for the transit vehicles for the westbound direction are listed in Table 5-6. The results are presented for all the different developed scenarios and for all the consecutive corridor segments. Figures 5-11 and 5-12 represent graphically the average travel time results. Figure 5-11 includes all the measurements from the unconditional priority implementations, while Figure 5-12 the measurements from the conditional priority strategies along with the base model.

The transit movements were also benefited from the implementation of the priority strategies with the savings from the base model to reach 60% on specific corridor segments. Negative results were located for a few segments due to the geometry of the road and the traffic conditions. All the models enhanced the transit movement's mobility, through the implementation of different priority strategies. The scenario with the highest improvements was the TSP, while the models that didn't perform as efficiently as the rest of the models are the FSP and the conditional FSP Type I that excluded vehicle class 5.

The overall travel time measurements in seconds for the eastbound and westbound directions on Sunrise Boulevard for all the priority strategies and all the transport modes are presented in Table 5-7. The graphical representation of the results from the Table and are presented in Figures 5-13, 5-14 and 5-15.

The analysis of Table 5-7 along with its Figures showed that all the scenarios in comparison to the base model had improvements on the travel time for all vehicles and for each transport mode separately. The lowest performance was identified in the TSP scenario since it was implemented to favor only the transit movements. The highest improvements were mainly located on the unconditional priority strategies. The specific scenarios had to accommodate the highest number of priorities calls in comparison with the rest of the scenarios. Thus, it is justifiable the presence of a high reduction in the average travel time for those scenarios.

Table 5-6: Average Travel Time (s) per Segment – Transit Vehicles – WB Direction

Average Travel Time (s) per Segment – Transit Vehicles – WB Direction									
Segment #	**Corridor Segment**	**Base Model**	**FSP**	**Cond. FSP Type I**	**Cond. FSP Type II**	**TSP**	**FSP/ TSP**	**Cond. FSP Type I / TSP**	**Cond. FSP Type II / TSP**
1	**NW 31st Ave - NW 27th Ave**	140.67	149.37	143.10	139.73	128.60	127.00	126.83	127.10
2	**NW 27th Ave - NW 24th Ave**	75.90	86.72	84.20	75.21	71.76	63.36	65.15	74.45
3	**NW 24th Ave - I-95**	58.50	56.17	52.90	54.57	31.57	58.23	39.63	32.80
4	**I-95 – NW 16th Ave**	58.60	61.37	67.45	69.66	61.47	52.06	72.93	65.65
5	**NW 16th Ave - NW 15th Ave**	18.00	15.90	14.70	21.83	18.00	21.10	13.80	19.33
6	**NW 15th Ave - NW 9th Ave**	162.50	128.10	156.27	135.23	141.63	143.80	139.50	150.83
7	**NW 9th Ave - NW 7th Ave**	127.03	49.33	97.50	60.80	64.57	69.57	50.77	58.00
8	**NW 7th Ave - Andrews Ave**	85.67	92.97	81.50	85.67	93.38	81.23	99.30	85.10
9	**Andrews Ave - NE 4th Ave**	55.50	64.41	64.19	70.95	62.97	67.55	71.63	61.94
10	**NE 4th Ave - N Flagler Dr**	79.63	68.27	53.70	51.70	41.17	51.50	60.07	43.87
11	**N Flagler Dr - N Federal Hwy (West)**	70.77	42.53	46.83	49.20	37.33	29.90	39.40	40.20
12	**N Federal Hwy (West) – NE 9th Ave**	15.83	11.53	15.53	14.27	11.47	14.93	14.20	12.20
13	**NE 9th Ave – NE 10th Ave**	18.39	13.49	15.19	15.76	15.80	11.77	13.06	14.89
14	**NE 10th Ave - NE 12th Ave**	25.41	25.33	24.93	25.07	24.61	24.20	24.09	24.60
15	**NE 12th Ave – NE 15th Ave**	25.73	21.71	21.35	24.25	22.10	23.17	24.00	25.05
16	**NE 15th Ave – NE 16th Ter**	44.80	51.28	52.05	56.82	60.23	57.78	60.55	58.88
17	**NE 16th Ter – NE 17th Way**	34.88	34.70	33.60	34.18	33.53	33.57	34.78	34.87
18	**NE 17th Way – N Federal Hwy (East)**	63.23	47.23	57.20	45.13	32.53	33.10	32.80	36.40
19	**N Federal Hwy (East) – NE 20th Ave**	109.73	120.70	75.87	106.07	66.83	104.07	55.77	65.40
SUNRISE BLVD PROJECT LIMITS		**1270.77**	**1141.11**	**1158.05**	**1136.10**	**1019.55**	**1067.89**	**1038.26**	**1031.55**

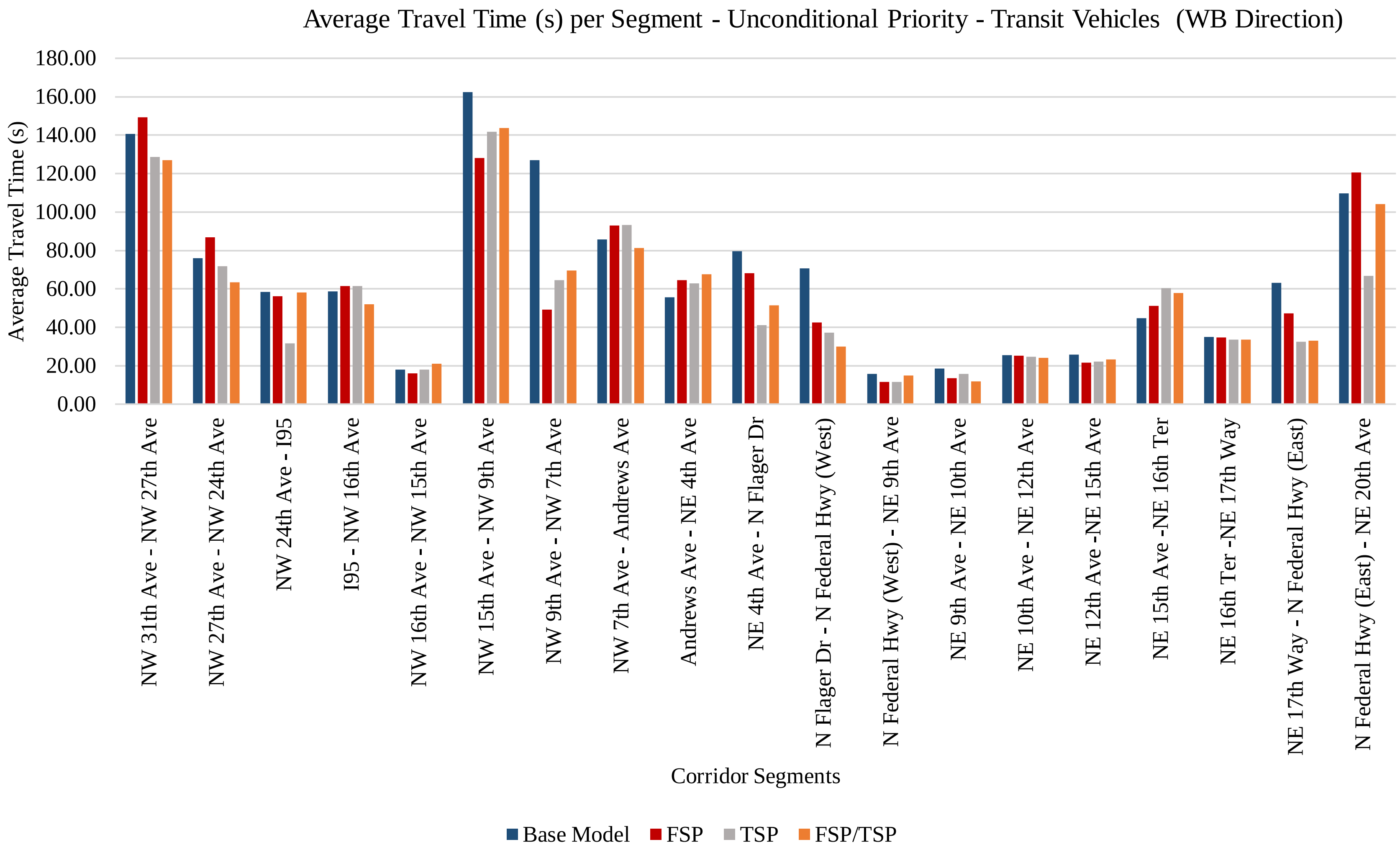

Figure 5-11: Average Travel Time (s) per Segment - Unconditional Priority - Transit Vehicles (WB Direction)

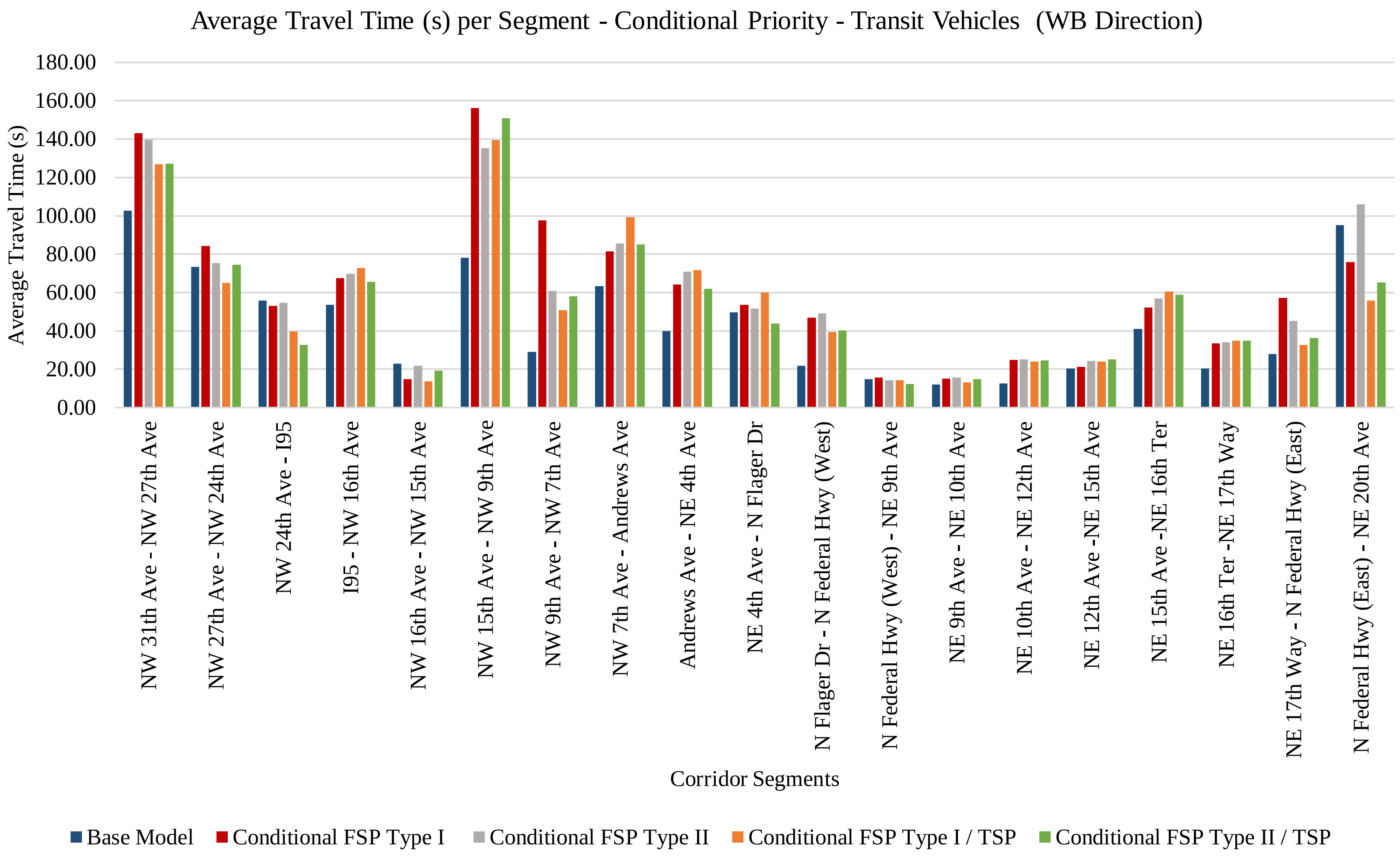

Figure 5-12: Average Travel Time (s) per Segment - Conditional Priority - Transit Vehicles (WB Direction)

Table 5-7: Average Travel Time for All Scenarios and All Transport Modes (EB & WB Directions)

	Base Model	FSP	Cond. FSP Type I	Cond. FSP Type II	TSP	FSP /TSP	Cond. FSP Type I / TSP	Cond. FSP Type II / TSP
Average Travel Time (s) – All Vehicles								
Eastbound Direction	853.58	725.80	745.25	779.66	796.01	711.86	743.66	853.58
Westbound Direction	834.76	750.59	780.14	772.12	816.62	716.03	742.81	834.76
Average Travel Time (s) – Freight Vehicles								
Eastbound Direction	944.17	764.38	772.82	825.41	878.14	734.69	775.59	812.08
Westbound Direction	936.92	761.64	799.72	821.47	884.40	763.19	798.86	832.90
Average Travel Time (s) – Transit Vehicles								
Eastbound Direction	1307.93	1106.46	1173.86	1163.00	1162.67	1033.90	994.86	1061.15
Westbound Direction	1270.77	1141.11	1158.05	1136.10	1019.55	1067.89	1038.26	1031.55

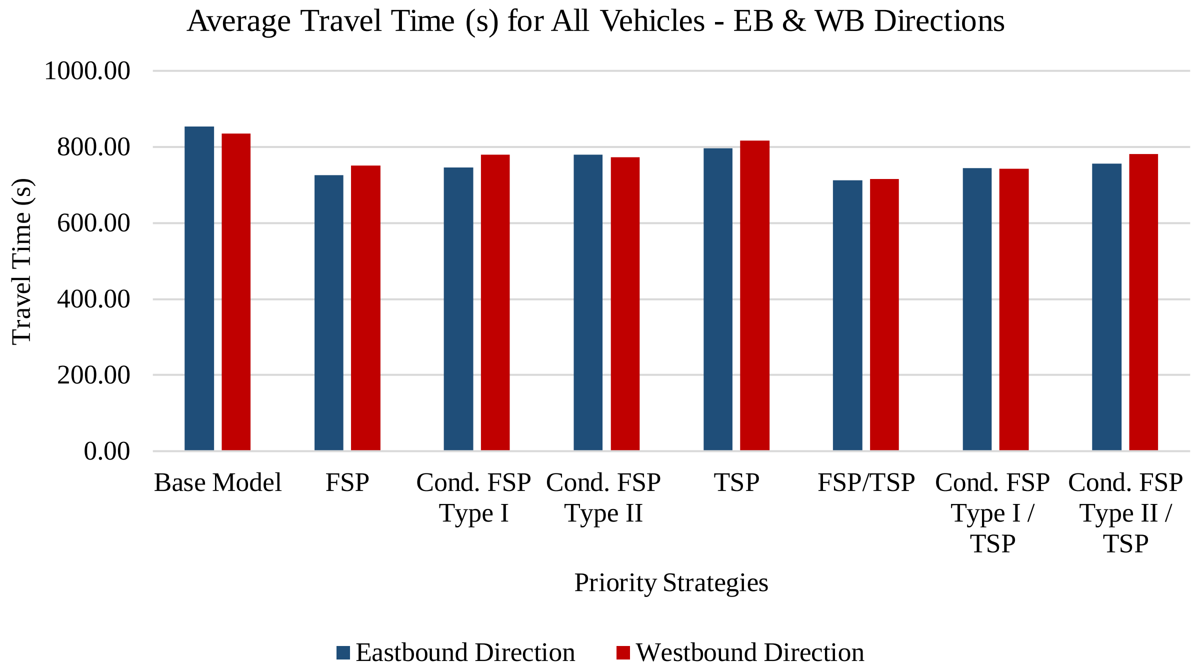

Figure 5-13: Average Travel Time (s) for All Vehicles - EB & WB Directions

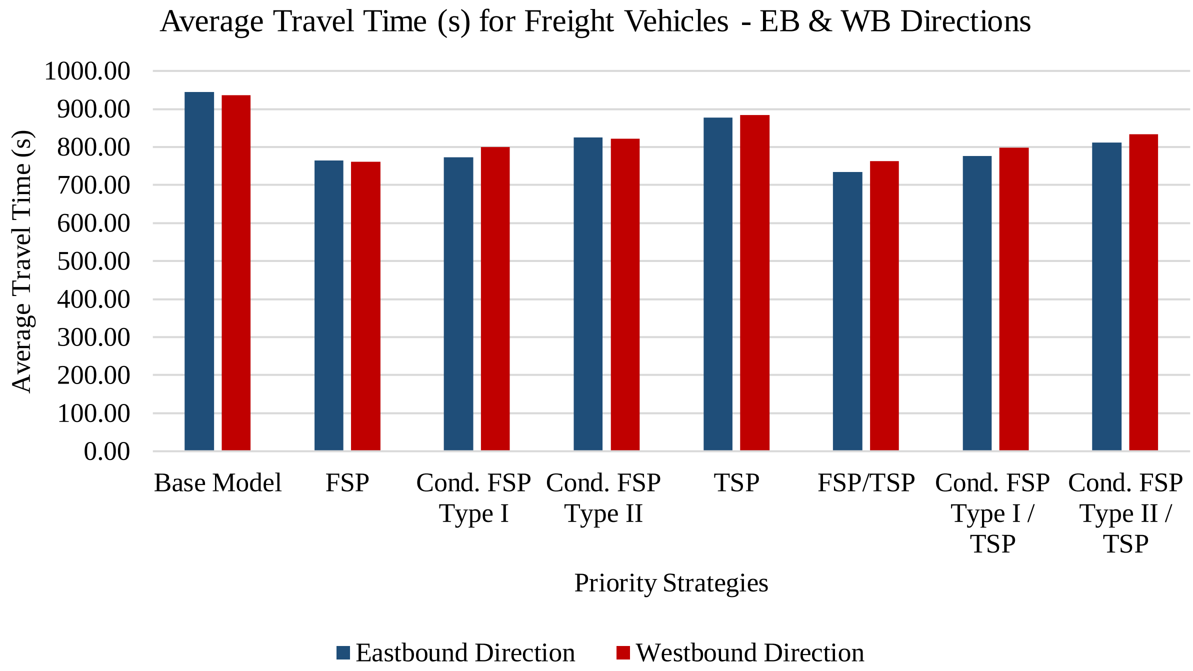

Figure 5-14: Average Travel Time (s) for Freight Vehicles - EB & WB Directions

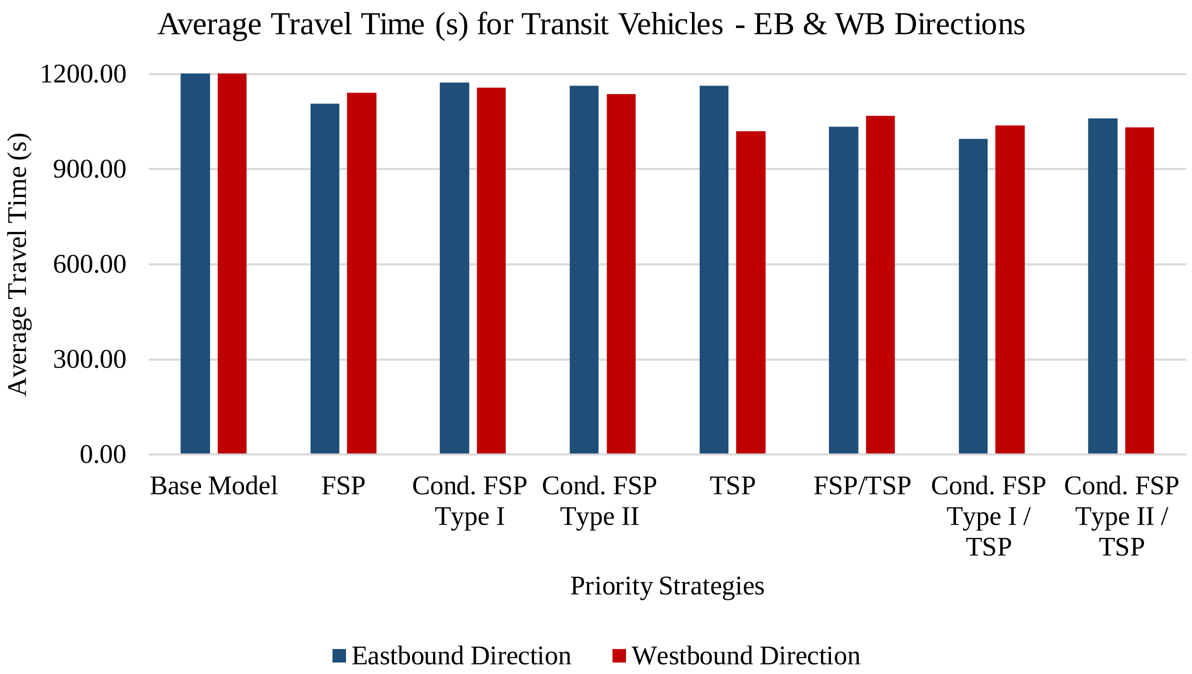

Figure 5-15: Average Travel Time (s) for Transit Vehicles - EB & WB Directions

Table 5-8: Travel Time Savings (%) for All Scenarios and All Transport Modes (EB & WB Directions)

	FSP	Cond. FSP Type I	Cond. FSP Type II	TSP	FSP /TSP	Cond. FSP Type I / TSP	Cond. FSP Type II / TSP
Average Travel Time Savings (%) – All Vehicles							
Eastbound Direction	14.97	12.69	8.66	6.74	16.60	12.88	11.43
Westbound Direction	10.08	6.54	7.50	2.17	14.22	11.02	6.45
Average Travel Time Savings (%) – Freight Vehicles							
Eastbound Direction	19.04	18.15	12.58	6.99	22.19	17.86	13.99
Westbound Direction	18.71	14.64	12.32	5.61	18.54	14.74	11.10
Average Travel Time Savings (%) – Transit Vehicles							
Eastbound Direction	15.40	10.25	11.08	11.11	20.95	23.94	18.87

Westbound Direction	10.20	8.87	10.60	19.77	15.97	18.30	18.83

Table 5-8 presents the travel time savings in percentage for both directions, all the priority strategies, and all the transport modes. The graphical representation of the results from the Table and are presented in Figures 5-16, 5-17 and 5-18.

