**Center for Advanced Multimodal Mobility Solutions and Education**

**Project ID: 2018 Project 07**

# EVOLUTION OF ADVANCED TRANSIT SIGNAL PRIORITY WITH GAP-BASED SIGNAL RECOVERY STRATEGY

**Final Report**

by

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**September 2019**

# ACKNOWLEDGEMENTS

This project was funded by the Center for Advanced Multimodal Mobility Solutions and Education (CAMMSE @ UNC Charlotte), one of the Tier I University Transportation Centers that were selected in this nationwide competition, by the Office of the Assistant Secretary for Research and Technology (OST-R), U.S. Department of Transportation (US DOT), under the FAST Act. The authors are also very grateful for all of the time and effort spent by DOT and industry professionals to provide project information that was critical for the successful completion of this study.

# DISCLAIMER

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# EXECUTIVE SUMMARY


A Transit Signal Priority (TSP) system's fundamental job is to give priority to transit vehicles enabling faster passage through signalized intersections. Through a system that responds to transit vehicles approaching an intersection, green phase extension or red truncation is granted to minimize transit travel time. With emerging technologies TSP has the potential of doing so without disturbing general traffic flows.

In this study, an evaluation of the overall state of practice for TSP is conducted to upgrade the quality of TSP. Certain parameters were found to be significant in TSP performance, like transit occupancies, transit arrival times, traffic volume, network capacity, system quality and green time. These multiple parameters affecting TSP performance from various studies are gathered and tested in three different cases: 1) Isolated intersection, 2) Main corridor with cross-streets and 3) Case study: Austin downtown network. This study focused on developing different TSP response scenarios to test what is the best way to handle bus requests. These scenarios represent the three TSP system types: passive, active and adaptive. Through multiple scenarios, technology to minimize bus delays while also minimizing effects on general traffic delays was developed.

The objective of this project is to develop a network-based model to study the impacts of TSP at a network-level, rather than at the traditional corridor-based level. This report evaluates the overall state of TSP practice as well as identifies and investigates new ways to improve TSP. Some of the approaches that were evaluated examine the effect of adding/removing a bus lane, adding extra green signal time to bus travel direction with compensating cross street traffic for green time loss. Volume to capacity (V/C) ratios for both bus travel direction and the cross-street were evaluated to determine the (V/C) ratios that would benefit from TSP implementation. This effort will lead to a better understanding of the factors affecting TSP.

# Chapter 1. Introduction

Car-based commuting has typically been a preferred mode of transportation for home-based work trips. However, work trip automobile occupancies are only slightly greater than one person per vehicle and this tends to create peak hour travel demands (measured in vehicles per hour) that exceed infrastructure capacities (National Household Travel Survey (NHTS), 2009). Wherever travel demands exceed capacities, automobile congestion results, and this is a worldwide problem.

Congestion solutions can be summarized into three categories: 1) Expanding existing infrastructure such as adding lanes to existing highways or building new ones; 2) Reducing the number of vehicles by providing alternatives that increase vehicle occupancies such as improving public transportation systems (more buses/trains), promoting carpool-vanpool programs, or travel demand management; or 3) Operating networks more efficiently by other means. The last option can be the least expensive in some cases because it may involve very little infrastructure investment.

Looking for smart and cost-effective solutions to relieve traffic congestion, city planners have turned to improving the public transportation system as an option. However, one of the biggest issues for public transportation is reliability. Commuters might be willing to utilize public transportation only if it provides a better alternative. The majority of people prefer to drive a private vehicle over other modes of transportation on a daily basis due to comfort, flexibility, and mobility. As cities continue to expand outward, urban sprawl has contributed to private car use. Even with increasing traffic congestion, most people still prefer individual travel opposed to public transportation due to perceptions, motivations, and context. People must see physical and perceived differences in the public transportation system before ridership will increase. Transit signal priority systems aim to enhance the speed and reliability of bus travel by providing buses with priority at signalized intersections. Basic TSP has been proven to be successful in improving transit efficiency, schedule adherence, enhancing transit information and network efficiency in multiple studies.

TSP systems have been an area of extensive research in the last decade and have been described to potentially help move more people in the corridor and reduce emissions, thereby benefiting both transit users and the network. Transit signal priority (TSP) systems fall into the third congestion solution category since they do not call for an expansion of infrastructure nor a reduction in vehicles.