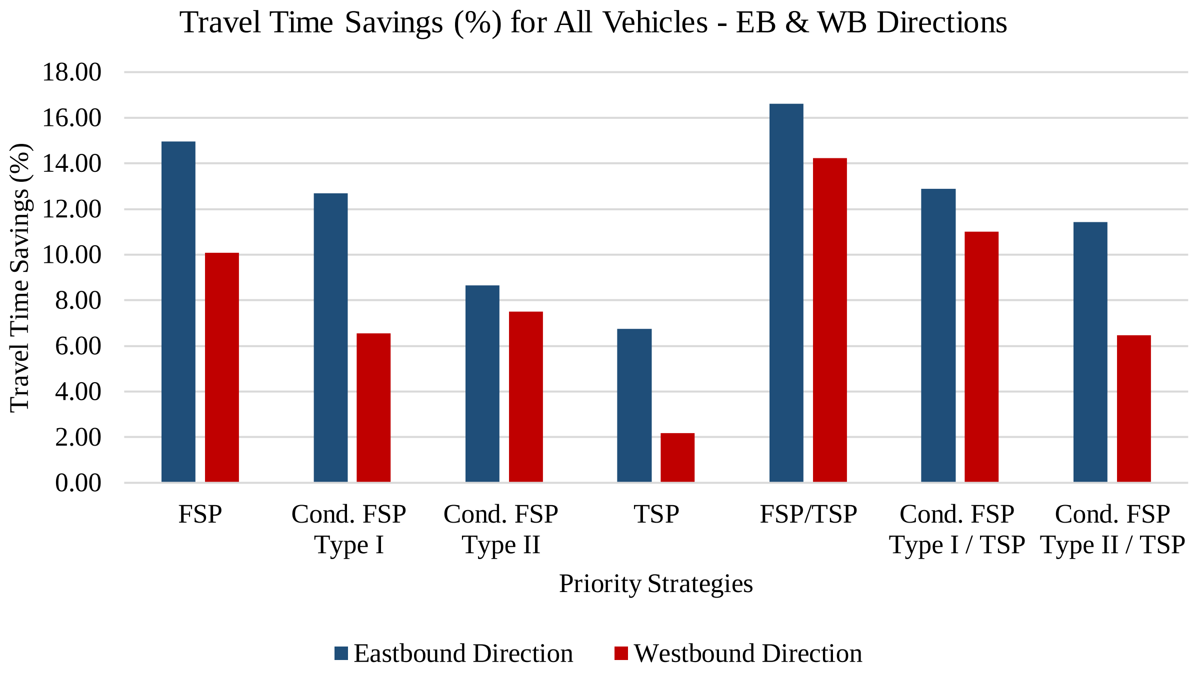

Figure 5-16: Travel Time Savings (%) for All Vehicles - EB & WB Directions

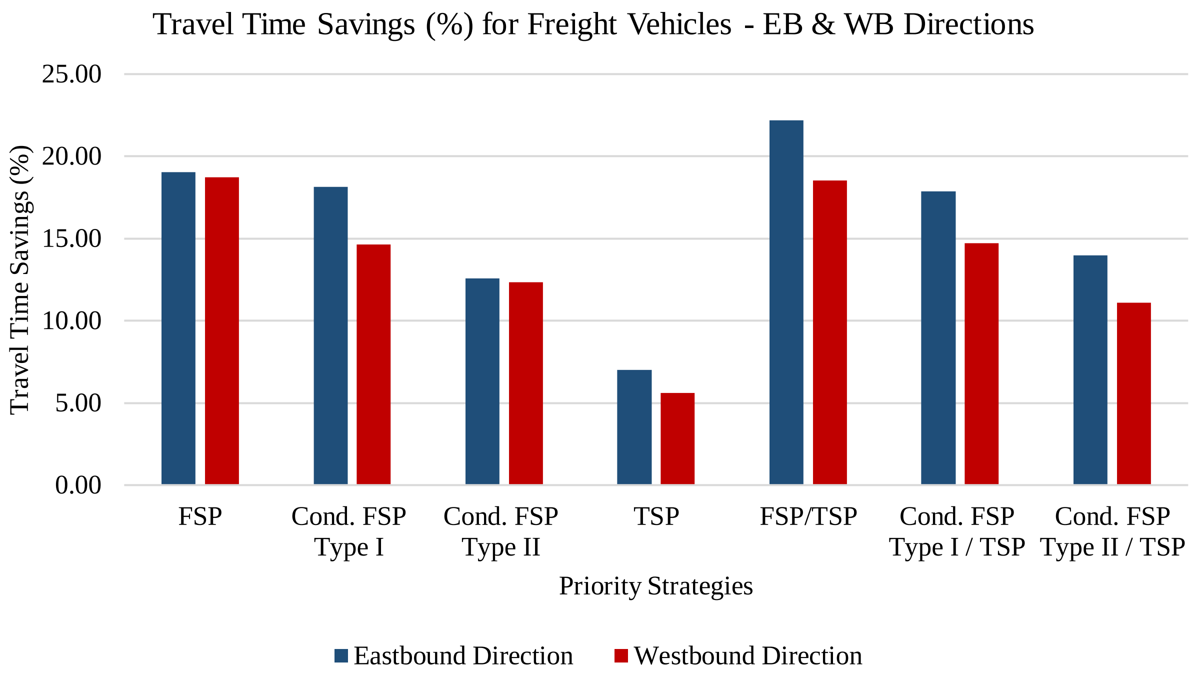

Figure 5-17: Travel Time Savings (%) for Freight Vehicles - EB & WB Directions

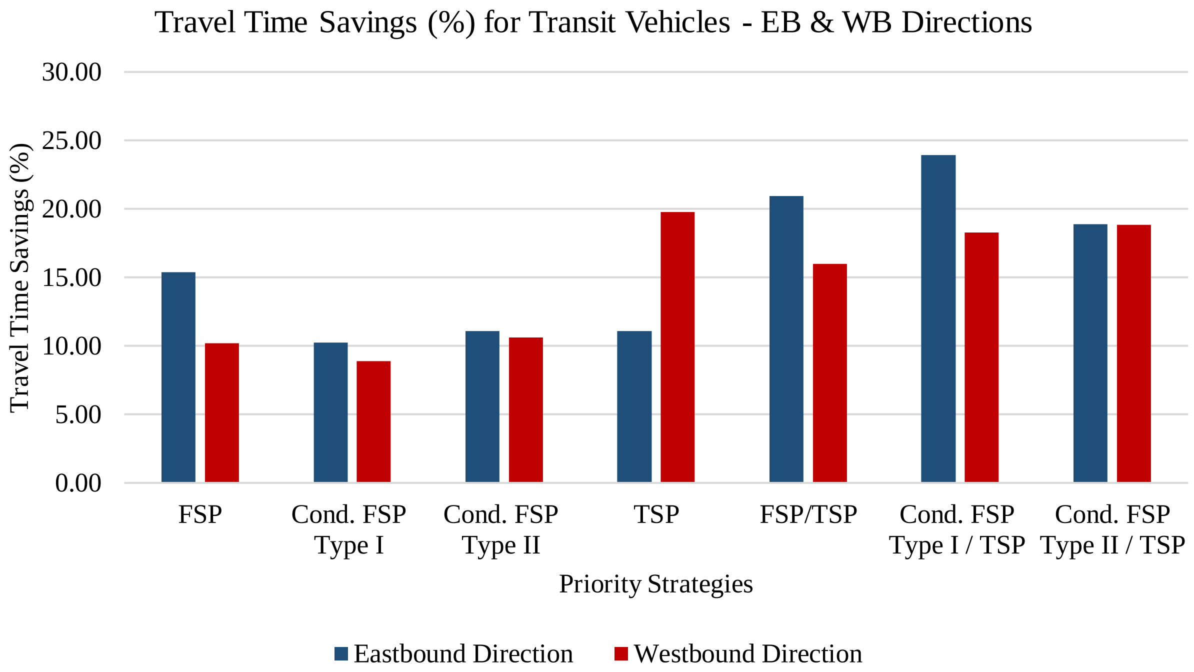

Figure 5-18: Travel Time Savings (%) for Transit Vehicles - EB & WB Directions

5.2 Delay Analysis

Delay is an important measure of effectiveness widely used for evaluating the benefits of signal timing improvements for individual intersections or facilities. The average delay results in seconds for all vehicles extracted from all scenarios are presented in the following Table 5-9. The results are presented for all the different developed scenarios and for all the consecutive corridor segments. Figure 5-19 includes all the measurements from the unconditional priority implementations, while Figure 5-20 the measurements from the conditional priority strategies along with the base model.

In general, the delays of the vehicles along the eastbound direction of Sunrise Boulevard were significantly enhanced. The average delay savings on corridor segments reached 50% in comparison with the base model. Few segments presented an increase in the delays that were up to 20 seconds. The problematic conditions on those segments were related mainly to the geometry of the road and the high volumes of vehicles aiming to turn left to the side streets.

All the different scenarios had positive results regarding the base model. The models with the highest performance were the FSP and FSP/TSP. Both scenarios provided unconditionally priority to all vehicles that requesting to be prioritized and they had lower delays in comparison with the conditional priorities. Thus, along with the movement of the priority vehicles, the rest of the network was also benefited.

Table 5-9: Average Delay per Segment - All Vehicles – EB Direction

Average Delay (s) per Segment – All Vehicles – EB Direction									
Segment #	**Corridor Segment**	**Base Model**	**FSP**	**Cond. FSP Type I**	**Cond. FSP Type II**	**TSP**	**FSP/ TSP**	**Cond. FSP Type I / TSP**	**Cond. FSP Type II / TSP**
1	**NW 31st Ave - NW 27th Ave**	24.86	28.58	34.25	31.30	24.18	24.12	23.90	28.56
2	**NW 27th Ave - NW 24th Ave**	47.94	35.89	35.28	44.38	43.31	35.26	38.38	35.46
3	**NW 24th Ave - I-95**	16.79	14.14	15.18	16.05	16.45	13.64	15.97	16.06
4	**I-95 – NW 16th Ave**	71.70	31.83	28.54	41.08	49.30	24.48	27.23	37.00
5	**NW 16th Ave - NW 15th Ave**	16.96	15.30	14.54	14.71	14.75	11.95	14.04	15.30
6	**NW 15th Ave - NW 9th Ave**	58.35	34.86	31.98	35.01	43.41	29.41	32.12	37.21
7	**NW 9th Ave - NW 7th Ave**	9.09	12.62	19.87	11.93	15.85	12.08	14.04	12.65
8	**NW 7th Ave - Andrews Ave**	33.98	23.21	21.55	32.21	30.08	21.07	26.52	26.72
9	**Andrews Ave - NE 4th Ave**	15.42	15.28	12.38	25.56	8.01	13.28	18.20	13.62
10	**NE 4th Ave - N Flagler Dr**	31.83	16.29	19.02	17.35	30.47	17.30	22.33	21.27
11	**N Flagler Dr - N Federal Hwy (West)**	25.64	16.22	16.76	15.99	19.96	16.34	16.33	16.93
12	**N Federal Hwy (West) – NE 9th Ave**	5.79	2.74	2.12	3.30	5.67	2.90	3.14	3.03
13	**NE 9th Ave – NE 10th Ave**	0.52	0.44	0.50	0.43	0.49	0.47	0.44	0.49
14	**NE 10th Ave - NE 12th Ave**	1.59	1.15	1.28	1.17	1.45	1.19	1.07	1.26
15	**NE 12th Ave – NE 15th Ave**	22.89	16.42	21.75	21.89	21.81	12.88	21.29	20.77
16	**NE 15th Ave – NE 16th Ter**	6.60	2.33	3.07	6.56	5.80	2.37	4.28	4.67
17	**NE 16th Ter – NE 17th Way**	6.59	6.57	11.31	6.55	3.59	13.84	4.96	9.13
18	**NE 17th Way – N Federal Hwy (East)**	12.58	10.94	14.73	14.84	15.39	16.10	17.11	15.79
19	**N Federal Hwy (East) – NE 20th Ave**	6.99	3.58	4.56	4.17	4.74	4.77	4.06	3.88
SUNRISE BLVD PROJECT LIMITS		**416.10**	**288.40**	**308.66**	**344.50**	**354.69**	**273.44**	**305.42**	**319.80**

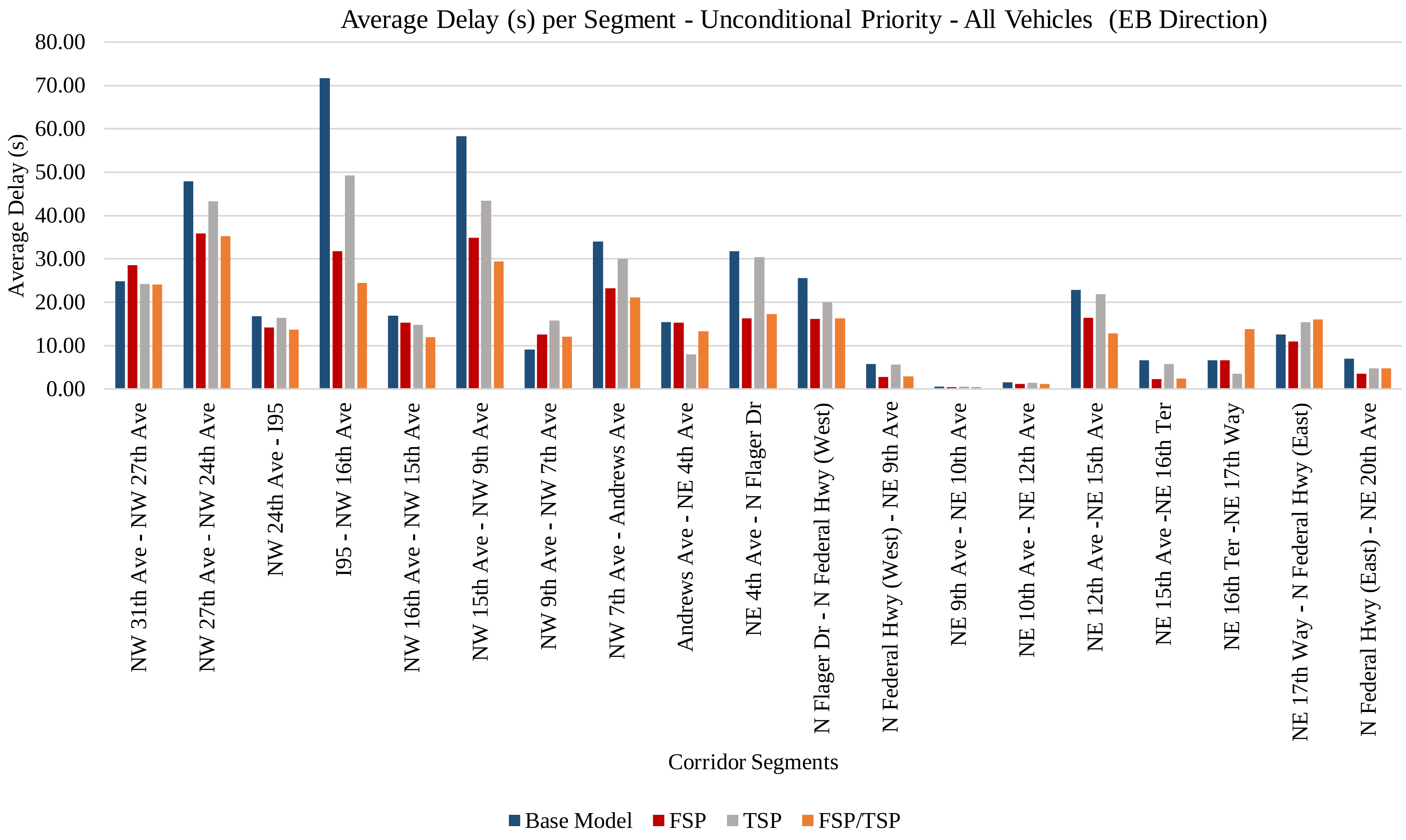

Figure 5-19: Average Delay (s) per Segment - Unconditional Priority - All Vehicles (EB Direction)

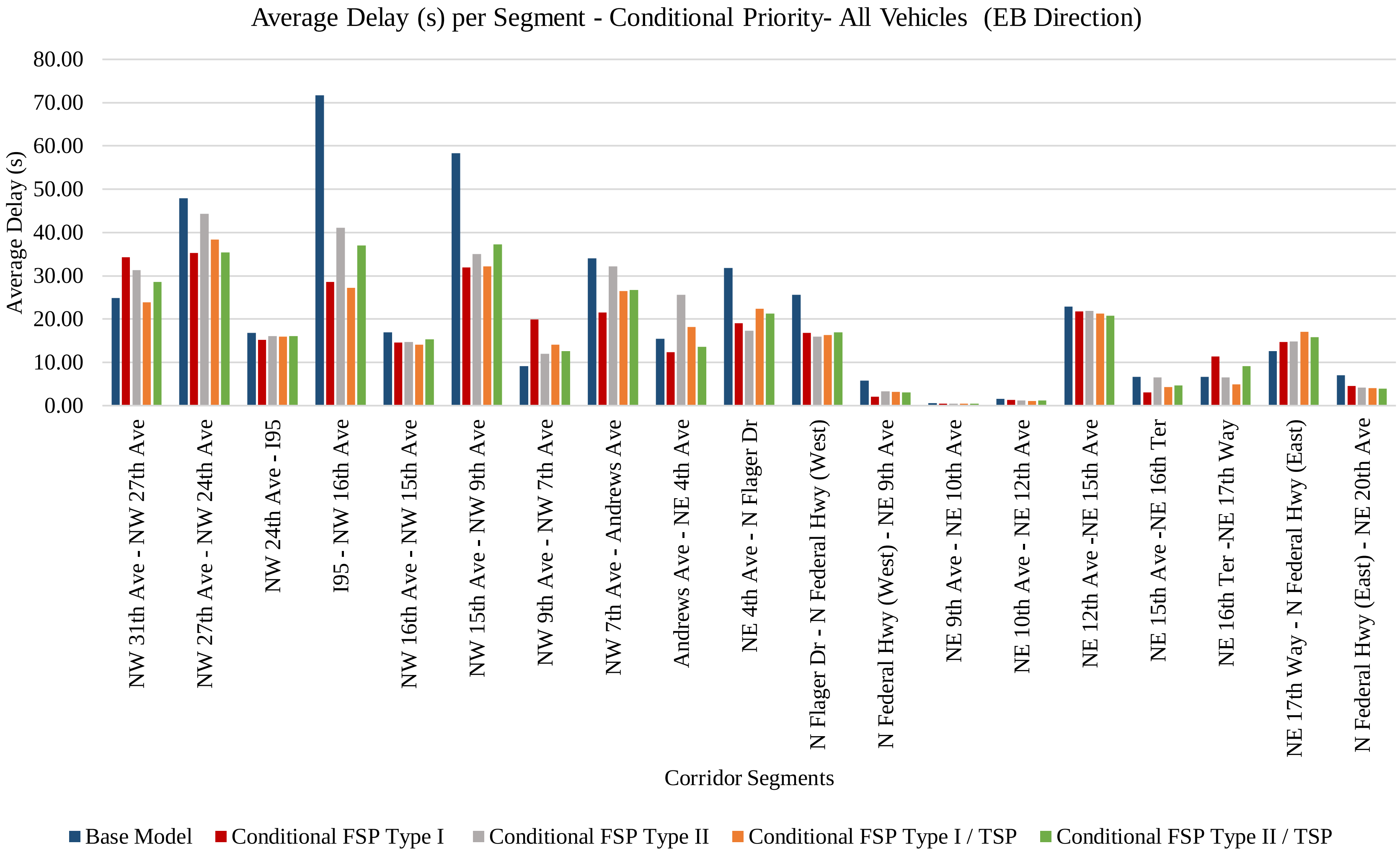

Figure 5-20: Average Delay (s) per Segment - Conditional Priority- All Vehicles (EB Direction)

In Table 5-10, the average delay measurements in seconds for the freight vehicles for the eastbound direction are listed. Figures 5-21 and 5-22 represent graphically the average delay results. Figure 5-21 includes all the measurements from the unconditional priority implementations, while Figure 5-22 the measurements from the conditional priority strategies along with the base model.

The results showed improvements in the time that trucks need to travel from the west entrance of Sunrise Boulevard, until the east exit. In most of the segments the average delay reduction was significant, and, in some cases, it had a reduction of 50% compared with the base model. On specific segments, the delay was stable or had minor reductions, while on a few corridor segments it was increased. The corridor segments that had a negative impact on the freight mobility were NW 31st Avenue - NW 27th Avenue, NW 9th Avenue - NW 7th Avenue and Andrews Avenue – NE 4th Avenue. The increase of average delay on these segments was related to the high vehicle volumes that aimed to turn left to the side streets and the increase wasn’t higher than 20-25 seconds.

The comparison of the priority scenarios with the base model concluded on the positive impact of all the developed scenarios. The unconditional priority strategies had higher improvements than the conditional ones and the TSP scenario was the one with the lowest reduction on the average delay. The highest performance was identified on the FSP and FSP/TSP scenarios with around 30% savings on the trucks’ delays along Sunrise Boulevard.

The average delay measurements in seconds for the transit vehicles for the eastbound direction are listed in Table 5-11. The results are presented for all the different developed scenarios and for all the consecutive corridor segments. Figures 5-23 and 5-24 represent graphically the average travel time results. Figure 5-23 includes all the measurements from the unconditional priority implementations, while Figure 5-24 the measurements from the conditional priority strategies along with the base model.

The transit movements were also benefited from the implementation of the priority strategies with the savings from the base model to reach 50-60% on specific corridor segments. Negative results were located on a few segments due to the geometry of the road and the traffic conditions. All the models enhanced the transit movements’ mobility, through the implementation of different priority strategies. The scenario with the highest improvements was the conditional FSP Type I / TSP, while the models that didn’t perform as efficiently as the rest of the models were the conditional FSP Type I and Type II.