TSP has multiple parameters that can directly and indirectly affect system performance. Previous studies have examined a range of TSP implementation concepts, however, in this study an evaluation of the overall state of TSP practice will be conducted and new approaches to improving TSP will be investigated. A network based model will be formulated to study the network impacts of TSP instead of the traditional corridor-based approach.

## 1.1 Background

There has been an ongoing increase in single-rider trips, which has added more demand to the limited supply of transportation networks. In 2013, Most Americans, 76.4%, commuted to work alone by automobile, an increase from 64.4% in 1980 (McKenzie, 2015). Increased congestion and limited capacity in cities around the world have prompted traffic engineers to promote commute alternatives to help decrease the load on the network.

Public transportation has been regarded as a good alternative, offering benefits over biking, walking, and carpooling as an alternative to car use. Biking and walking are sustainable alternatives, but can be difficult for those living far from the desired destination (Redman et al. 2012). Carpooling is another viable option that decreases the number of vehicles on the road. However, public transit still has benefits over carpooling. Not only can increased ridership decrease congestion, but also the transit rider does not have to worry over finding a parking spot in a densely populated city. Locating parking can result in wasted time and costs to park are often high. Although buses can solve the problems associated with traffic and parking, people often still choose to drive due to increased speed and reliability.

Today, commuters are more informed than ever, as many systems are now designed to update with expected transit travel time. Close to 85% of transit agencies report dynamic transit travel information (USDOT, 2010). However, changes in traffic conditions can leave commuters with greater than expected wait times. While commuters may look at the schedule before walking to the bus stop, they may end up having to wait for the bus longer than expected. Especially during peak hours, buses run the risk of running late because of heavy traffic.

Transit signal priority systems aim to enhance the speed and reliability of buses by providing the buses priority at signalized intersections to minimize stop time. Lin et al (2013) developed a model that specifically used passenger wait time at the next bus stop for deciding signal timings at an intersection. His model was successful in capturing how long passengers waited and if it is worth giving priority to the bus. Also, along with reduced wait time, reduction in running time is expected to increase ridership and rider satisfaction (Hensher et al., 2003), therefore making public transportation more appealing.

In general, signalized intersections are designed with single-occupancy vehicular movements in mind, rather than transit. This study introduces the idea that transit flow in some cases is more important than single occupancy vehicle flow. TSP systems have been giving priority for transit vehicles since 1968 (Courage and Wallace, 1977) and have shown success in improving transit efficiency, schedule adherence, enhancing transit information, and road network efficiency (ITS America, 2004). TSP is widely used now in the US with at least 36 major transit agencies adopting the technology for over 7000 transit vehicles. (USDOT, 2010).

## 1.2 Problem Statement

Traditionally, transit signal priority systems are being evaluated and tested at the corridor level rather than the network level. These systems have been a controversial topic in traffic research for mainly two reasons: 1) the fact that these systems are developed and tested on a singular corridor, or isolated intersection sometimes makes their outputs very limited; and 2) testing any alteration in traffic on a small scale does not reflect the impacts seen on a bigger scale. Flow models prove that traffic flow interruptions have a cascading effect as discussed in Mirchandani 2001, Smith 2002, Nicholas and Bullock 2004, LI et al 2016. Regardless of the size of the cascading phenomena, it exists and needs to be studied to identify the best model and system.

## 1.3 Research Objectives and Contribution

The goal of this study is to develop a network-based model to study the network impacts of TSP rather than the traditional corridor-based approach. Also, this report will evaluate the overall state of TSP practice as well as identify and investigate new approaches to improving TSP. Some of the approaches that will be evaluated examine the effect of adding/removing a bus lane, adding extra green signal time to bus travel direction with compensating cross street traffic for green time loss. Exploring different vehicle over capacity ratios for both bus travel direction and cross-street to determine when TSP would be beneficial and deciding what the threshold might be. This effort will lead to a better understanding of the factors that affect TSP and how to utilize these factors to improve TSP.

## 1.4 Overview

This report will be structured in 7 chapters. This first chapter provides an introduction to issues regarding modern day commuting and transit as an alternative to car use. The second chapter introduces transit signal priority systems, their history and potential impacts as a solution to prevent additional stress on the transportation network. The third chapter will describe the proposed solutions to reach the goals of this study and test these solutions based on simulations for an isolated signalized intersection. The next two chapters will test a bigger segment, four and five will cover a one-way corridor case and two-way corridor case, respectively. A case study will be built based on the City of Austin downtown network. Chapters 3 through 6 will describe the implementation and evaluation criterion of the solution methods. The last chapter, seven, will cover the summary of this study.

# Chapter 2. Literature Review

This chapter summarizes the literature review that was used to build this study.

## 2.1 History of TSP

Transit signal priority systems have been researched since the late 1960s when Wilbur Smith explored a basic model of TSP and concluded that TSP can increase quality of service through improving schedule adherence and reducing travel time. A basic TSP system can be described as a system where priority would be given to transit vehicles approaching an intersection through extending the green traffic signal or truncating the red signal and starting the green for the bus travel direction. This model has been studied and continuously developed in the last 50 years. The motivation behind TSP is to make buses travel faster by minimizing the bus wait time at each intersection.

## 2.2 Urban Traffic Control

In general, a traffic network is a set of intersecting streets. A traditional traffic simulator model uses links and nodes to represent roads and intersections, respectively. Traffic using urban networks consists of mostly passenger vehicles. Although, transit vehicles and trucks are also major flow components of an urban network. Increasing population brings increases in travel demand, therefore increasing congestion problems. Ways to increase flow throughout the network include adding more roads or making the existing roads bigger, however, these options can be very expensive and impossible to implement in some cases. Smarter usage of existing infrastructure (such as traffic signals) could help increase speeds and reduce travel times. Traffic signals can be used to control and optimize flow in an urban network.

Just like other vehicles, transit vehicles traveling through intersections experience delays. Given the fact that passenger vehicles have an average occupancy of slightly over one person 1.1 for work trips (NHTS, 2009) compared to buses that can hold up to 50 passengers and even more on average during peak hours, buses can basically fit 45 vehicles in terms of trip purposes while only using roughly 5% of road space. In that case, special delay reduction treatments for buses can be rather easily justified. Preferred treatment of buses at intersections can be supported by a vehicle occupancy argument. Additionally, preferred treatment could help transit services adhere to schedules and attract even more transit riders. Ideally, with improved services, people will eventually start shifting from traditional single occupancy vehicle trips to public transit.

A widely examined special bus treatment called Transit Signal Priority (TSP) shows great potential for minimizing bus travel time and overall delays. TSP attempts to change signal timing to improve transit vehicle speed and reliability. TSP is described by Intelligent Transportation Society of America (2004) as an operational strategy in traffic signal-controlled intersections that facilitates the movement of transit vehicles. Moreover, transit ridership is directly related to the performance of transit travel time. Sunkari (1995) discussed that TSP can reduce bus delay by 10-25% in urban areas. In Los Angeles, CA ridership increased up to 40% after implementing a TSP system (Smith 2005). These facts and more highlight the potential benefits that can come from enhancing TSP systems to minimize bus travel time and overall delays.

## 2.3 Traffic Signal Controllers

Investing in traffic signal systems is a cheap and effective way to improve travel time and reduce delays. As Sunkari (2004) concluded, for every dollar invested in traffic signal systems there is up to $40 dollars gained in user benefit. Traffic control systems not only help to improve traffic flow, but also help to reduce vehicle emissions by minimizing fuel consumption. Also, improving traffic signal timing has shown to reduce the frequency and severity of traffic crashes (Bonneson, 2011), which leads to even further decreases in delay.