Table 5-10: Average Delay (s) per Segment - Freight Vehicles – EB Direction

Average Delay (s) per Segment – Freight Vehicles – EB Direction									
Segment #	**Corridor Segment**	**Base Model**	**FSP**	**Cond. FSP Type I**	**Cond. FSP Type II**	**TSP**	**FSP/ TSP**	**Cond. FSP Type I / TSP**	**Cond. FSP Type II / TSP**
1	**NW 31st Ave - NW 27th Ave**	31.38	34.62	40.95	43.29	34.67	32.91	33.18	36.21
2	**NW 27th Ave - NW 24th Ave**	85.26	62.54	50.90	59.10	63.29	52.54	52.41	53.29
3	**NW 24th Ave - I-95**	27.84	26.41	28.09	28.23	29.63	25.53	28.35	28.80
4	**I-95 – NW 16th Ave**	92.70	44.57	43.25	54.48	69.35	37.47	43.83	51.27
5	**NW 16th Ave - NW 15th Ave**	26.96	24.07	24.13	22.66	22.32	20.61	23.94	23.86
6	**NW 15th Ave - NW 9th Ave**	79.08	57.43	41.95	51.26	62.20	45.14	44.20	59.59
7	**NW 9th Ave - NW 7th Ave**	15.13	17.83	26.91	23.60	30.26	17.63	22.43	18.65
8	**NW 7th Ave - Andrews Ave**	40.96	26.74	23.45	40.17	40.32	25.68	34.59	34.00
9	**Andrews Ave - NE 4th Ave**	17.32	21.14	18.04	34.33	15.20	19.70	27.62	20.63
10	**NE 4th Ave - N Flagler Dr**	49.94	20.56	24.18	19.35	46.92	24.40	23.63	32.26
11	**N Flagler Dr - N Federal Hwy (West)**	35.94	24.80	27.96	23.93	27.94	23.22	19.90	22.92
12	**N Federal Hwy (West) – NE 9th Ave**	10.17	6.00	6.19	6.42	9.59	7.44	6.31	8.55
13	**NE 9th Ave – NE 10th Ave**	1.94	1.71	1.71	1.74	1.84	1.92	1.68	2.12
14	**NE 10th Ave - NE 12th Ave**	2.97	2.64	2.60	2.83	2.91	2.95	2.66	3.40
15	**NE 12th Ave – NE 15th Ave**	32.91	25.38	26.42	26.95	32.74	17.61	29.86	31.91
16	**NE 15th Ave – NE 16th Ter**	9.67	4.67	4.66	9.01	9.59	4.24	7.22	6.50
17	**NE 16th Ter – NE 17th Way**	7.29	8.52	11.25	11.94	6.10	11.57	8.38	11.23
18	**NE 17th Way – N Federal Hwy (East)**	22.83	15.45	26.88	20.50	25.60	23.31	25.83	22.64
19	**N Federal Hwy (East) – NE 20th Ave**	18.40	6.83	10.77	9.22	8.92	8.96	7.82	11.11
SUNRISE BLVD PROJECT LIMITS		**608.70**	**431.92**	**440.28**	**489.01**	**539.39**	**402.85**	**443.83**	**478.91**

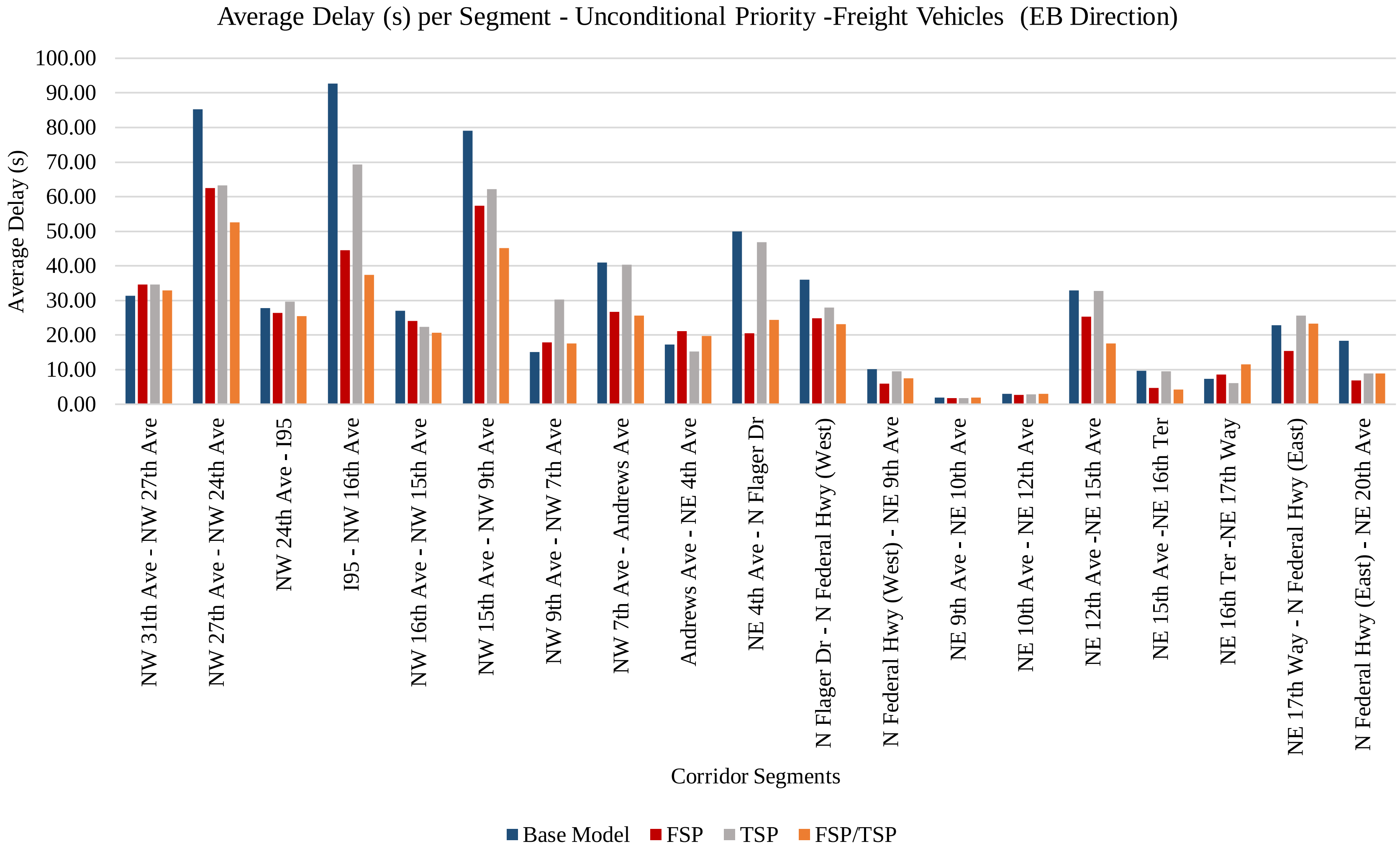

Figure 5-21: Average Delay (s) per Segment - Unconditional Priority -Freight Vehicles (EB Direction)

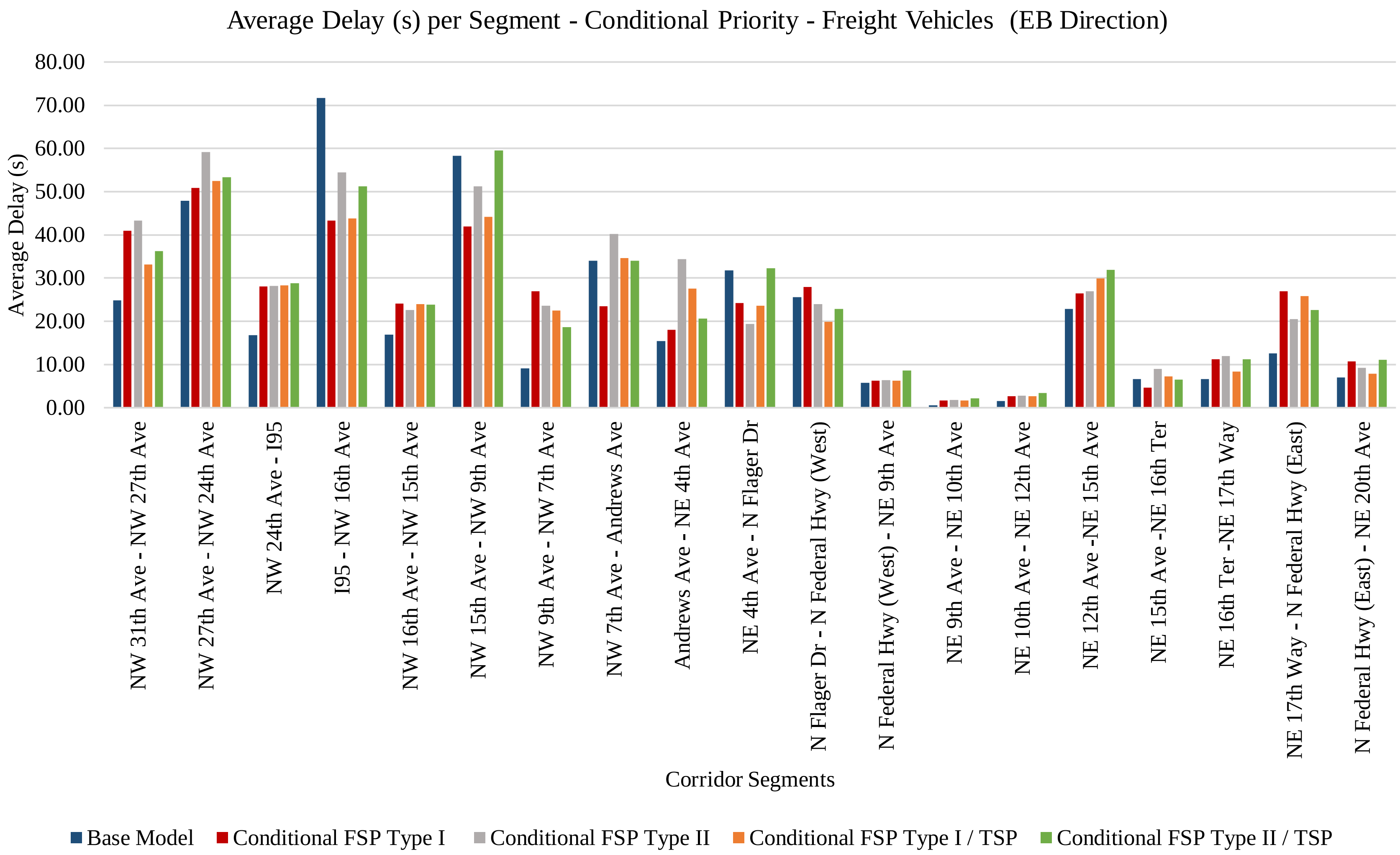

Figure 5-22: Average Delay (s) per Segment - Conditional Priority - Freight Vehicles (EB Direction)

Table 5-11: Average Delay (s) per Segment - Transit Vehicles – EB Direction

Average Delay (s) per Segment – Transit Vehicles – EB Direction									
Segment #	**Corridor Segment**	**Base Model**	**FSP**	**Cond. FSP Type I**	**Cond. FSP Type II**	**TSP**	**FSP/ TSP**	**Cond. FSP Type I / TSP**	**Cond. FSP Type II / TSP**
1	**NW 31st Ave - NW 27th Ave**	68.60	70.57	90.47	67.53	74.60	69.93	56.20	74.67
2	**NW 27th Ave - NW 24th Ave**	80.60	33.50	28.60	36.27	63.07	31.40	42.97	40.07
3	**NW 24th Ave - I-95**	26.50	28.70	37.33	38.40	36.77	24.30	21.73	36.20
4	**I-95 – NW 16th Ave**	94.17	53.10	46.83	61.57	50.80	37.87	23.40	23.90
5	**NW 16th Ave - NW 15th Ave**	11.87	10.60	8.30	3.83	12.37	3.40	3.87	9.63
6	**NW 15th Ave - NW 9th Ave**	104.58	74.07	97.43	91.53	85.50	61.57	44.27	81.65
7	**NW 9th Ave - NW 7th Ave**	44.75	50.83	39.10	39.30	39.43	48.88	37.65	38.70
8	**NW 7th Ave - Andrews Ave**	65.58	65.28	78.25	80.13	71.08	60.58	64.05	60.28
9	**Andrews Ave - NE 4th Ave**	105.10	66.65	69.55	77.53	62.73	40.55	57.48	40.75
10	**NE 4th Ave - N Flagler Dr**	17.88	16.63	29.70	26.50	18.80	19.78	18.78	17.18
11	**N Flagler Dr - N Federal Hwy (West)**	22.45	16.53	11.95	24.05	29.20	20.80	26.40	32.23
12	**N Federal Hwy (West) – NE 9th Ave**	14.63	17.95	12.63	10.10	16.08	13.63	11.40	12.15
13	**NE 9th Ave – NE 10th Ave**	2.60	2.44	2.13	1.80	2.20	2.01	2.28	1.70
14	**NE 10th Ave - NE 12th Ave**	29.10	27.99	28.14	29.01	27.66	27.94	29.04	27.42
15	**NE 12th Ave – NE 15th Ave**	62.53	36.39	42.90	33.24	32.99	41.89	24.41	26.41
16	**NE 15th Ave – NE 16th Ter**	18.17	14.61	16.93	15.87	16.04	16.26	17.16	17.87
17	**NE 16th Ter – NE 17th Way**	17.67	18.90	21.84	20.26	18.80	17.06	17.30	20.79
18	**NE 17th Way – N Federal Hwy (East)**	8.53	14.35	11.05	11.38	7.45	7.13	14.55	6.48
19	**N Federal Hwy (East) – NE 20th Ave**	32.73	16.93	22.90	17.33	18.45	18.35	14.58	13.15
SUNRISE BLVD PROJECT LIMITS		**828.02**	**636.01**	**696.03**	**685.61**	**683.99**	**563.29**	**527.50**	**581.22**

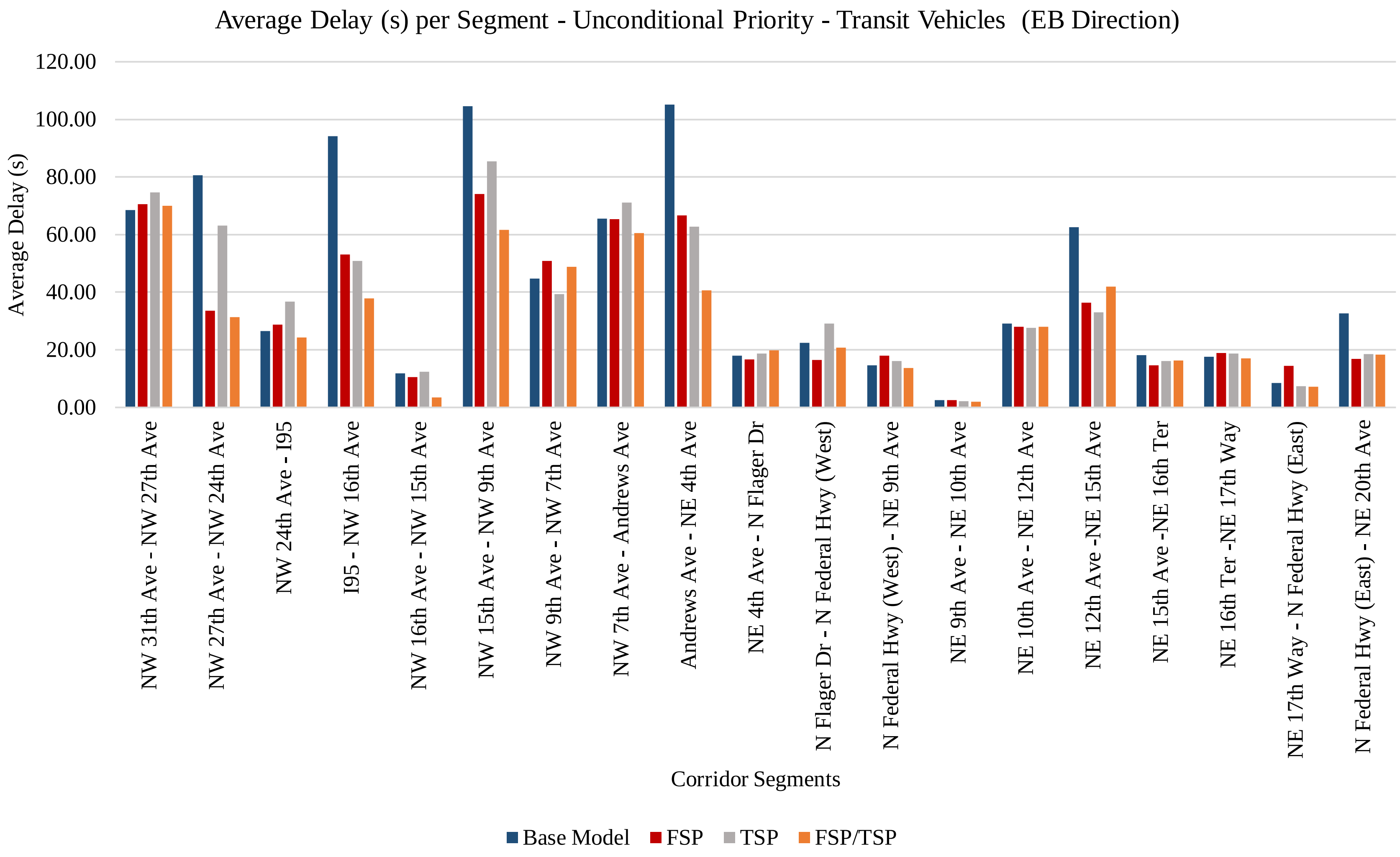

Figure 5-23: Average Delay (s) per Segment - Unconditional Priority - Transit Vehicles (EB Direction)

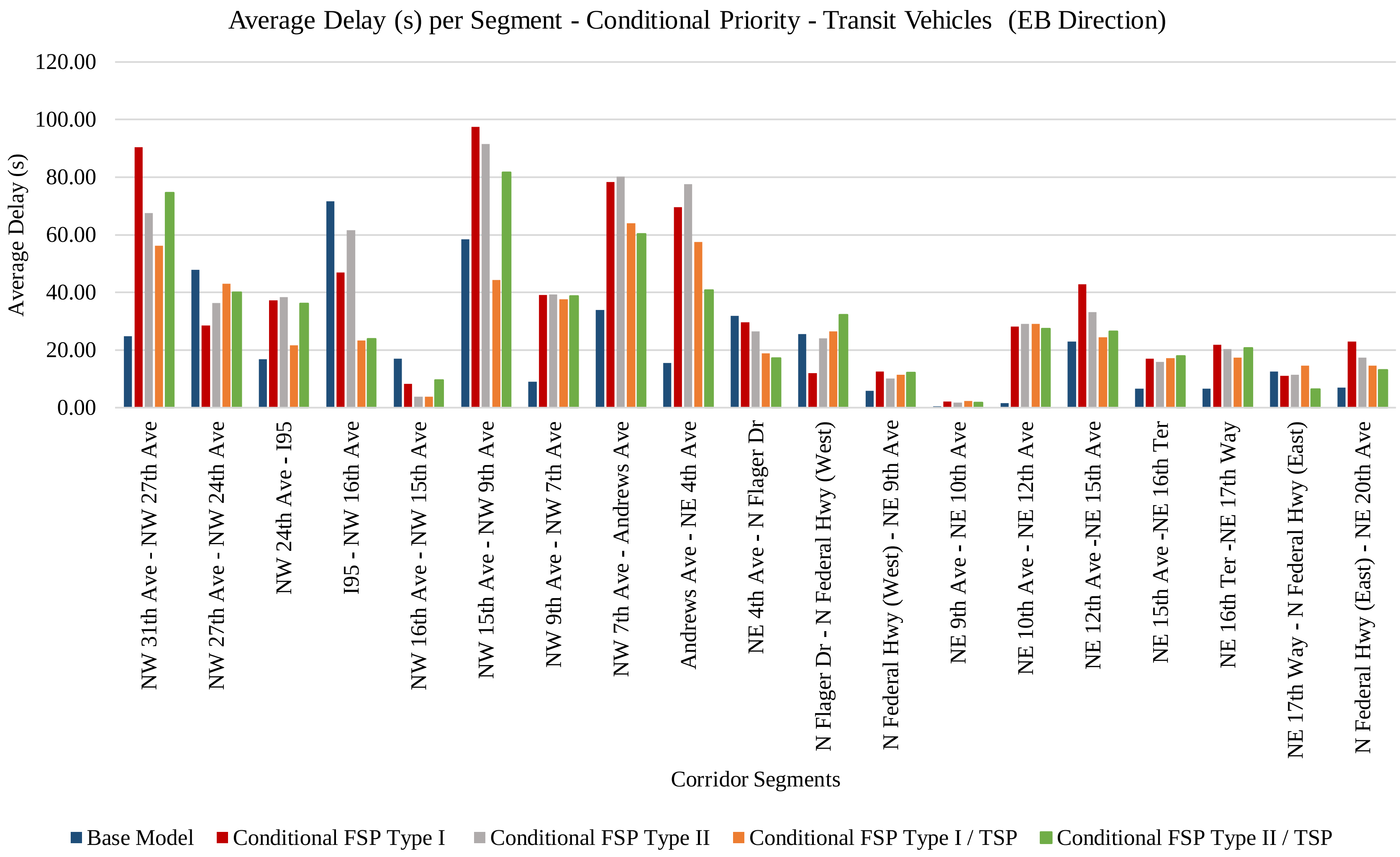

Figure 5-24: Average Delay (s) per Segment - Conditional Priority - Transit Vehicles (EB Direction)

In Table 5-12, the average delay measurements in seconds for all the vehicles for the westbound direction are listed. Figures 5-25 and 5-26 represent graphically the average delay results. Figure 5-25 includes all the measurements from the unconditional priority implementations, while Figure 5-26 the measurements from the conditional priority strategies along with the base model.

The improvements in the average delays for all the vehicles were visible for all the implemented scenarios. In most of the segments. The average delay was reduced and segments the reduction reached 40% compared with the base model. In some segments the delays were stable or had minor reductions, while on a few corridors segments the delays were increased. The corridor segment that had a negative impact on the movements of the vehicle was NW 9th Avenue - NW 7th Avenue, where the delay increase was related to the high vehicle volumes that aimed to turn left to the side streets and the increase wasn’t higher than 10 seconds.

By comparing all the priority scenarios, the conclusion reached was that the higher reduction of the average delay was identified on the FSP/TSP scenario with a 27% savings on delays, while the lowest reduction was on the TSP scenario with a 5% savings, due to the limited number of priority request coming only from the buses.

The average delay measurements in seconds for the freight vehicles for the westbound direction are listed in Table 5-13. Figures 5-27 and 5-28 represent graphically the average delay results. Figure 5-27 includes all the measurements from the unconditional priority implementations, while Figure 5-28 the measurements from the conditional priority strategies along with the base model.

The evaluation of the table displays similar results with the average delay Table for all the vehicles. In general, freight movements faced a reduction in their delays along the westbound direction of Sunrise Boulevard. The average delay savings on corridor segments reached 55% in comparison with the base model. Few segments presented an increase in the delays that were up to 20 seconds. The problematic conditions on those segments were related mainly to the geometry of the road and the high volumes of vehicles aiming to turn left to the side streets.

The comparison of the priority strategies with the base model showed the positive effect that the priorities had on the corridor regarding the reduction of the delays. The models with the highest performance were the FSP and FSP/TSP with a 28% savings on delays. Both scenarios provided unconditionally priority to all vehicles that requesting to be prioritized and they had lower delays in comparison with the conditional priorities. Thus, along with the movement of the priority vehicles, the rest of the network was also benefited.

Table 5-12: Average Delay (s) per Segment – All Vehicles – WB Direction

Average Delay (s) per Segment – All Vehicles – WB Direction									
Segment #	**Corridor Segment**	**Base Model**	**FSP**	**Cond. FSP Type I**	**Cond. FSP Type II**	**TSP**	**FSP/ TSP**	**Cond. FSP Type I / TSP**	**Cond. FSP Type II / TSP**
1	**NW 31st Ave - NW 27th Ave**	60.64	36.45	29.28	30.65	57.14	24.54	27.38	32.87
2	**NW 27th Ave - NW 24th Ave**	39.67	30.32	34.52	39.10	38.78	23.35	25.52	34.21
3	**NW 24th Ave - I-95**	28.99	17.17	23.61	23.19	27.78	16.96	16.79	20.00
4	**I-95 – NW 16th Ave**	18.71	13.74	16.57	18.32	16.44	14.05	14.57	17.29
5	**NW 16th Ave - NW 15th Ave**	10.92	8.24	9.23	9.74	8.60	10.68	10.10	9.70
6	**NW 15th Ave - NW 9th Ave**	27.67	24.67	27.57	27.13	27.13	24.06	24.94	27.18
7	**NW 9th Ave - NW 7th Ave**	13.18	18.12	22.42	13.06	21.96	11.64	16.14	32.00
8	**NW 7th Ave - Andrews Ave**	25.93	16.66	29.64	15.11	24.85	19.64	20.44	25.90
9	**Andrews Ave - NE 4th Ave**	16.84	14.33	19.08	20.58	13.19	16.74	20.88	17.83
10	**NE 4th Ave - N Flagler Dr**	37.33	30.10	29.86	28.34	33.31	27.21	29.85	28.91
11	**N Flagler Dr - N Federal Hwy (West)**	10.51	9.84	9.02	9.67	10.18	10.17	9.76	8.66
12	**N Federal Hwy (West) – NE 9th Ave**	4.53	3.59	4.26	4.52	4.44	4.30	3.83	3.83
13	**NE 9th Ave – NE 10th Ave**	6.72	4.71	4.51	6.06	6.18	2.98	4.35	4.05
14	**NE 10th Ave - NE 12th Ave**	2.80	1.61	1.74	2.40	2.24	1.15	1.52	1.32
15	**NE 12th Ave – NE 15th Ave**	4.74	2.91	3.40	3.38	3.29	2.82	2.80	3.33
16	**NE 15th Ave – NE 16th Ter**	27.93	25.03	23.45	26.56	24.30	24.37	27.09	27.02
17	**NE 16th Ter – NE 17th Way**	2.55	2.16	1.78	2.30	2.13	1.60	2.07	2.06
18	**NE 17th Way – N Federal Hwy (East)**	7.37	7.03	7.04	4.38	6.82	6.43	4.64	7.10
19	**N Federal Hwy (East) – NE 20th Ave**	83.92	83.20	83.14	87.81	83.10	71.84	82.16	88.75
SUNRISE BLVD PROJECT LIMITS		**430.96**	**349.87**	**380.12**	**372.32**	**411.87**	**314.54**	**344.85**	**392.03**

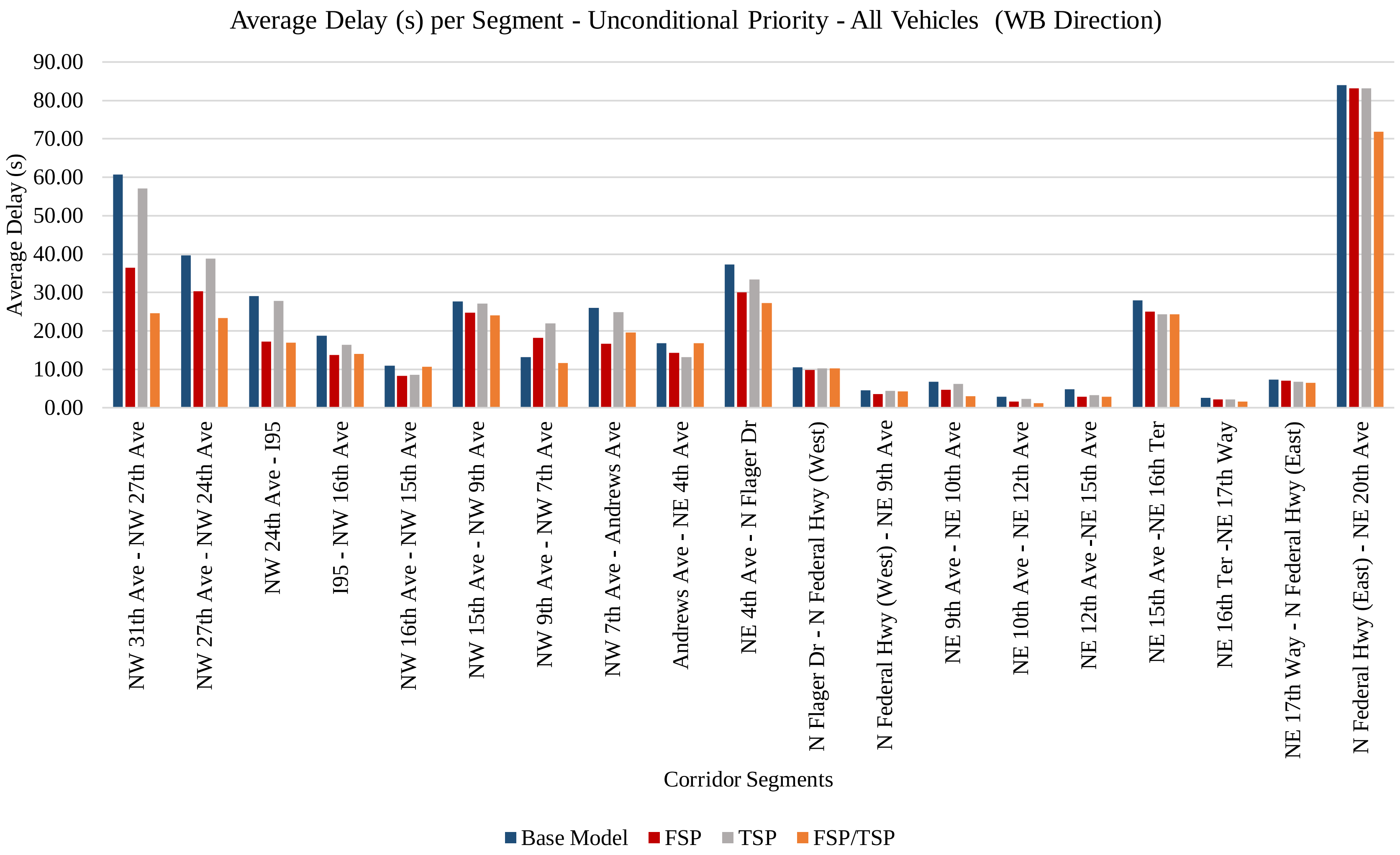

Figure 5-25: Average Delay (s) per Segment - Unconditional Priority - All Vehicles (WB Direction)

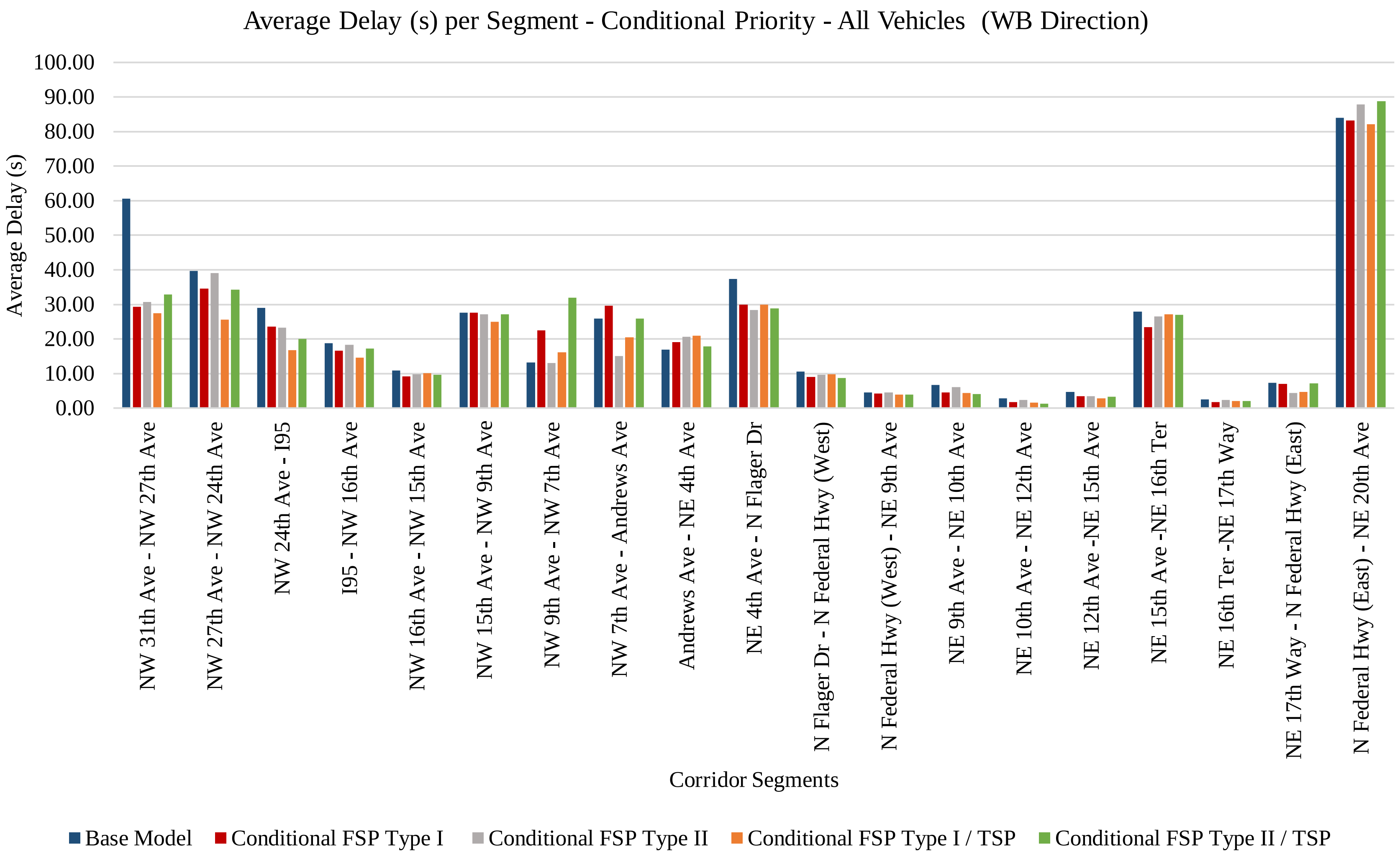

Figure 5-26: Average Delay (s) per Segment - Conditional Priority - All Vehicles (WB Direction)

Table 5-13: Average Delay (s) per Segment - Freight Vehicles - WB Direction

Average Delay (s) per Segment – Freight Vehicles – WB Direction									
Segment #	**Corridor Segment**	**Base Model**	**FSP**	**Cond. FSP Type I**	**Cond. FSP Type II**	**TSP**	**FSP/ TSP**	**Cond. FSP Type I / TSP**	**Cond. FSP Type II / TSP**
1	**NW 31st Ave - NW 27th Ave**	76.09	40.48	39.58	38.17	75.61	24.23	38.73	36.19
2	**NW 27th Ave - NW 24th Ave**	62.94	36.47	44.36	55.01	51.74	35.42	40.24	49.58
3	**NW 24th Ave - I-95**	35.65	22.23	34.75	27.09	35.46	19.59	22.87	29.38
4	**I-95 – NW 16th Ave**	29.58	24.30	30.45	29.42	25.89	22.60	25.40	29.18
5	**NW 16th Ave - NW 15th Ave**	16.24	9.42	12.66	14.03	14.10	14.58	15.19	12.82
6	**NW 15th Ave - NW 9th Ave**	37.47	34.21	43.65	39.92	40.01	32.55	37.87	34.56
7	**NW 9th Ave - NW 7th Ave**	22.17	20.48	26.40	17.81	33.32	18.23	26.06	22.15
8	**NW 7th Ave - Andrews Ave**	37.76	26.11	37.64	28.52	35.64	28.97	34.92	33.48
9	**Andrews Ave - NE 4th Ave**	31.26	15.83	15.78	24.66	11.09	31.09	28.39	20.64
10	**NE 4th Ave - N Flagler Dr**	38.27	25.65	35.66	29.70	37.82	32.23	29.20	31.14
11	**N Flagler Dr - N Federal Hwy (West)**	22.54	10.18	12.10	12.19	22.02	15.90	19.54	13.40
12	**N Federal Hwy (West) – NE 9th Ave**	10.55	3.12	9.38	7.66	10.07	8.26	6.09	6.58
13	**NE 9th Ave – NE 10th Ave**	11.42	5.94	6.78	8.78	11.14	3.79	5.88	5.71
14	**NE 10th Ave - NE 12th Ave**	4.67	2.49	3.04	4.33	4.15	2.30	2.82	2.52
15	**NE 12th Ave – NE 15th Ave**	6.68	5.56	6.81	6.52	6.58	6.62	5.88	6.47
16	**NE 15th Ave – NE 16th Ter**	27.75	24.28	25.01	24.54	19.07	24.23	33.90	30.21
17	**NE 16th Ter – NE 17th Way**	6.57	6.12	5.99	6.37	6.21	5.15	5.62	6.41
18	**NE 17th Way – N Federal Hwy (East)**	17.98	10.93	8.95	17.30	10.91	9.20	10.22	16.22
19	**N Federal Hwy (East) – NE 20th Ave**	107.89	106.16	71.51	99.38	102.37	97.79	78.54	115.28
SUNRISE BLVD PROJECT LIMITS		**603.47**	**429.97**	**470.51**	**491.38**	**553.20**	**432.74**	**467.36**	**501.91**

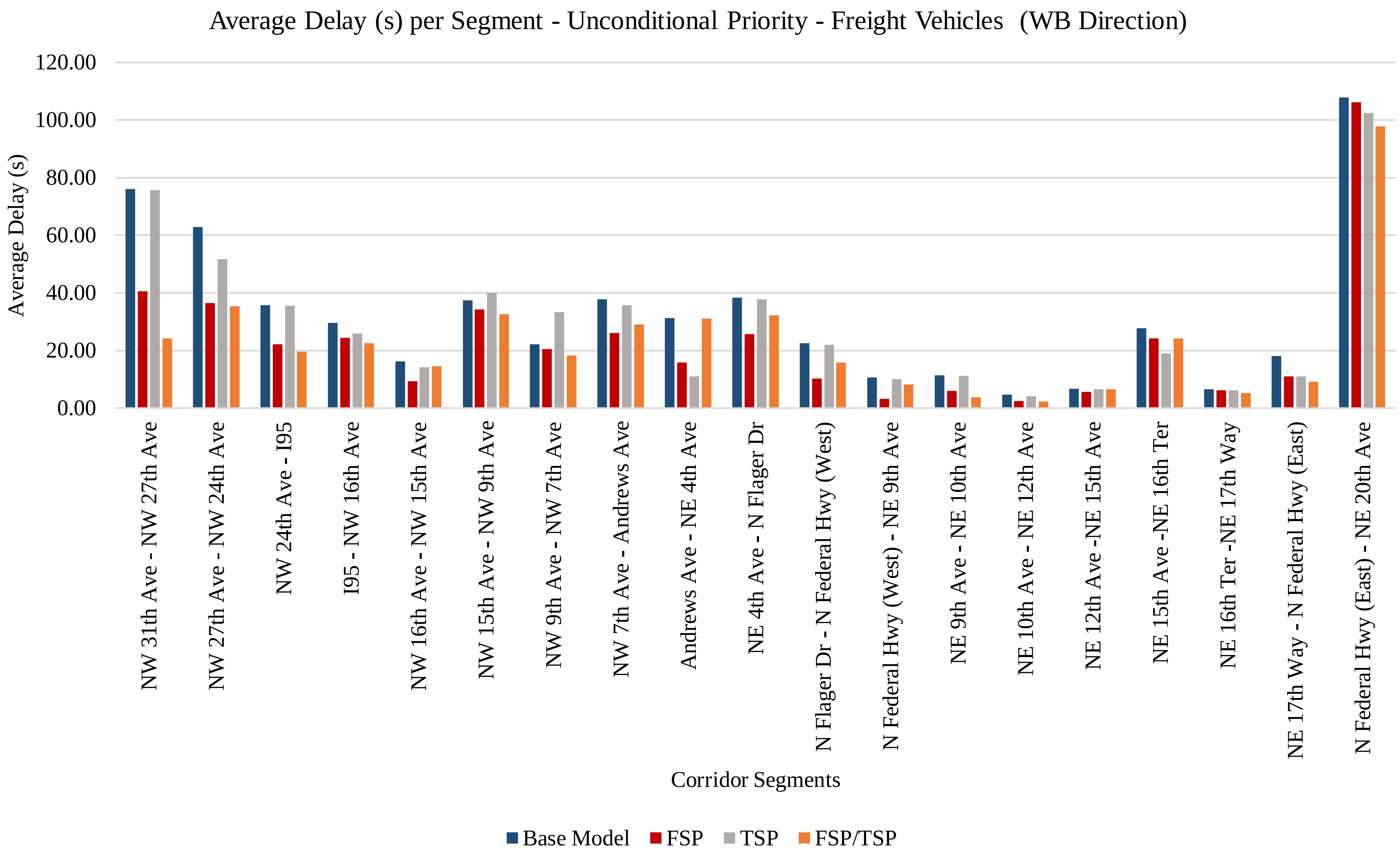

Figure 5-27: Average Delay (s) per Segment - Unconditional Priority - Freight Vehicles (WB Direction)

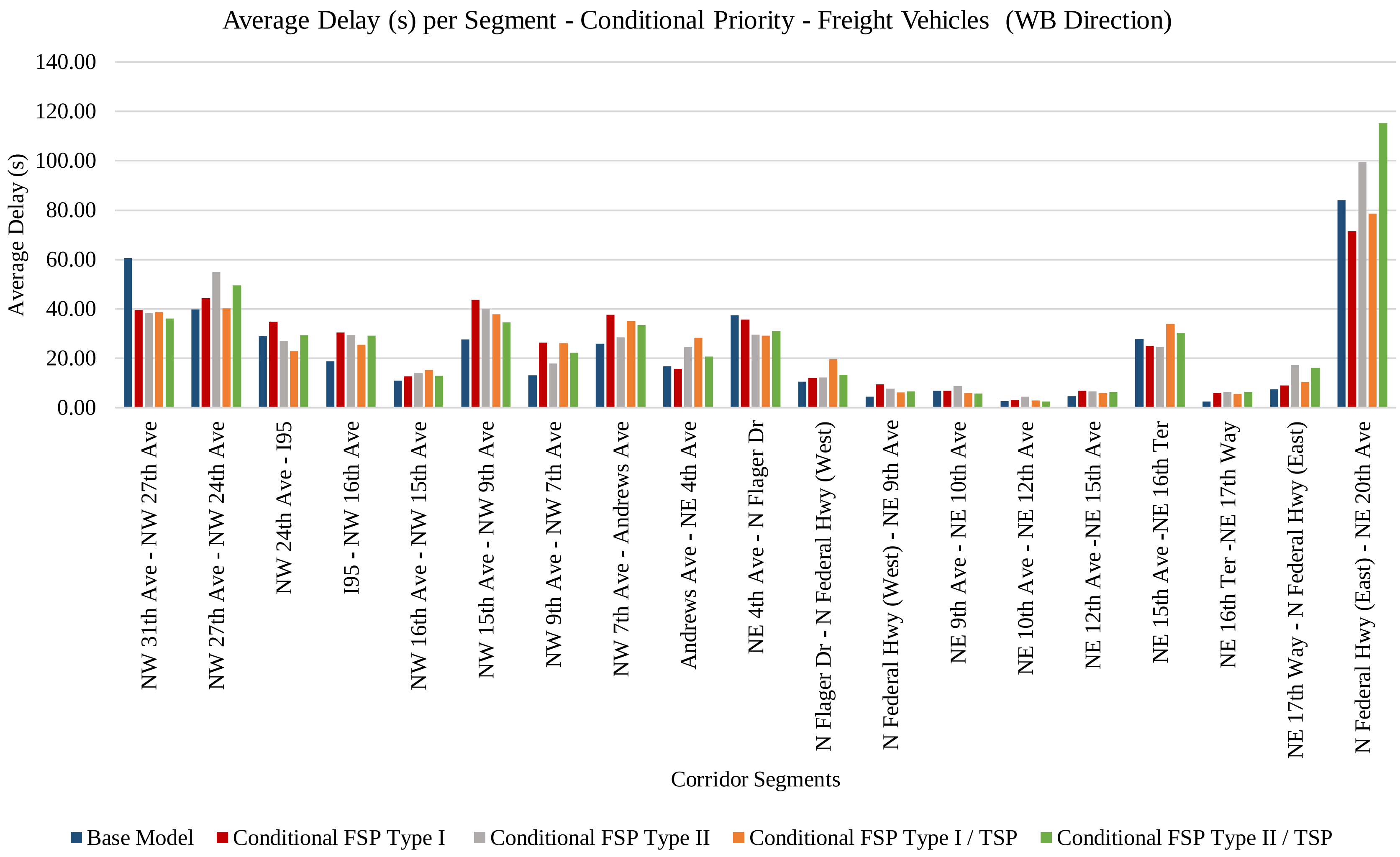

Figure 5-28: Average Delay (s) per Segment - Conditional Priority - Freight Vehicles (WB Direction)

Table 5-14 presents the average delay measurements in seconds for the transit vehicles for the westbound direction. The results are presented for all the different developed scenarios and for all the consecutive corridor segments. Figures 5-29 and 5-30 represent graphically the average travel time results. Figure 5-29 includes all the measurements from the unconditional priority implementations, while Figure 5-30 the measurements from the conditional priority strategies along with the base model.