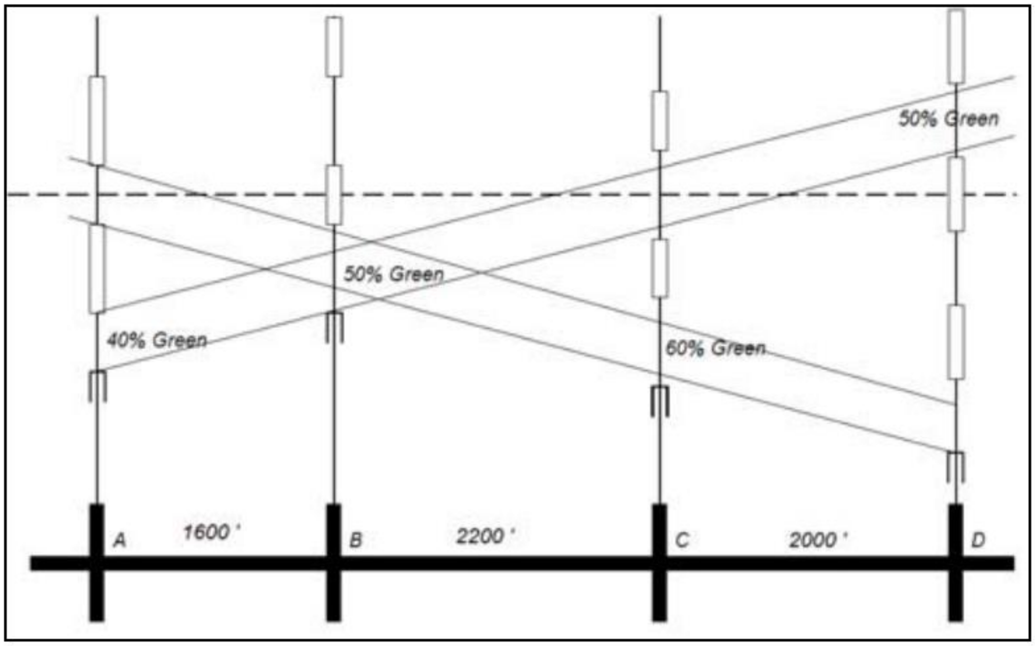
Two families of traffic signal controllers include pre-timed and actuated categories. According to the Federal Highway Administration Traffic Control Systems Handbook, pre-timed controllers are appropriate for grid networks where signal coordination is typically provided. Actuated controllers are appropriate choices for isolated intersections, but not usually for intersections within an urban grid network. The reason behind this is that any change in the traffic cycle will most probably affect any signal coordination that might be in effect. Typical urban networks and especially downtown areas use coordinated pretimed signals during rush hours. Signal timings can achieve that by using a basic pre-timed signal coordination plan. However, a bigger urban network will have more constraints which will eventually limit the impact of pretimed signals which make them harder to work with. On the other hand, using real-time vehicle detection, actuated signals can know where traffic is mostly concentrated, providing the ability to change cycle and phase durations based on demand (Bonneson, 2011). However, real-time detection devices can be costly, which puts us back in the dilemma between choosing the most cost-effective way to control an intersection, factors like the size of the grid network, isolated intersections and traffic volumes are all considered in choosing between pre-timed or actuated controllers.

### 2.3.1 Pre-Timed Signal Control

Grid network traffic signal systems usually use pre-timed signal controllers to provide a system of progression that minimizes numbers of stops therefore allowing many users to travel long distances without stopping. Progression coordination has been used in most cities around the world since the 1930's. Progression coordination creates a bandwidth of green time that can allow traffic to travel through multiple intersections without the need to stop. Successive intersections have a time offset value that is the travel time from the previous intersection to the next at the desired progression speed, allowing platoons of vehicles to travel along the street as long as they maintain the progression speed. Excellent progression solutions can be derived for corridors with higher traffic volumes traveling in only one direction.

Maintaining progression in a grid network can be complicated when considering two-way streets and demands that exceed capacity. Introducing simultaneous progression coordination for two directional traffic demands on one street usually leads to conflicts among timing parameters that limit system effectiveness. Henry (2005) discussed the Kell method as a graphical means of providing two-way progression and the additional parameters that affect the bandwidth value. The Kell method starts by identifying the distance between successive intersection along the desired direction of travel, on the horizontal axis. The vertical axis shows the green/red signal phases where the designer/engineer can use the green phases to draw a straight line where traffic can basically drive through these green gaps without stopping. Figure 2.1 shows that output of the Kell method.

**Figure 2.1: Final step of the Kell method (Henry, 2005)**




Henry, also discussed that the Kell method sensitivity to green and red changes can dramatically decrease the chances of having a large-enough green band for platoons to travel through. Also, another issue would arise if a split phase was going to be applied to any of these intersections, which ultimately limits the flexibility of changing parameters along that line of travel. Moreover, traffic demands exceeding capacity lead to control system failure characterized by spillback and queuing and require more advanced traffic control techniques than basic pre-timed progression (NCHRP Report 812). Some of these control techniques can include devices that help better allocate green time such as actuated signals can be introduced to enable use of real-time data in favor of reducing wasted green time and reduced delay in intersections.