The transit movements were also benefited from the implementation of the priority strategies with the savings from the base model to reach 60-70% on specific corridor segments. The improvements in some segments were stable or minor as well. Negative results were located on a few segments due to the geometry of the road and the traffic conditions. All the models enhanced the transit movements' mobility, through the implementation of different priority strategies. The best performing scenarios in regards of delay reduction were the TSP and the conditional FSP Type II / TSP, while the models that didn't perform as efficiently as the rest of the models were the FSP and the conditional FSP Type I and Type II, that excluded the specific vehicle classifications.

The overall delay measurements in seconds for the eastbound and westbound directions on Sunrise Boulevard for all the priority strategies and all the transport modes are presented on the Table. The graphical representation of the results from Table 5-15 and are presented on Figures 5-31, 5-32 and 5-33.

The analysis of the Table along with its Figures showed that all the scenarios in comparison to the base model had improvements on the average delays for all vehicles and for each transport mode separately. The lowest performance was identified in the TSP scenario since it was implemented to favor only the transit movements. The highest improvements were mainly located on the unconditional priority strategies. The specific scenarios had to accommodate the highest number of priorities calls in comparison with the rest of the scenarios. Thus, it was expected the presence of high delays for those scenarios.

Table 5-16 presents the travel time savings on percentage for both directions, all the priority strategies, and all the transport modes. The graphical representation of the results from the Table and are presented in Figures 5-34, 5-35 and 5-36.

Table 5-14: Average Delay (s) per Segment – Transit Vehicles – WB Direction

Average Delay (s) per Segment – Transit Vehicles – WB Direction									
Segment #	**Corridor Segment**	**Base Model**	**FSP**	**Cond. FSP Type I**	**Cond. FSP Type II**	**TSP**	**FSP/ TSP**	**Cond. FSP Type I / TSP**	**Cond. FSP Type II / TSP**
1	**NW 31st Ave - NW 27th Ave**	97.10	105.77	99.57	96.13	84.97	83.43	83.27	83.53
2	**NW 27th Ave - NW 24th Ave**	40.77	55.25	50.81	42.56	38.95	30.93	35.53	41.77
3	**NW 24th Ave - I-95**	29.47	29.07	25.87	27.60	11.00	31.23	20.60	10.70
4	**I-95 – NW 16th Ave**	22.00	26.57	32.65	34.80	26.70	17.29	38.19	30.78
5	**NW 16th Ave - NW 15th Ave**	7.53	14.43	3.27	10.43	7.00	10.63	3.33	7.87
6	**NW 15th Ave - NW 9th Ave**	115.97	81.67	109.77	88.70	95.17	97.23	93.03	104.37
7	**NW 9th Ave - NW 7th Ave**	111.00	26.30	81.43	44.77	48.57	53.53	28.70	41.97
8	**NW 7th Ave - Andrews Ave**	46.77	54.43	42.90	46.17	54.80	42.73	60.87	45.37
9	**Andrews Ave - NE 4th Ave**	30.43	40.85	40.44	46.16	40.19	44.27	48.33	38.13
10	**NE 4th Ave - N Flagler Dr**	66.30	54.93	40.33	38.37	27.83	38.17	46.70	30.53
11	**N Flagler Dr - N Federal Hwy (West)**	59.40	31.17	35.53	37.87	25.97	18.60	28.07	28.87
12	**N Federal Hwy (West) – NE 9th Ave**	4.77	3.77	4.07	3.53	3.03	4.17	3.43	3.53
13	**NE 9th Ave – NE 10th Ave**	12.69	7.80	9.53	10.04	10.11	6.07	7.36	9.19
14	**NE 10th Ave - NE 12th Ave**	14.93	14.80	14.49	14.63	14.14	13.70	13.60	14.11
15	**NE 12th Ave – NE 15th Ave**	7.45	7.38	4.48	7.45	5.32	6.43	7.20	7.23
16	**NE 15th Ave – NE 16th Ter**	32.50	37.97	38.75	45.55	48.95	44.52	48.27	45.60
17	**NE 16th Ter – NE 17th Way**	16.42	16.07	14.97	15.53	14.88	14.90	16.12	16.22
18	**NE 17th Way – N Federal Hwy (East)**	41.73	25.77	35.67	23.60	11.07	11.57	11.20	14.93
19	**N Federal Hwy (East) – NE 20th Ave**	97.40	110.40	63.60	93.77	54.53	91.77	43.43	53.07
SUNRISE BLVD PROJECT LIMITS		**854.63**	**744.38**	**748.12**	**727.66**	**623.17**	**661.17**	**637.23**	**627.76**

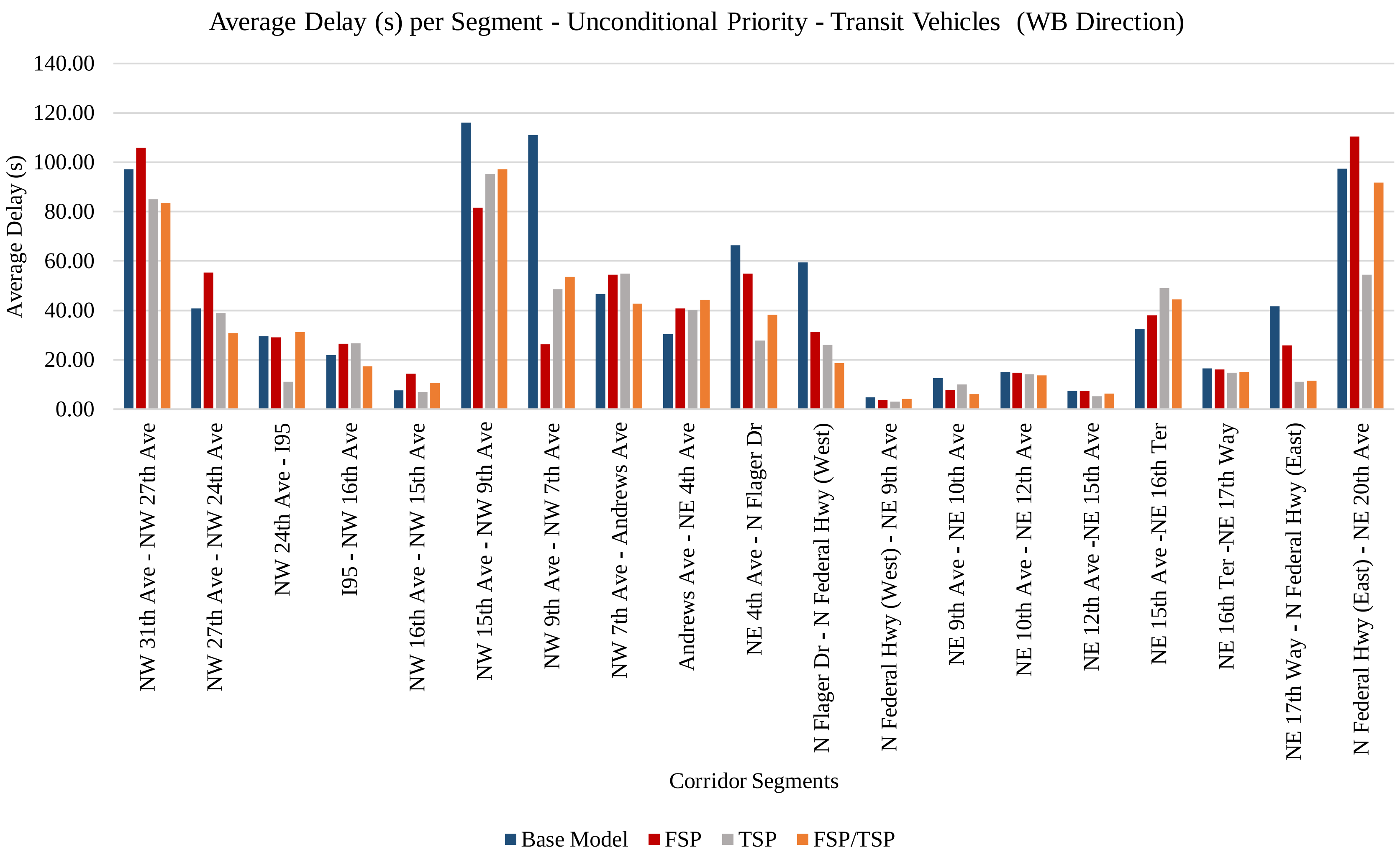

Figure 5-29: Average Delay (s) per Segment - Unconditional Priority - Transit Vehicles (WB Direction)

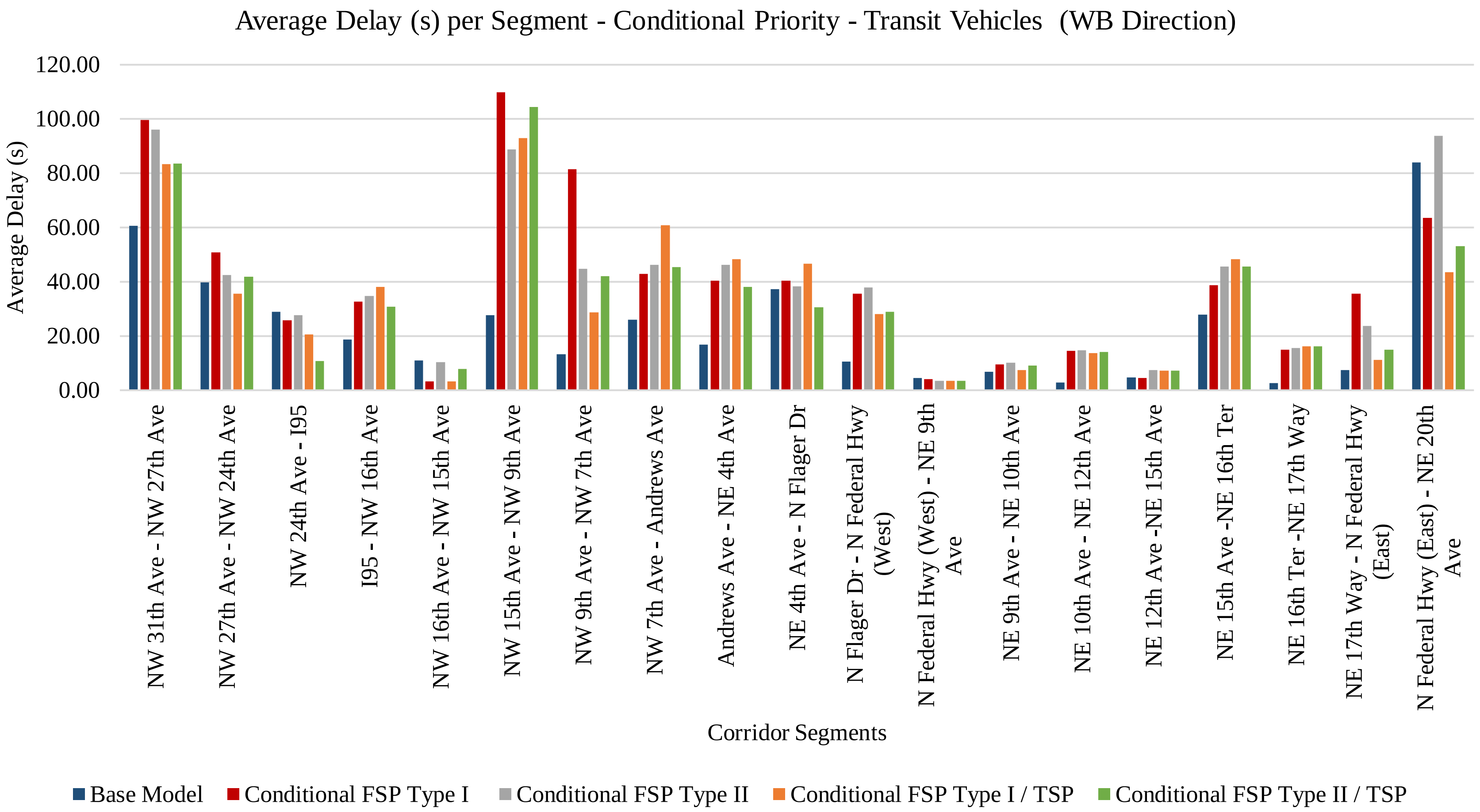

Figure 5-30: Average Delay (s) per Segment - Conditional Priority - Transit Vehicles (WB Direction)

Table 5-15: Average Delay (s) for All Scenarios and All Transport Modes (EB & WB Directions)

	Base Model	FSP	Cond. FSP Type I	Cond. FSP Type II	TSP	FSP /TSP	Cond. FSP Type I / TSP	Cond. FSP Type II / TSP
Average Delay (s) – All Vehicles								
Eastbound Direction	416.10	288.40	308.66	344.50	354.69	273.44	305.42	319.80
Westbound Direction	430.96	349.87	380.12	372.32	411.87	314.54	344.85	392.03
Average Delay (s) – Freight Vehicles								
Eastbound Direction	608.70	431.92	440.28	489.01	539.39	402.85	443.83	478.91
Westbound Direction	603.47	429.97	470.51	491.38	553.20	432.74	467.36	501.91
Average Delay (s) – Transit Vehicles								
Eastbound Direction	828.02	636.01	696.03	685.61	683.99	563.29	527.50	581.22
Westbound Direction	854.63	744.38	748.12	727.66	623.17	661.17	637.23	627.76

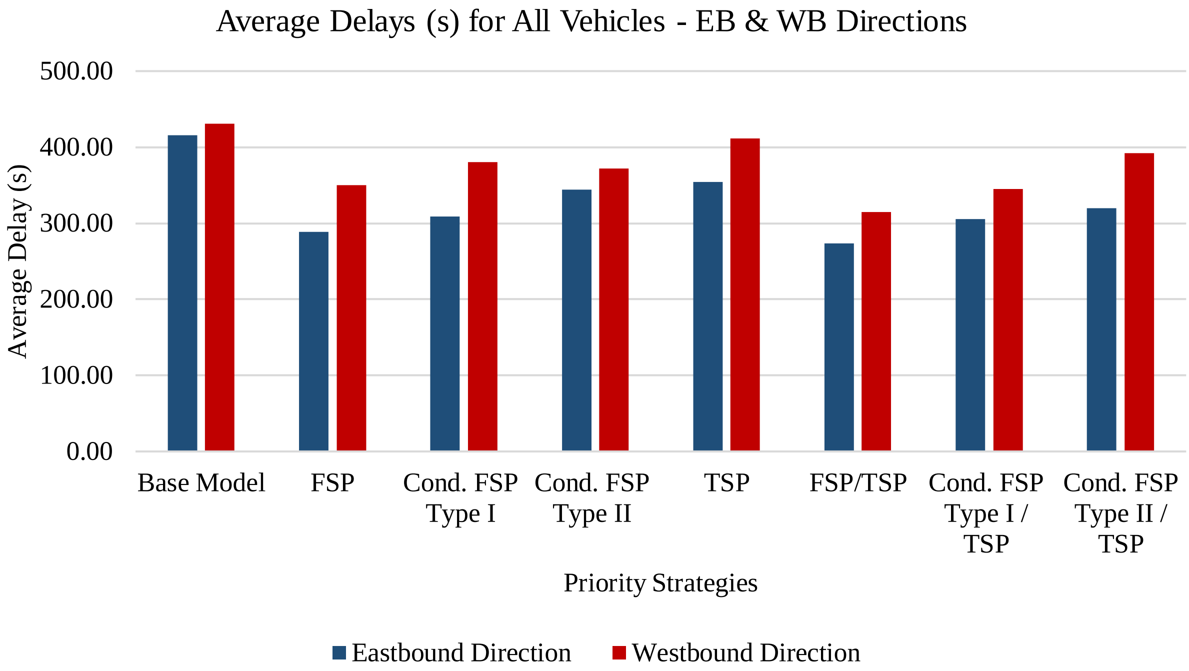

Figure 5-31: Delays (s) for All Vehicles - EB & WB Directions

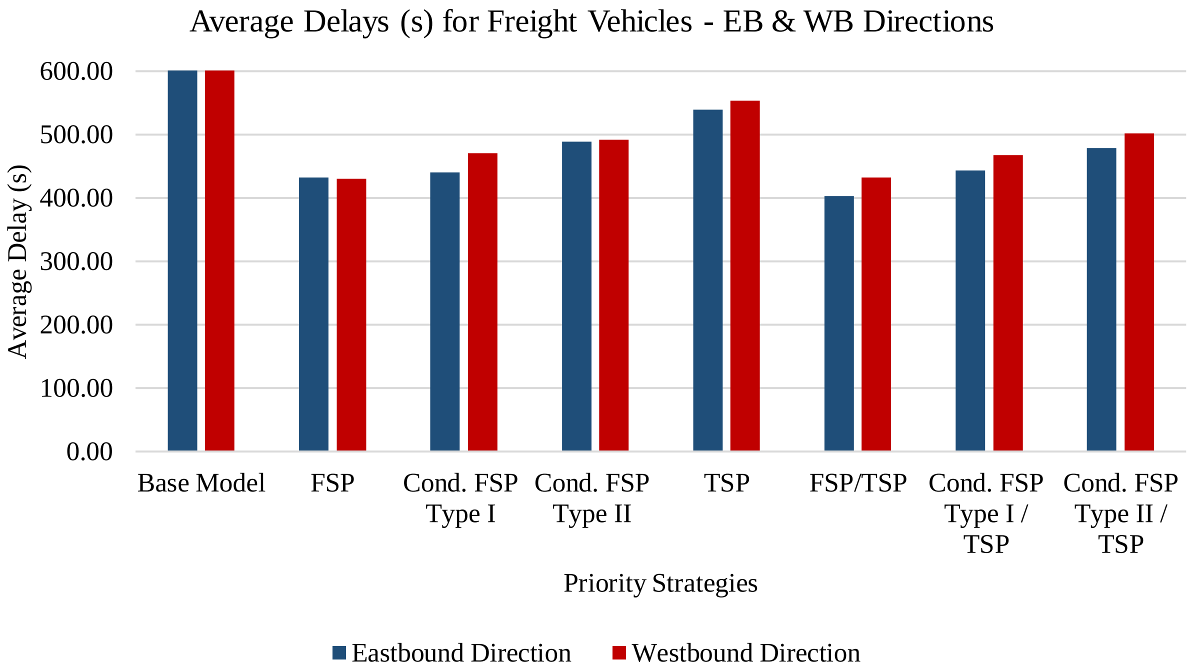

Figure 5-32: Average Delays (s) for Freight Vehicles - EB & WB Directions

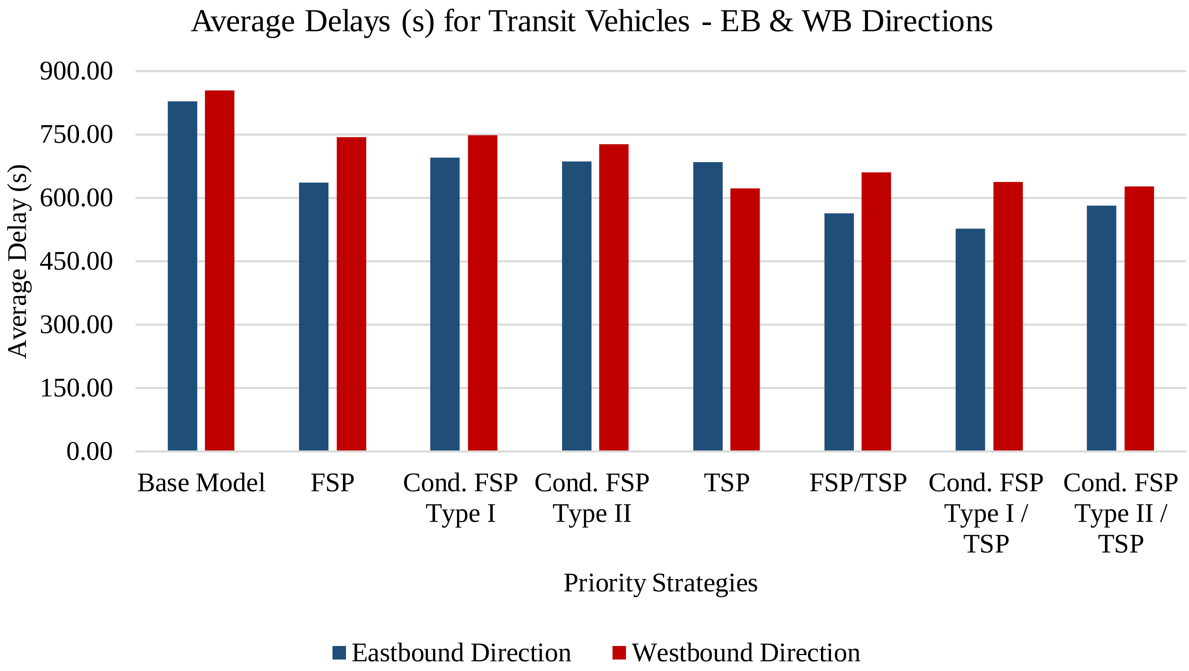

Figure 5-33: Average Delays (s) for Transit Vehicles - EB & WB Directions

Table 5-16: Average Delay Savings (%) for All Scenarios and All Transport Modes (EB & WB Directions)

	FSP	Cond. FSP Type I	Cond. FSP Type II	TSP	FSP /TSP	Cond. FSP Type I / TSP	Cond. FSP Type II / TSP
Average Delay Savings (%) – All Vehicles							
Eastbound Direction	30.69	25.82	17.21	14.76	34.29	26.60	23.14
Westbound Direction	18.82	11.80	13.61	4.43	27.01	19.98	9.03
Average Delay Savings (%) – Freight Vehicles							
Eastbound Direction	29.04	27.67	19.66	11.39	33.82	27.09	21.32
Westbound Direction	28.75	22.03	18.57	8.33	28.29	22.55	16.83
Average Delay Savings (%) – Transit Vehicles							
Eastbound Direction	23.19	15.94	17.20	17.39	31.97	36.29	29.81
Westbound Direction	12.90	12.46	14.86	27.08	22.64	25.44	26.55

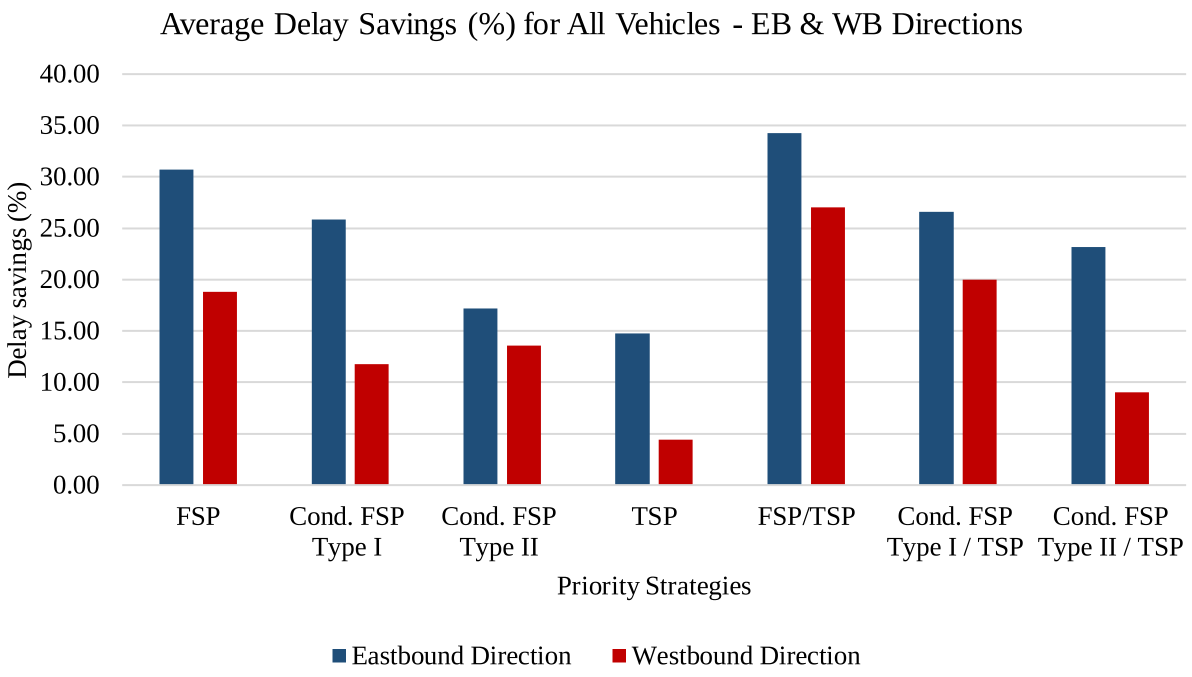

Figure 5-34: Average Delay Savings (%) for All Vehicles - EB & WB Directions

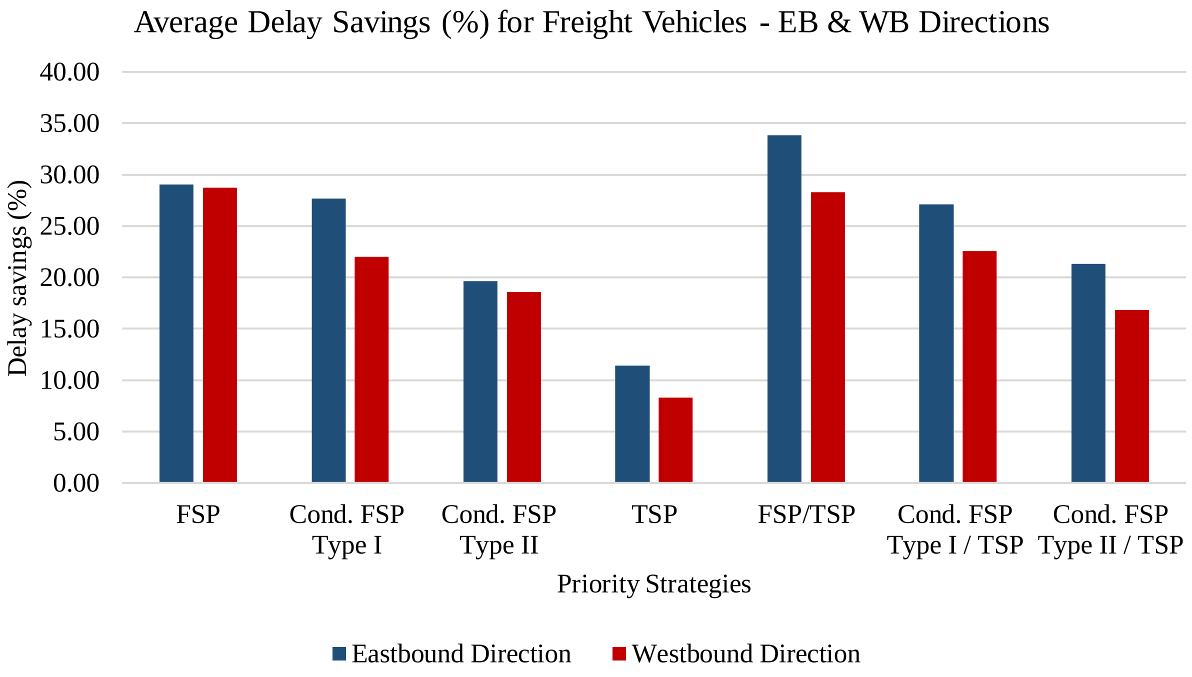

Figure 5-35: Average Delay (%) Savings for Freight Vehicles - EB & WB Directions

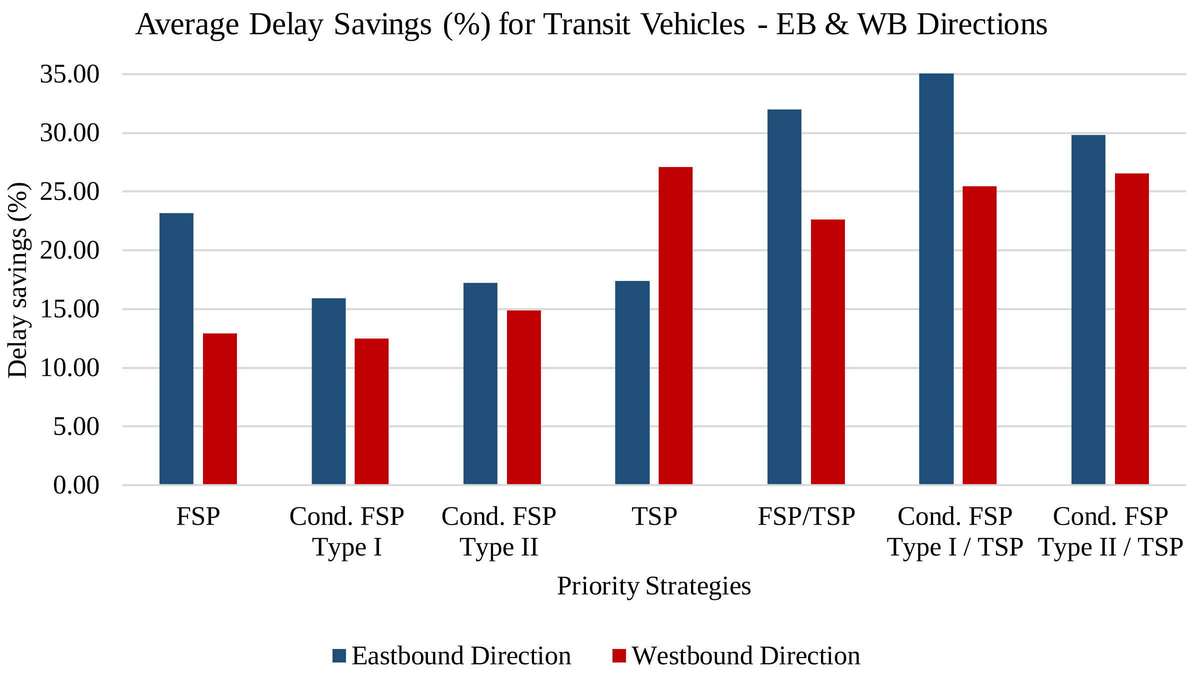

Figure 5-36: Average Delay Savings (%) for Transit Vehicles - EB & WB Directions

5.3 Side Street Delays

Table 5-17 displays the measurements of the average delays in seconds for all side street movements and for all the developed scenarios. The values of the average delays for all the priority scenarios are also presented in Figures 5-37 and 5-38. Figure 5-37 includes all the measurements from the unconditional priority implementations, while Figure 5-38 shows the measurements from the conditional priority strategies along with those for the base model.

In general, an increase in the average delay was identified for all priority strategies. The purpose of the signal priority is to favor the priority vehicles along a corridor. The prioritization is completed through the extension of green time or through red truncation. Thus, the implementation of the priority strategies on the main direction leads to alterations of the signal timing and the duration of each signal phase. Consequently, changes in the side streets' delays were expected.

The delays, in general, showed an increase of fewer than 60 seconds per vehicle, while in a few streets the delays did not increase or even decreased. The most problematic conditions occurred on the side streets with high vehicle volumes, were the delay difference from the base model reached almost 2 minutes per vehicle. This happened for example on N Federal Highway, NW 31st Avenue, and NW 9th Avenue; which are corridors with high volumes like Sunrise Boulevard. Thus, any reduction or alteration on their signal phases affected the delays along with them. This indicates that the application of the guidance proposed in this study will most likely shows that it is not recommended the priorities on these intersections.

In addition, the results differ for each priority scenario. The highest increase in delays was presented in the case of the unconditional FSP/TSP and FSP scenarios. The specific scenarios had to accommodate the highest number of priorities calls in comparison with the rest of the scenarios. Thus, high delays on the side streets are expected for those scenarios. The TSP scenario had the lowest delays since the priority was developed only for the transit vehicles, that had lower volumes than the trucks and the passenger's vehicles. After the TSP, the conditional FSP Type II/ TSP scenario presented the lowest increase in the delays in comparison with the rest of the priority strategies. Thus, the conditional scenarios provided lower delays than the unconditional ones, since they were defined to provide priority to fewer vehicles. Consequently, taking into consideration the delays on the side streets, the optimal option for combining the FSP and TSP strategies is through scenario VII that excluded two truck categories from the prioritization process.

Table 5-17: Average Side Streets Delay (s)

Average Side Streets Delay (s)									
Segment #	**Corridor Segment**	**Base Model**	**FSP**	**Cond. FSP Type I**	**Cond. FSP Type II**	**TSP**	**FSP/ TSP**	**Cond. FSP Type I / TSP**	**Cond. FSP Type II / TSP**
1	**NW 31st Ave**	67.74	132.04	143.39	102.50	94.89	137.62	132.62	112.16
2	**NW 27th Ave**	105.36	149.67	145.97	121.66	110.65	152.49	187.00	121.00
3	**NW 24th Ave**	126.07	218.80	207.94	166.83	140.46	200.40	204.00	166.20
4	**I-95**	28.96	15.94	15.82	16.81	16.66	15.59	16.19	16.81
5	**NW 16th Ave**	85.43	162.43	113.88	101.25	83.21	174.13	141.30	103.75
6	**NW 15th Ave**	30.98	29.40	30.31	32.48	31.55	30.76	31.49	32.48
7	**NW 9th Ave**	152.23	226.40	215.81	198.90	181.96	247.48	226.20	199.80
8	**NW 7th Ave**	165.27	235.33	217.48	206.60	179.88	249.23	218.23	205.60
9	**Andrews Ave**	136.32	218.34	201.21	179.54	167.26	215.71	198.20	179.54
10	**NE 4th Ave**	133.26	190.53	190.68	157.69	141.89	204.33	170.68	157.68
11	**N Flagler Dr**	190.78	240.00	224.85	208.80	200.00	237.26	230.46	212.80
12	**N Federal Hwy (West)**	13.14	13.04	13.02	12.43	12.38	10.43	11.73	12.43
13	**NE 9th Ave**	24.48	14.91	19.72	14.28	13.56	14.25	14.58	14.28
14	**NE 10th Ave**	14.97	13.77	13.10	13.42	16.01	14.31	13.26	13.40
15	**NE 12th Ave**	17.19	16.90	16.98	17.67	17.78	16.68	17.29	17.17
16	**NE 15th Ave**	131.11	206.07	178.11	166.85	153.90	204.87	172.37	166.80
17	**NE 16th Ter**	13.27	10.32	11.06	12.12	11.37	11.80	10.71	12.12
18	**NE 17th Way)**	88.17	98.22	114.25	85.85	85.19	99.75	84.66	85.85
19	**N Federal Hwy (East)**	92.63	92.63	90.10	76.68	48.24	99.90	66.84	76.68
20	**NE 20th Ave**	88.11	97.30	98.69	97.76	89.88	99.98	88.15	97.76

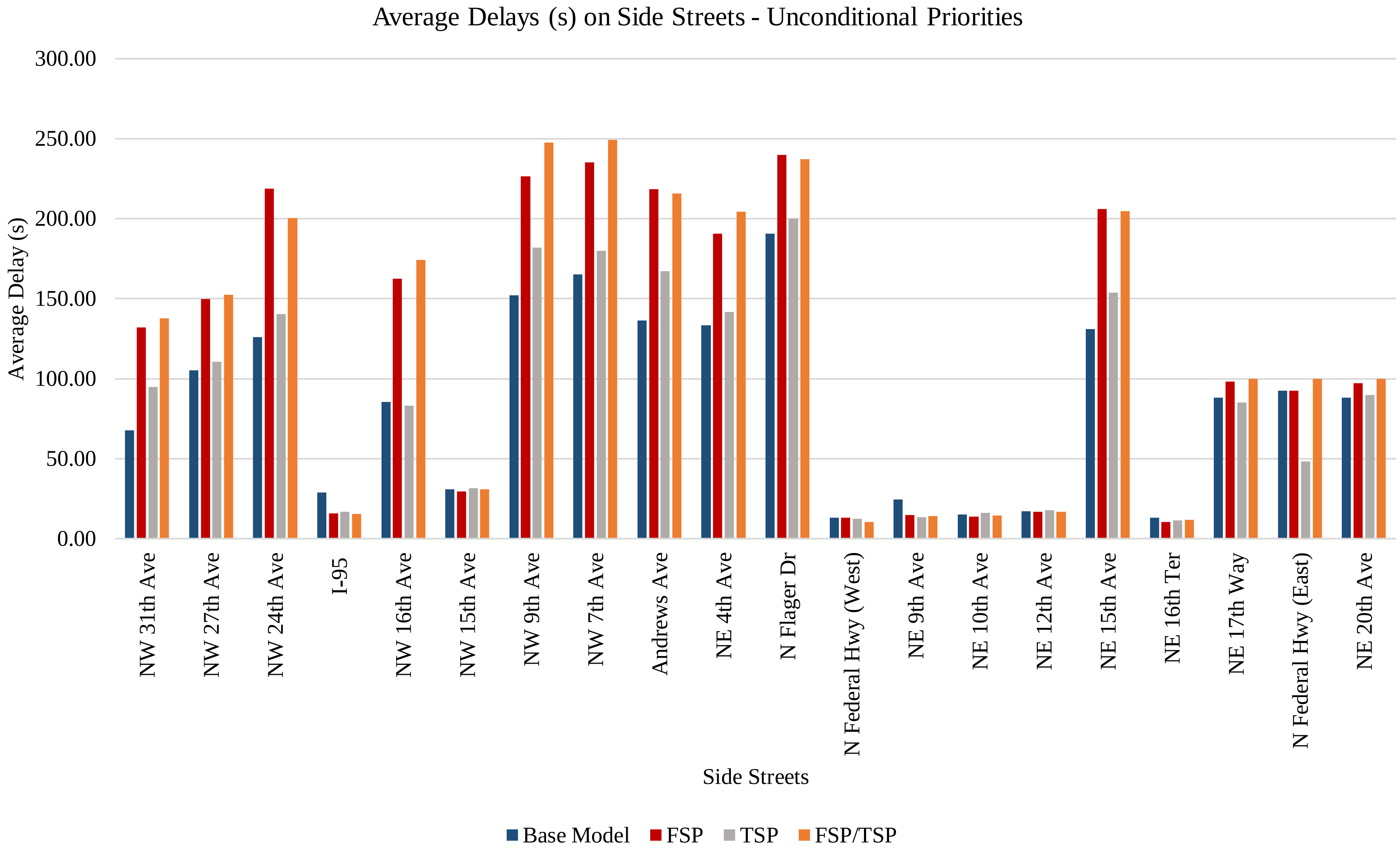

Figure 5-37: Average Delays (s) on Side Streets - Unconditional Priorities

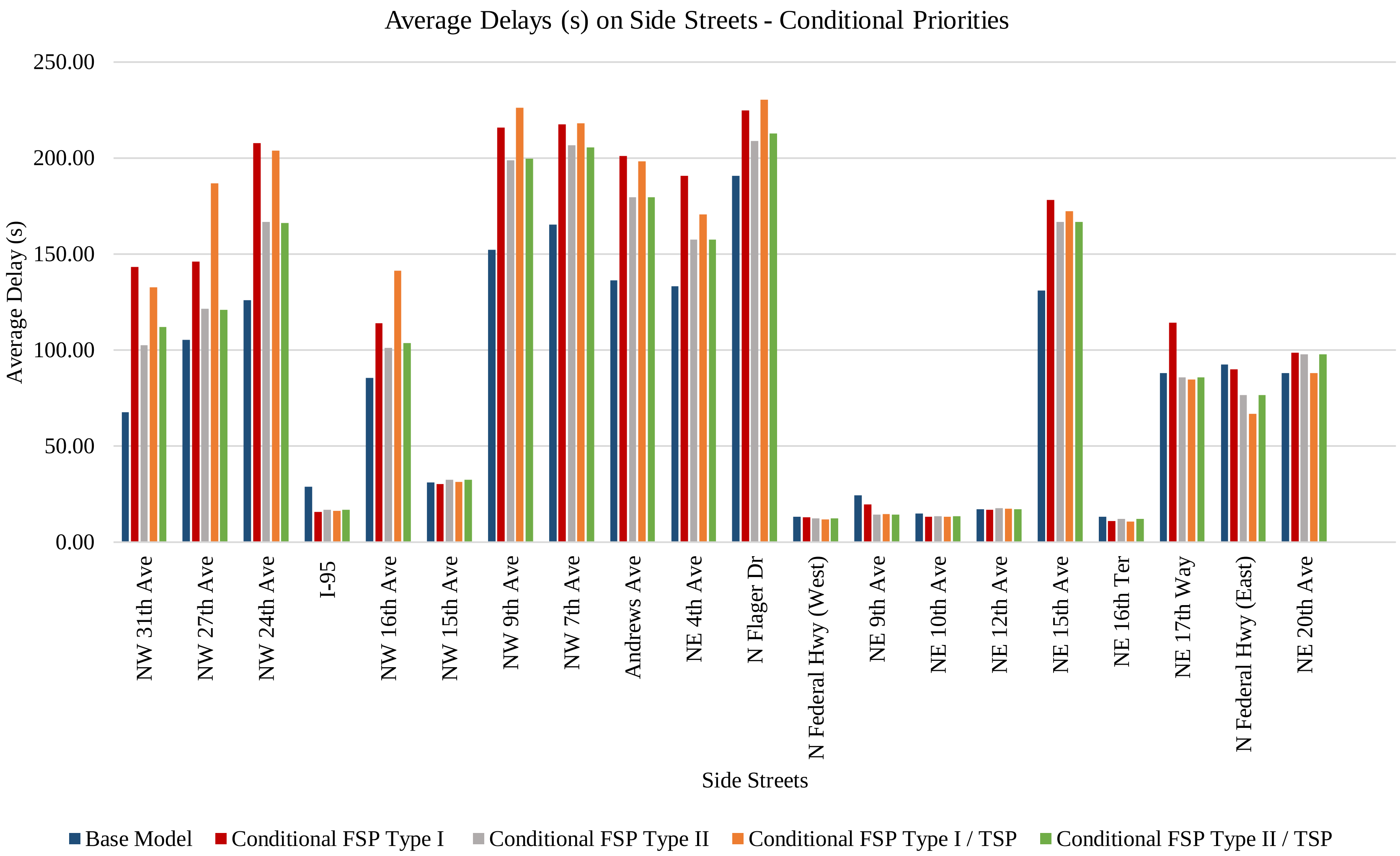

Figure 5-38: Average Delays (s) on Side Streets - Conditional Priorities

5.4 Green Time Duration

The green time duration is considered as another significant measure for evaluating the effectiveness of the newly developed methodology. The values of the average green time duration have been collected for the eastbound and westbound directions.

Table 5-18 presents the values of the average green time duration for the traffic lights on the eastbound direction of Sunrise Boulevard for all the priority strategies along with the base model. The values of the green time for all the priority scenarios are also presented in Figures 5-39 and 5-40. Figure 5-39 includes all the measurements from the unconditional priority implementations, while Figure 5-40 the measurements from the conditional priority strategies along with the base model.

The analysis of the table and the figures displayed that the average green time increased in most of the signalized intersections for all the priority scenarios. Due to the implementation of the priority scenarios along the eastbound direction, the signal controllers had to provide to that signal phase an extended green time or a green sign sooner than programmed, in order to favor the movements of the priority vehicles. Thus, the increased green time duration was an expected consequence, proving that the priority strategies are working properly. Furthermore, in some intersections, the green time duration was constant with time differences up to 2 seconds from the measurements of the base model.