### 2.3.2 Actuated Signal Control

Actuated signal control is a step more than pre-timed signal control in that it provides a bigger range of flexibility in terms of controlling traffic. The basic pre-timed signal can only be set in specific timing/cycle plans beforehand, depending on empirical and historical traffic data. Actuated signal control uses some sort of detecting technique/device to be able to monitor traffic and respond accordingly. As discussed earlier, this sort of signal control is ideal for isolated intersections and will decrease delay dramatically as traffic demand varies through a typical day compared to pre-timed control. However, in grid networks the challenge of allocating green time arises because there are more added constraints. However, actuated control can be used outside of peak hours to smoothly shift when traffic demand is variable. Further exploring actuated control in the literature, there is increased use of actuated control and the next few sub-chapters will explain more about the state of practice.

### 2.3.3 Advanced Signal Timing Concepts

Traffic systems can be divided into two subcategories: preemption systems and priority-based systems. Preemption systems respond to a transit vehicle by immediately terminating the cross-street green signal and giving the bus the right of way, regardless of signal coordination or any other variables. National Transportation Communications for Intelligent Transportation Systems Protocol (NTCIP, 2004) defines preemption signal control systems as the “control which requires terminating normal traffic control to provide the service needs of the special task” such as allowing an emergency vehicle to pass. While preemption terminates cross-street traffic, priority systems give priority to buses but do not necessarily terminate cross-street flow. Some priority systems may add more green time (green extension), while others might start the next green earlier (early green). Adaptive systems follow the same logic of green extension or early green. However, adaptive systems consider more variables when a bus approaches (transit location, signal coordination, traffic flow in intersection, etc.), and then decide whether to add more green time, terminate cross-street green, or not respond based on pre-programmed criteria. To summarize, the difference between preemption and priority is that preemption interrupts the signal operation regardless of other factors, and signal priority adjusts signal operation to accommodate traffic flow needs.

## 2.4 Transit Signal Priority Systems

According to NTCIP 1211, TSP systems are usually a combination of the following 4 components:

1. Detection system: reads the location of transit vehicles

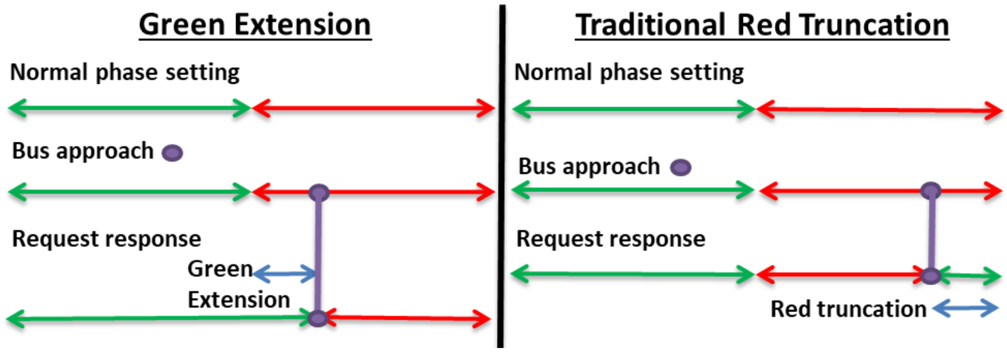
2. Priority request generator: requests priority from the traffic control system

3. Software to handle priority requests and respond based on programed control strategies

4. Software that manages the system

Those four components work together in order to receive the bus signal and generate a response that accommodates the bus fast and safe passage through the intersection. The priority request generator is either the bus being detected by a detection device or the driver manually sending a signal.  The signal is received by a priority request server which can be as small as a box in an isolated intersection controller which represents a distributed TSP system, or as large as a traffic control center representing a centralized TSP system. These requests can result in extension of the green time or truncating the red and starting a new green light phase. Figure 2.2 shows how these two responses work. Different systems apply these responses differently, in the next few sub-chapters a run down on TSP systems will be shown to provide a better explanation on how each system works.

**Figure 2.2: TSP general request responses.**




In general, complete TSP systems cost around $30,000 per intersection with loop detectors. Also, bus transponders that help the bus communicate with the system cost around $100 per bus (Smith 2005). These systems are called distributed systems if all components are located at the intersection. If components are located at one central location it is called a centralized system. The pros of having a centralized TSP system are that it minimizes the parameters that are considered when making a response decision which leads to faster convergence times. Also, maintenance cost may be minimized as the system is easier to fix with fewer components. Centralized systems may provide an overall faster passage for transit but also introduce connectivity issues in terms of how fast and reliably detection requests and responses would arrive at intersections.