Moreover, the measurements of the average green time duration in seconds for the westbound approach of Sunrise Boulevard are presented in Table 5-19. The Table includes the values for all the priority strategies along with the base model. The values of the green time for all the priority scenarios are also presented in Figures 5-41 and 5-42. Figure 5-41 includes all the measurements from the unconditional priority implementations, while Figure 5-42 the measurements from the conditional priority strategies along with the base model.

The results for the westbound approach are very similar to the results of the eastbound approach. The average green time duration was again increased in many signalized intersections, due to the implemented priority strategies that altered the signal controllers' operations for providing priority to the trucks and/or the buses. In addition, in some intersections, the green time duration was constant with time differences up to 2 seconds from the measurements of the base model.

Table 5-18: Average Green Time Duration (s) – EB Direction

Average Green Time Duration (s) – EB Direction									
Segment #	**Corridor Segment**	**Base Model**	**FSP**	**Cond. FSP Type I**	**Cond. FSP Type II**	**TSP**	**FSP/ TSP**	**Cond. FSP Type I / TSP**	**Cond. FSP Type II / TSP**
1	**NW 31st Ave**	74.3	92.8	84	83.6	81.5	95	96.8	95
2	**NW 27th Ave**	88.5	99.3	93.2	91.2	96.3	98	97.1	91.2
3	**NW 24th Ave**	90.2	102.2	102.4	99.3	92.5	106.2	101.5	99.3
4	**I-95**	58.6	57.6	59.8	58.8	59.2	60.8	57.6	58.8
5	**NW 16th Ave**	120	118.8	116.8	119.6	120	120	116.2	119.6
6	**NW 15th Ave**	85.9	85.1	83.9	84.3	87.2	81.9	85	84.3
7	**NW 9th Ave**	84.5	97.5	95.6	96.5	88.3	106.9	102	96.5
8	**NW 7th Ave**	102.3	104.5	104	103.3	101.2	102.1	105.8	103.3
9	**Andrews Ave**	83.5	98.4	96.5	93.7	87.5	102.5	97.8	96.5
10	**NE 4th Ave**	96.8	100.2	100.1	99.8	101.4	101.8	95.6	100.9
11	**N Flagler Dr**	113.5	108.5	109	108	114	106.2	103.1	108
12	**N Federal Hwy (West)**	70.7	80	77.7	75.3	73.23	75.7	75.09	75.36
13	**NE 9th Ave**	120	116.5	115.9	111.6	120	119.5	120	120
14	**NE 10th Ave**	120	112.5	115.7	110.3	116.5	119.5	120	118.5
15	**NE 12th Ave**	118.6	120	119.8	118.2	120	120.6	120	118.6
16	**NE 15th Ave**	94.1	100.3	104.1	102.9	98.2	112.7	104.2	102.9
17	**NE 16th Ter**	120	120	119.5	119.7	119.7	120	118.6	118.9
18	**NE 17th Way)**	120	111.8	110.7	110.9	119.9	118.9	115.5	114.5
19	**N Federal Hwy (East)**	71.9	89.2	80.6	71.8	71.2	78.1	79.2	71.8
20	**NE 20th Ave**	120	120.3	120	120	118.5	120.6	118.6	119

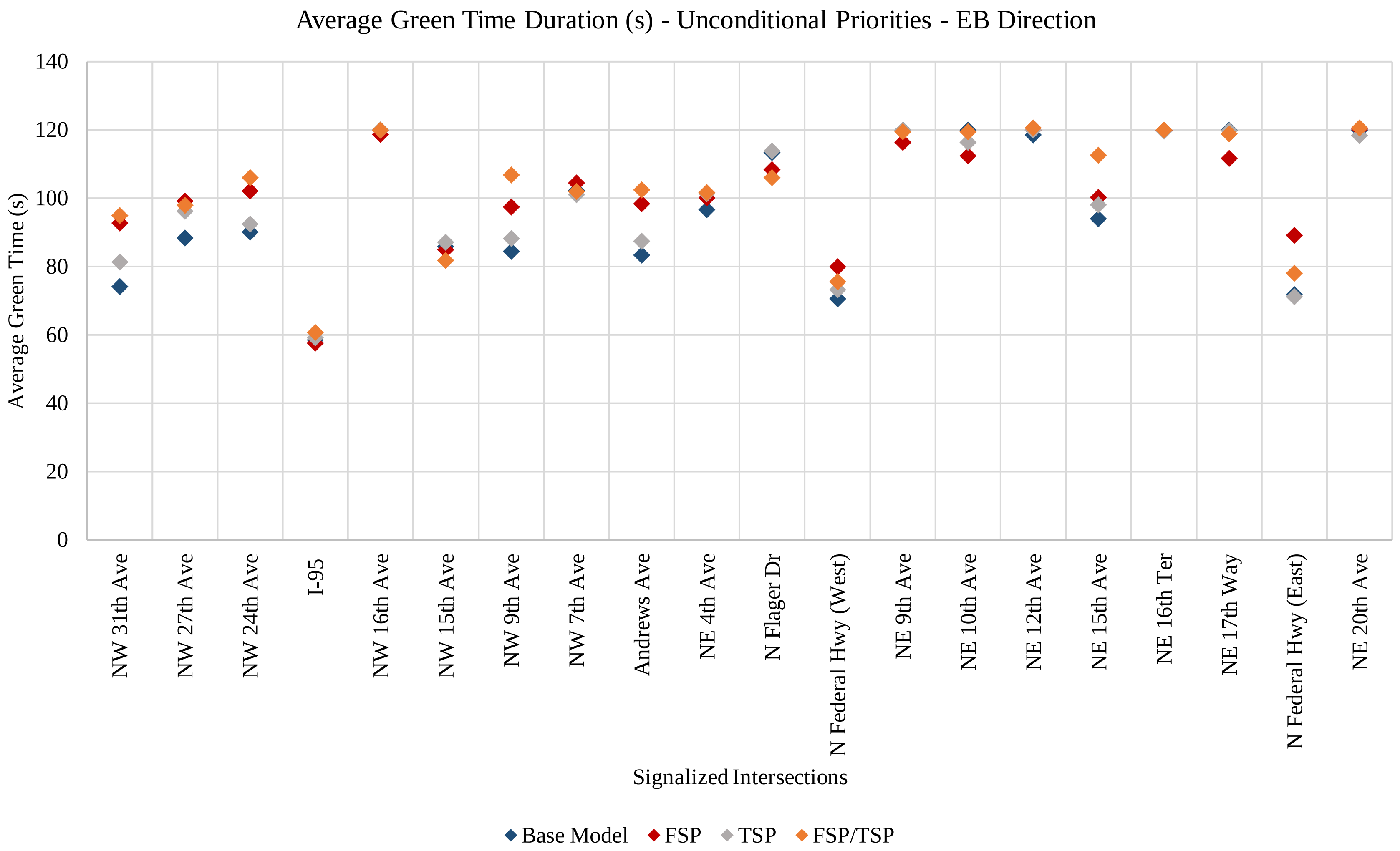

Figure 5-39: Average Green Time Duration (s) - Unconditional Priorities - EB Direction

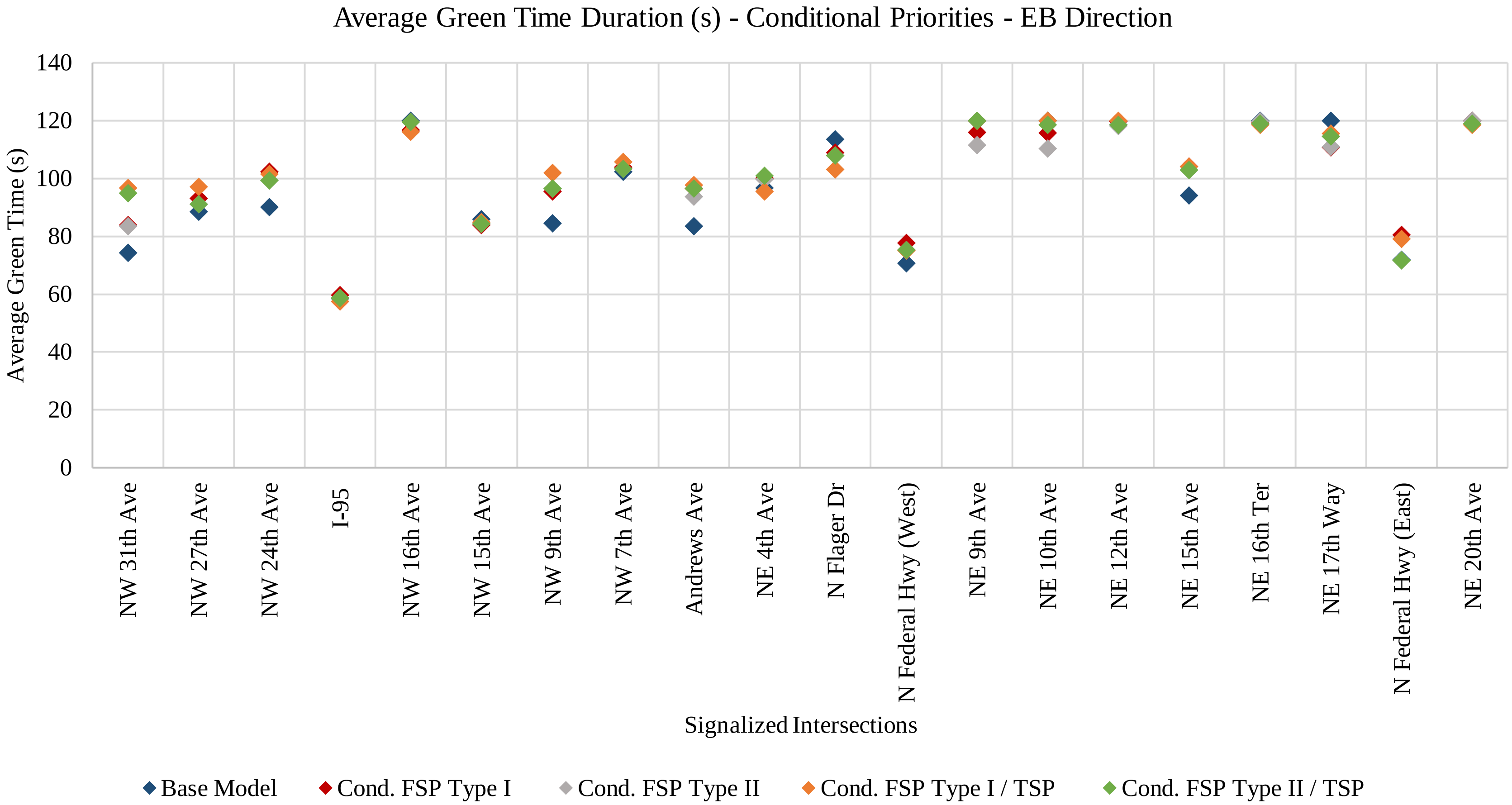

Figure 5-40: Average Green Time Duration (s) - Conditional Priorities - EB Direction

Table 5-19: Average Green Time Duration (s) – WB Direction

Average Green Time Duration (s) – EB Direction									
Segment #	**Corridor Segment**	**Base Model**	**FSP**	**Cond. FSP Type I**	**Cond. FSP Type II**	**TSP**	**FSP/ TSP**	**Cond. FSP Type I / TSP**	**Cond. FSP Type II / TSP**
1	**NW 31st Ave**	69.8	91.5	80.3	80.5	77.5	92.3	93.2	91.5
2	**NW 27th Ave**	105.3	109.1	104.1	105.4	106.5	108	101.7	105.4
3	**NW 24th Ave**	104.5	109.5	109.3	106.7	105.7	113.4	110	106.7
4	**I-95**	58.6	57.6	59.8	58.8	59.2	60.8	57.6	58.8
5	**NW 16th Ave**	120	120	117.2	120	120	120	117.5	120
6	**NW 15th Ave**	55.5	51.3	47.9	48.8	54	48.4	48.9	48.8
7	**NW 9th Ave**	75.4	88.8	90	88.8	79	103.7	95.8	88.8
8	**NW 7th Ave**	102.2	104.8	104	103.7	104.8	102.2	105.9	103.7
9	**Andrews Ave**	73.8	91.5	89.6	88	79	97.7	91.3	89.6
10	**NE 4th Ave**	78.4	90.3	88.2	85.9	84.7	91.9	85.3	90.9
11	**N Flagler Dr**	113.5	108.5	101.3	108	114	106.2	103.1	108
12	**N Federal Hwy (West)**	70.7	80	77.7	75.3	73.23	75.7	75.09	75.36
13	**NE 9th Ave**	120	116.5	115.9	111.6	120	119.5	120	120
14	**NE 10th Ave**	120	112.5	115.7	110.3	116.5	119.5	120	118.5
15	**NE 12th Ave**	118.6	120	119.8	118.2	120	120.6	120	118.6
16	**NE 15th Ave**	85.5	98.1	103.4	97.8	92.5	109.7	99.5	97.8
17	**NE 16th Ter**	120	120	119.5	119.7	119.7	120	118.6	118.9
18	**NE 17th Way)**	120	117.3	111.8	110.9	120	116.3	115.5	114.5
19	**N Federal Hwy (East)**	40.37	42.3	39	39.7	40.2	54.3	44.05	48.9
20	**NE 20th Ave**	120	120.3	120	120	118.5	120.6	118.6	119

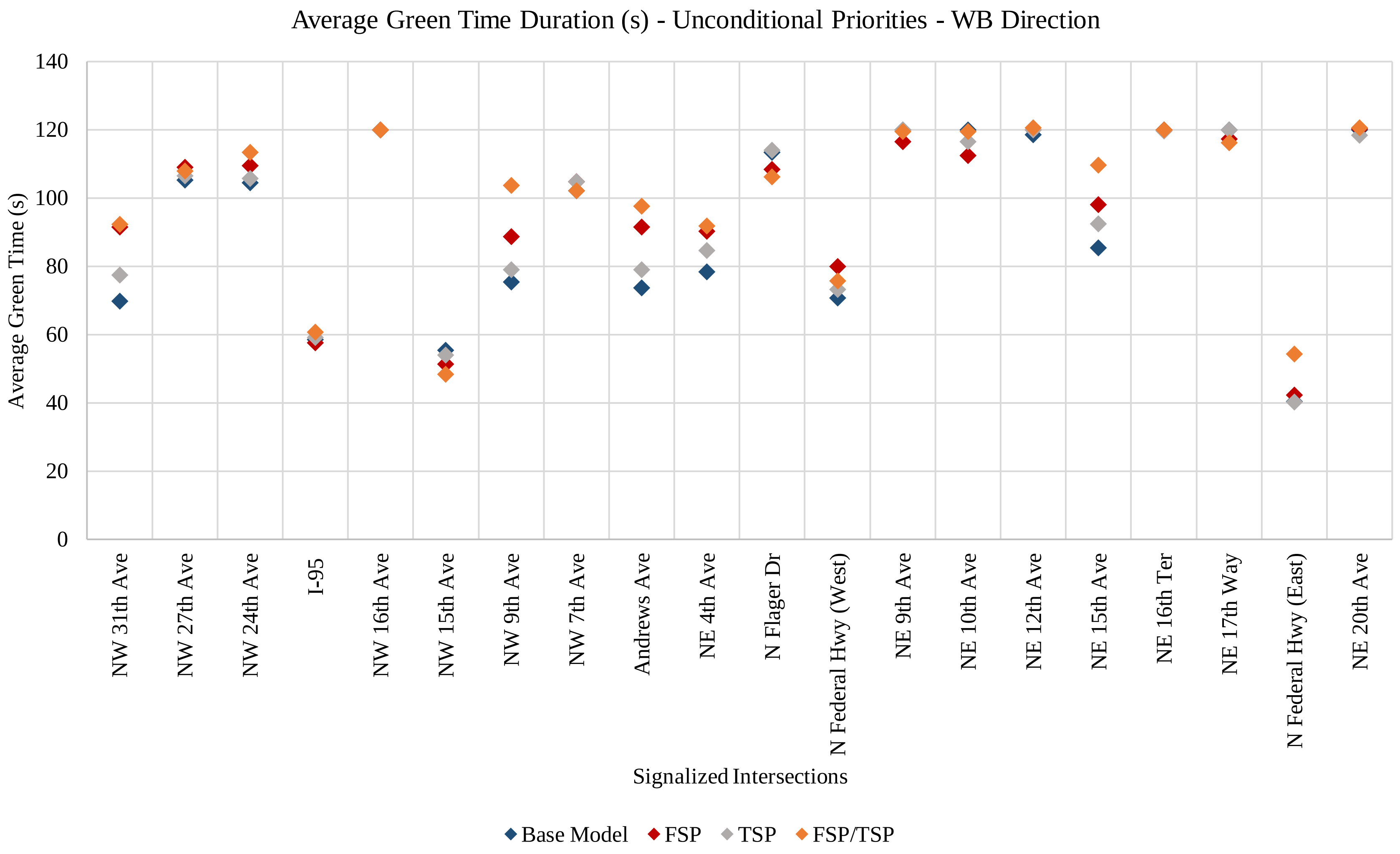

Figure 5-41: Average Green Time Duration (s) - Unconditional Priorities - WB Direction

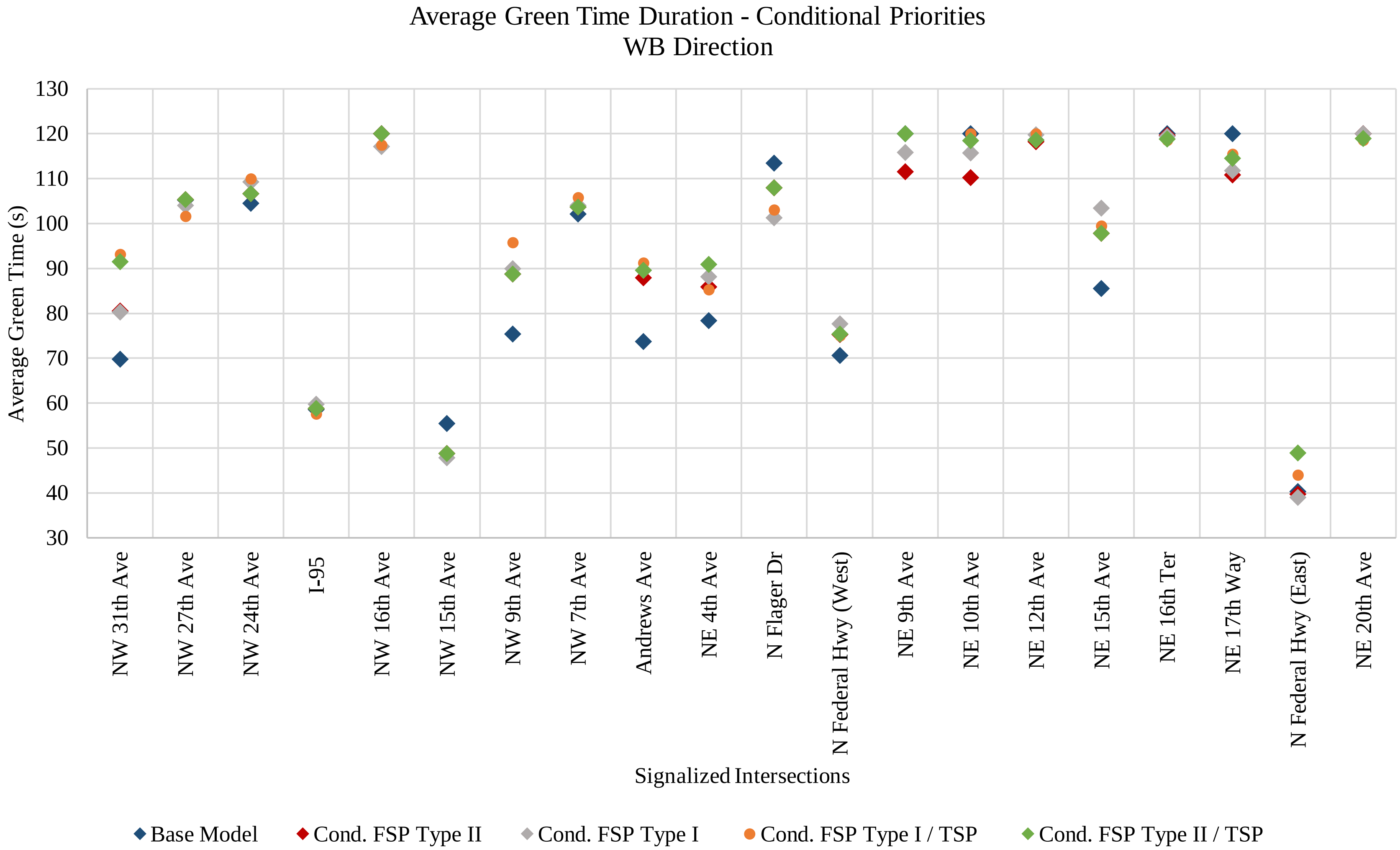

Figure 5-42: Average Green Time Duration (s) - Conditional Priorities - WB Direction

After analyzing the measurements of all the scenarios and for both the eastbound and westbound directions, the conclusion reached is that in most of the signalized intersections the average green time durations increased on the main street. Through that increase, the signal controllers were able to assist the prioritization of the freight and transit vehicles that sent a priority request. On many signalized intersections the green time duration was constant with minor differences of 1-2 seconds in comparison to the base model. The signal controllers of those intersections were able to favor the priority vehicles by sustaining the predefined times of the signal phases and without interfering in a great extent with them.

The highest values of the average green time duration were located on the unconditional FSP/TSP and FSP scenarios. Specifically, the scenarios I and V had the highest green time duration for the eastbound and westbound approaches. The scenarios had to prioritize all the priority vehicles; thus, they had the highest number of priority calls and the urge to provide green time as often as possible.

However, the extra time given to the eastbound and westbound through movements were extracted from the green duration of the rest of the phases, since the cycle length was kept constant. Thus, the greatest the increase in the green time for the main direction, the greatest the reduction on the green time for the other phases. Consequently, in some cases, the remaining durations for rest of the phases couldn't accommodate the traffic demands, increasing the side streets' delays. This indicates that the best option for favoring the priority vehicles and simultaneously sustaining a good level for the overall traffic operations is the selection of the scenarios VI or VII. The green time values of the two scenarios with the conditional FSP and TSP were closer to the base model's values, thus they didn't interfere significantly with the signal phases and provided smother operations on the side streets as well.

The FSP and TSP had multiple benefits to freight and transit vehicles, improving their operations and reliability. Both transport modes provided a higher level of service and improved the safety and environmental conditions on the network. In addition, the strategies, through their implementation, contributed to relieving the heavy traffic conditions along an arterial, without interfering with the operations of the side roads.

6 Guideline Validation

As mentioned, this study developed decision support models to determine the optimal signal priority configuration utilizing a combination of machine learning and simulation, as described earlier in this document. This decision support considers traffic volume, freight volume, and transit frequency of major and minor directions as an input to the model and provides a recommendation of implementing TSP and/or FSP on the major and/or minor directions. Simulation modeling was used to evaluate and validate the developed decision support models. The decisions of the developed model to select between different priority options were demonstrated.

Parameters and inputs in models were based on the closest available real-world data for the AM peak of the case study. The models were set to report various performance measures such as travel time and delays. Each scenario was run for five simulation runs with different seed numbers (with the same sequence of random seeds among scenarios). Each of the simulation run was an hour and 15 minutes long (with 15-minute warm-up time). The results of the simulation experiments were averaged and divided into separate categories.

6.1 Guideline Application

The developed guideline (decision support models) described in section 4.2.4 was applied for the Sunrise Boulevard corridor. The demonstration follows the flowchart presented in Figure 4-24. The first step of the process is to check for an available slack time at each intersection. As mentioned before, slack time is calculated subtracting all pedestrian clearance time and minimum left-turn green times from the cycle time. Table 6-1 lists the slack time check results for all intersections along the corridor. The table shows that all the intersections passed the slack time condition. Therefore, all intersections on the corridor are suitable for TSP and/or FSP implementation.

Table 6-1. Slack Time Checklist

Intersection Name	Slack Time ≥ 5 Seconds
MLK.Jr Ave	Yes
NW 27 Ave	Yes
NW 24 Ave	Yes
NW 16 Ave	Yes
NW 15 Ave	Yes
NW 9 Ave	Yes
NW 7 Ave	Yes
N Andrews Ave	Yes
NE 4 Ave	Yes
N Flagler Dr	Yes
NE 20 Ave	Yes
NE 17 Way	Yes
NE 15 Ave	Yes
NE 12th Ave	Yes

In the second step, the guideline was implemented to determine whether signal priority is recommended to be implemented on the major or minor or both directions. In this study, signal priority is only considered for the through movements on the main street.

The third step is to check the applicability of FSP and TSP on the selected direction (major direction). Table 6-2 provides the details for the FSP and TSP implementation checklist based on the information provided in Table 4-12. It shows that the TSP satisfied all the conditions on the checklist. Therefore, TSP on the main street can be considered as a signal priority option along the major direction of the corridor. FSP satisfied four out of the five conditions of the checklist and can be an alternative consideration. Thus, the case study considers three alternatives for signal priority on the main street: TSP, FSP, or both.

Table 6-2. TSP/FSP Checklist

TSP		
	Checklist	Satisfied/Unsatisfied
1	Express Bus Service	Satisfied
2	Bus stop location at Far side or midblock. If not, then planning to relocate the bus stop locations	Satisfied
3	Agencies want to reduce transit delay and increase the reliability	Satisfied
FSP		
	Checklist	Satisfied/Unsatisfied
1	Important truck route	Satisfied
2	Uphill/downhill	Unsatisfied
3	Safety issues	Satisfied
4	Environmental issue	Satisfied
5	Agencies want to reduce freight delay and increase the reliability.	Satisfied

In the fourth step, both the developed guidance and simulation were used to find out the optimum priority option for various intersections on the corridor. Table 6-3 shows the results.

Table 6-3. Guideline Recommendation

Intersection Name	VC Major	VC Minor	Truck Volume Major	Truck Volume Minor	Major-Minor Truck Proportion	Only TSP	Only FSP	Both
MLK.Jr Ave	0.98	1.38	11	13	0.85	Sim	Sim	Sim
NW 27 Ave	1.25	1.26	18	8	2.25	Sim	Sim	Sim
NW 24 Ave	1.21	0.38	19	1	19.00	Sim	No	Sim
NW 16 Ave	1.28	0.92	22	1	22.00	Sim	Sim	Sim
NW 15 Ave	1.32	1.34	17	5	3.40	Sim	Sim	Sim
NW 9 Ave	1.29	0.90	14	7	2.00	Sim	Sim	Sim
NW 7 Ave	1.28	0.92	14	4	3.50	Sim	Sim	Sim
N Andrews Ave	1.11	1.10	13	4	3.25	Sim	Sim	Sim
NE 4 Ave	1.00	0.95	12	10	1.20	Sim	Sim	Sim
N Flagler Dr	0.81	0.19	14	1	14.00	No	No	No
NE 20 Ave	0.80	0.44	12	1	12.00	No	No	No
NE 17 Way	1.31	0.07	14	1	14.00	Sim	No	Sim
NE 15 Ave	1.08	1.03	11	4	2.75	Sim	Sim	Sim
NE 12th Ave	1.06	0.03	14	12	1.17	Sim	No	Sim
Total Number of Intersections						**14**	**14**	**14**
Recommended for Simulation						**12**	**8**	**12**
Recommended for No Simulation						**2**	**4**	**2**

** Sim = Simulation Required*

Table 6-3 shows that most of the intersections fulfill the requirements for further analysis using simulation for the three investigated signal configurations. Therefore, a details simulation was performed with these three different signal priority strategies:

1. TSP Only
2. FSP Only
3. TSP and FSP

6.2 Simulation Results

A simulation was performed with different signal configurations, as mentioned above. The benefit for each signal configuration was compared with the base condition (no signal priority). The travel time cost for each condition was calculated using the method mentioned in Section 4.2. Table 6-4 summarizes the results.

Table 6-4.Travel time Cost ($) at different Signal Configuration

Intersection Name	Base	FSP	TSP	Both
MLK.Jr Ave	5,497,679	6,288,429	6,214,712	6,450,207
NW 27 Ave	4,171,041	3,584,152	3,564,131	3,354,471
NW 24 Ave	3,356,505	2,406,207	2,583,641	2,712,381
NW 16 Ave	2,770,523	2,492,289	2,603,578	2,227,322
NW 15 Ave	2,116,348	1,541,225	1,920,809	1,602,288
NW 9 Ave	3,004,991	2,388,485	2,512,950	2,249,696
NW 7 Ave	2,215,771	2,143,086	2,402,430	2,428,847
N Andrews Ave	2,748,599	3,410,423	3,459,285	3,686,470
NE 4 Ave	2,599,698	2,749,258	2,162,395	2,115,287
N Flagler Dr	1,141,611	1,026,881	1,204,124	1,009,829
NE 20 Ave	766,595	821,812	722,591	1,150,408
NE 17 Way	1,304,732	1,406,695	1,175,474	1,311,347
NE 15 Ave	3,221,748	2,489,490	2,385,777	2,595,498
NE 12th Ave	862,037	658,345	967,895	748,697
Total:	35,777,878	33,406,778	33,879,792	33,642,748
Benefit	-	***6.63%***	***5.31%***	***5.97%***

Table 6-4 shows that the FSP could provide the highest benefit (6.63%) in terms of dollar value. However, TSP and FSP can be implemented together which could provide almost similar benefit (5.97%), while supporting these two modes of transportation. Thus, this is the preferred alternative.

6.3 Major Street Analysis

In Tables 6-5, the average travel time measurements are reported in seconds for all of the eastbound (EB) path transportation modes (the direction with priority). The findings are provided for all the different investigated scenarios and for all consecutive segments of the corridor. Table 6-6 indicates the average travel time measurements in seconds for the westbound (WB) movements for buses and HGVs.

The analysis of the network with various scenarios provided promising as well as unfavorable findings. The improvements were noticeable for most of the intersections. The lowest reduction on the average travel time in EB direction was identified with the TSP scenario, that priority vehicles included only buses, with 11.6% improvement for HGVs and 21.5% for buses. In some cases, the differences before and after the priority implementation were minor, while in some cases they were negligible. Further researches of the simulation models assume that the situations with negligible improvements were typically related to the intersection configuration and the turning movements. The lowest reduction of travel time in the WB direction relates again to the implementation of TSP with only a 4.7% enhancement in the travel time of HGVs and 20.3% in the travel time of buses.

The implementation of FSP only resulted in a truck travel time reduction of 19.8% (EB), and 21.1% (WB). The implementation of TSP only reduced bus travel times by 21.5% in the EB and 20.3% in the WB direction. FSP and TSP strategies implemented individually yielded the most benefit for the prioritized mode and around 10% to 15% for the passenger vehicles. When implemented together, FSP & TSP resulted in a reduction in bus travel times of 26.3% in the EB and 19% in the WB direction, compared to the base scenario. In terms of trucks' travel time, the application of FSP and TSP resulted in a reduction of 21.5% in the EB and 17% in the WB. The combined implementation of FSP & TSP shows significant improvements in transit and freight travel times over any strategy implemented individually. Therefore, from the perspective of all modes, the combination of these two strategies is highly desirable.

The main street traffic travel time improved individually for all vehicles and for each transport mode, with all priority scenarios. The overall improvement in travel time in all test scenarios was higher than 7 per cent.

Table 6-5 Average Travel Time (s) per Segment - EB Direction

Segments	Base		FSP		TSP		FSP & TSP	
EB	Bus	HGV	Bus	HGV	Bus	HGV	Bus	HGV
MLK.Jr Ave	79.94	60.89	30.10	23.52	23.82	61.62	28.93	47.01
NW 27 Ave	131.22	115.68	17.20	20.32	27.62	94.57	15.59	18.48
NW 24 Ave	48.97	55.86	22.57	22.74	46.01	47.74	40.03	16.25
I95	98.91	121.69	19.38	17.80	14.50	102.83	13.73	13.73
NW 16 Ave	35.05	44.37	25.61	25.86	25.10	38.60	21.89	16.97
NW 15 Ave	99.44	100.44	102.44	103.44	105.44	106.44	109.44	72.96
NW 9 Ave	48.53	38.26	15.37	12.12	30.40	42.32	51.33	12.27
NW 7 Ave	71.96	54.01	26.72	15.32	48.05	57.97	46.21	25.95
N Andrews Ave	83.48	37.42	39.48	17.69	22.93	34.86	17.08	19.10
NE 4 Ave	141.53	52.10	47.38	32.76	15.79	58.61	12.74	19.04
N Flagler Dr	51.05	56.87	23.56	7.18	19.07	37.10	7.29	3.85
NE 9 Ave	15.57	5.57	5.47	4.07	3.35	7.49	3.55	3.78
NE 20 Ave	29.84	20.44	23.61	10.34	19.29	15.46	20.06	17.12
N Federal Hwy (East)	34.94	23.42	7.12	3.42	7.97	21.90	5.39	8.02
N Federal Hwy (West)	22.42	19.74	17.91	9.75	15.55	13.72	8.72	9.08
NE 17 Way	60.62	26.56	26.88	7.93	13.71	28.11	5.83	7.50
NE 16th Terrace	56.21	17.50	26.07	11.87	8.38	13.78	8.31	14.26
NE 15 Ave	56.11	28.78	24.63	6.20	14.45	18.00	12.39	7.16
NE 12th Ave	93.04	39.98	23.51	8.77	14.27	12.00	11.01	9.85
NE 10 Ave	41.22	12.92	40.18	11.75	39.83	9.39	40.12	12.10
Total	1300.00	930.79	1118.20	746.59	1020.79	822.46	958.33	730.25
Compared to Base	N/A	N/A	-0.140	-0.198	-0.215	-0.116	-0.263	-0.215

Table 6-6 Average Travel Time (s) per Segment - WB Direction

Segments	Base		FSP		TSP		FSP & TSP	
WB	Bus	HGV	Bus	HGV	Bus	HGV	Bus	HGV
MLK.Jr Ave	139.00	111.53	133.13	75.90	127.43	124.46	87.63	69.84
NW 27 Ave	80.20	89.52	89.15	54.23	74.17	75.27	74.40	59.86
NW 24 Ave	53.84	54.21	35.18	42.09	32.59	42.06	54.51	47.90
I95	54.91	48.89	48.59	56.45	69.03	31.18	45.73	51.78
NW 16 Ave	15.05	28.76	22.22	21.35	18.92	33.56	27.71	25.42
NW 15 Ave	158.07	67.20	69.73	53.56	128.37	53.98	63.69	65.93
NW 9 Ave	129.20	30.91	47.77	25.69	40.98	22.11	27.43	34.17
NW 7 Ave	63.52	73.73	51.47	46.24	74.75	69.46	58.67	64.95
N Andrews Ave	48.20	53.66	91.59	38.21	63.17	45.95	67.00	47.68
NE 4 Ave	63.52	42.75	36.67	34.42	35.16	32.11	28.74	19.36
N Flagler Dr	63.26	20.98	32.31	20.24	32.00	15.93	26.48	10.76
NE 9 Ave	16.60	19.15	18.39	10.82	15.82	20.17	21.10	15.06
NE 20 Ave	89.08	21.94	46.36	21.49	34.36	24.48	58.99	39.32
N Federal Hwy (East)	75.75	131.21	124.41	100.87	68.59	158.85	105.19	104.68
N Federal Hwy (West)	18.61	17.38	25.07	22.56	17.93	21.11	24.35	18.22
NE 17 Way	74.68	30.56	71.12	24.44	35.49	28.26	55.39	23.21
NE 16th Terrace	34.06	18.84	39.91	22.07	32.22	13.42	47.22	15.44
NE 15 Ave	47.99	30.98	67.53	34.75	68.35	34.47	74.31	27.99
NE 12th Ave	26.32	21.07	41.89	14.34	18.97	22.87	55.07	17.05
NE 10 Ave	20.90	13.45	18.50	11.68	25.51	13.02	27.31	10.82
Total	1272.73	926.68	1110.96	731.40	1013.77	882.71	1030.89	769.42
Compared to Base	N/A	N/A	-0.127	-0.211	-0.203	-0.047	-0.190	-0.170

6.4 Minor Street Analysis

The side street total travel time for major intersections in different scenarios is presented in Figure 6-1. In most cases, the priority strategies resulted in higher travel times and as a consequence more delays for the crossing street traffic. However, these delays vary significantly, depending on the utilized strategy.

Figure 6-1 displays the measurements of the average travel time in seconds for side streets' movements for all of the developed scenarios. In most of the study area, unconditional priority (FSP & TSP) would result in the most significant delays for the cross-street traffic compared with the base model. The variation in the cross-street delays for different sections is possibly due to different traffic signal timings and variation in traffic flows in those intersections.

In general, for all investigated priority approaches, deterioration in average travel times of cross has been observed. The intention of the signal priority is to favor priority vehicles along a certain corridor. Prioritization is achieved either by green time extension or by red truncation. Therefore, changes in the travel time in side-streets were anticipated as a result of the implementation of priority strategies in the main direction leading to shifts in the signal timing and the length of each signal phase in the crossing streets.

As stated earlier, the results vary for each priority scenario, and in the case of the unconditional FSP & TSP and only FSP scenarios, the highest increase in travel times was reported. Compared with the other scenarios, the particular scenarios had to handle the largest number of priorities calls, and it is justifiable. The TSP scenario had the lowest travel times and delays since priorities were only established for transit vehicles with lower volumes than trucks and passenger vehicles.

Figure 6-2 shows the box plot of side-street delays for the base scenario in addition to the three considered scenarios. The box plot for the base model is smaller, meaning less variation in delays, whereas the taller box plot of the FSP & TSP priority means greater variation in the results. The solid line that divides the box into two parts represents the median. The box represents the middle 50% of the data. The upper box represents third quartile, whereas lower box represents second quartile. The box plot for FSP and TSP differs due to the number of vehicles that they provide priority for (buses versus trucks). The median of delay for TSP is less than that of FSP because of the differences in the volumes of vehicles.

Figure 6-1 Average Travel Time (s) on Side Streets

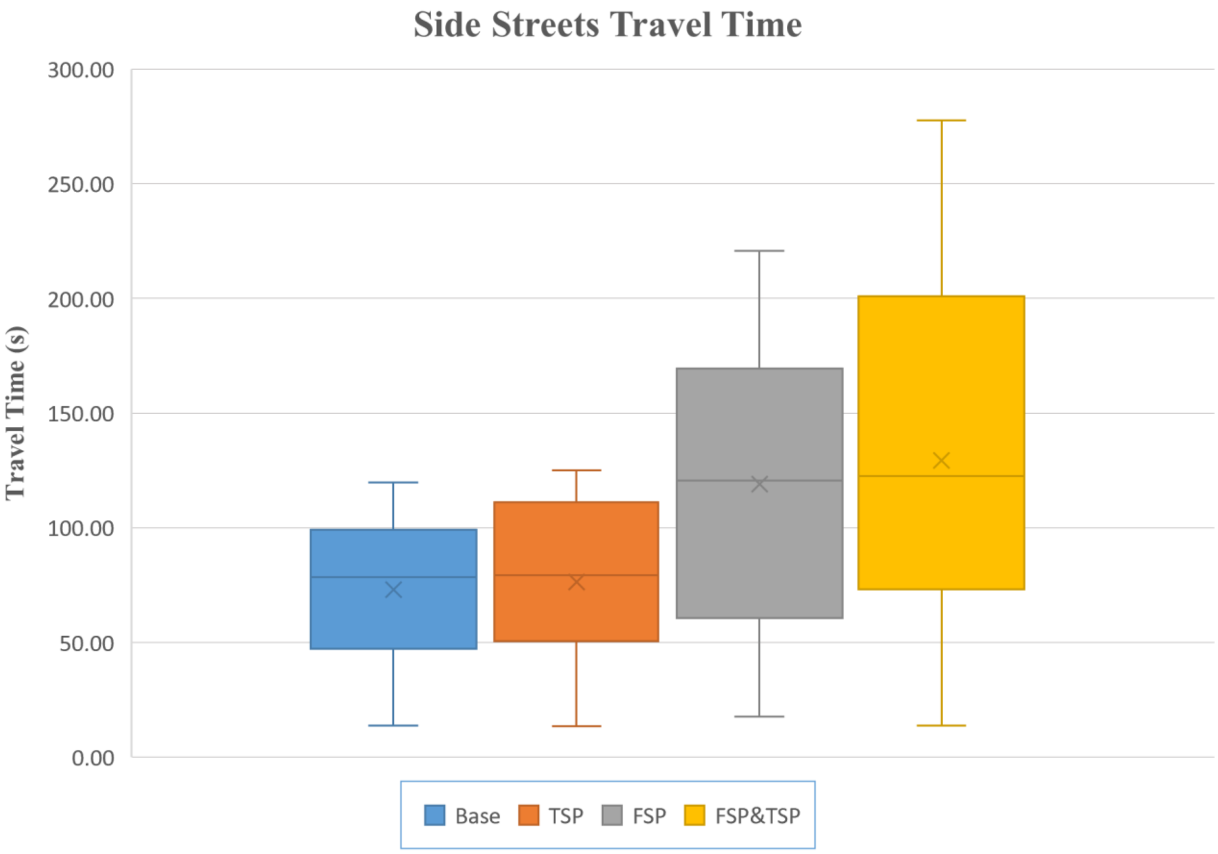

Figure 6-2 Average delay (s) on Side Streets

7 Conclusions

This project focuses on evaluating the effects of the simultaneous implementation of Freight and Transit Signal Priorities in multi-modal corridors. It aims to improve freight mobility, sustain good transit services, and enhance the congested traffic conditions of the overall traffic network.

Thus, the prioritization of the freight movements, through FSP, was the first step for providing fast and reliable freight operations. Concurrently, favoring the transit vehicles, through TSP, was an additional goal, for strengthening the transit operations. Through the facilitation of the freight and transit movements, the overall network traffic conditions along with the provided level of service were expected to be upgraded as well. Numerous scenarios were conducted, first with the separate implementation of each priority and later with their combination unconditionally and conditionally, and specific measures of effectiveness were taken into consideration for the evaluation of the results.

As expected, the evaluation of all the FSP and TSP scenarios presented a positive effect on the freight and transit movements on the main street. The travel time and the delays were reduced significantly on the majority of the corridor's main street segments, with some exceptions on few intersections, mostly due to the geometry of the road. Furthermore, the congested conditions along Sunrise Boulevard for all the transport modes were reduced as well.

Regarding the side streets, the impact of the priority strategies differs depending on the strategy applied. The implementation of the unconditional freight priorities caused a significant increase on the side streets delays, doubling the delay on the streets with high volumes, but preserving the same delay values on the streets with low volumes. Furthermore, the conditional priorities provided more positive results for the side street delays, since they excluded the truck category consisting of noncommercial vehicles. The increase of the delays for the high-volume side streets was minor and for the ones with lower volumes was stable.

The analysis and comparison of the measures of effectiveness from all the developed scenarios lead to the conclusion that the scenario that showed the highest mobility improvements only along Sunrise Boulevard is the Freight and Transit Signal Priority scenario. However, the best performing scenario for the overall network was the Conditional Freight Signal Priority Type II and Transit Signal Priority. This scenario presented improvements on freight and transit mobility on the main direction, while simultaneously its effect on the side roads was the minimum possible.

This project also developed guidelines for implementing the FSP and/or TSP on certain corridors including when the implementation is not recommended, recommended, and when simulation modeling is necessary. Based on the traffic data, this study used a combination of machine learning and simulation results to develop a decision support model of guidelines to determine the feasibility of FSP and/or TSP application. The guidelines consider traffic volume, freight percentage and transit frequency of major and minor direction as an input to the model and provide a recommendation of implementing TSP and/or FSP in major and/or minor directions.

In order to provide the demonstration of the guidelines, the developed guidelines were applied to the case study corridor in terms of implementing FSP and/or TSP at each certain intersection. The results indicate that the implementation of FSP could provide the highest benefit (6.63%) in terms of dollar value. In addition, the simultaneous implementation of FSP and TSP could result in almost similar benefits (5.97%).

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