## 2.5 Transit Signal Priority Strategies

### 2.5.1 Passive TSP (Unconditional)

The most basic TSP strategy is a passive system built on signal progression logic. Progression assumes that traffic travels at a chosen progression speed throughout the corridor, however, transit vehicles might have trouble maintaining that speed due to passenger boarding and alighting. Transit vehicles by nature stop every 500 to 1200 ft. (in urban areas) for boarding/alighting (TCRP Report 19). The idea behind a passive system is to set a progression bandwidth wide enough to ensure that buses can travel with minimum delays. This is the most affordable form of TSP as it does not require sensing devices or hardware/software installation. According to Smith (2005), passive TSP systems are built on the assumption that transit vehicles travel through intersections with progressing automobile platoons using green bands. Passive systems may be tuned to give bus priority based on expected bus travel times and route data and do not require detection devices.

Passive systems expect buses to travel with automobile platoons, but any unexpected bus delay will affect the system outcome and might lead to more negative impacts rather than improvements. Any increase in passenger ridership will increase the frequency and/or duration of bus stopping, which ultimately leads to an increase in the uncertainty of the bus aligning with the progressing platoon of traffic (Vincent et al., 1978).

### 2.5.2 Advanced TSP Systems (Conditional)

Bus detection devices are a critical part of advanced TSP systems. Active TSP systems give priority to transit vehicles by either adding extra green signal time to the direction of travel or starting the green signal earlier (red truncation). These detection devices require additional hardware and software that decide on which command to give to the traffic signal. Also, some adaptive TSP systems use bus and automobile detection to make decisions based on actual traffic conditions leading to optimization of the usage of the intersection.

Advanced TSP systems that use bus sensing are either active or adaptive. These systems, in comparison to passive systems, are more expensive as they require sensing and software/hardware installations. Both strategies are based on bus location updates that are necessary to maximize TSP performance. Table 2.1 compares the three main TSP strategies.

**Table 2.1: Comparison of Main TSP Strategies**

| | Passive | Active | Adaptive |
|---|---|---|---|
| Cost | No capital cost | 1- bus detection hardware 2-Software | 1- Bus and traffic detection hardware 2-Software |
| Maintenance & Operation cost | Updating progression in signal timings by updating bus: routes, stops, speed, dwelling values, etc. | Updating software & hardware maintenance for detection device | Updating software & hardware maintenance for detection device |
| Objective when a request is received | Bus travel time is minimized | 1- Bus travel time is minimized 2- Minimize impacts on signal coordination | 1- Bus travel time is minimized 2- Minimize impacts on signal coordination 3- minimize impacts on general traffic |
| Variables | Set timings based on bus data | Bus location + cycle status (Green/Red) | Same as active + person, vehicle or transit delay (depends on the system) |
| Parameters | - | Extension time, truncation time, phase choice | Same as active |
| Strategies & Responses | Set cycles so no response for bus arrivals | Green extension, Red truncation, *Phase insertion (Left turn & Queue jump) | Same as active |
| *special cases that require bus request to change the pre-timed cycles. | | | |

References: Chada (2002), Ngan (2004), Dion (2005), Smith (2005)

The table clearly shows that Passive TSP systems are basic with minimal variables, this implies that modern standards would automatically add more parameters that should be included to maximize potential benefits. Active systems would take into account additional parameters, but Adaptive systems are the most complex which ultimately lead to overall best implementation results.

#### 2.2.2.1. Active TSP

Active TSP systems require detection devices and basic software and hardware that can read and translate bus locations. Active systems use techniques that allow the bus to communicate with traffic control devices. An active system structure at the intersection level (Distributed TSP) is shown in Figure 2.3. As shown in the figure, the system is able to detect any bus approaching the intersection and as soon as a bus passes a certain point which is assigned a detector, the signal controller will be notified that a bus is approaching. The signal controller will then end the red light phase and start the green light phase or alternatively extend the existing green light to ensure the bus passage with minimal delay. Also, the same logic applied in Figure 2.4 showing a centralized active TSP system that reads the bus signal and responds to multiple intersections assuring bus passage is smooth and with no delays.

**Figure 2.3: Distributed Active TSP system**

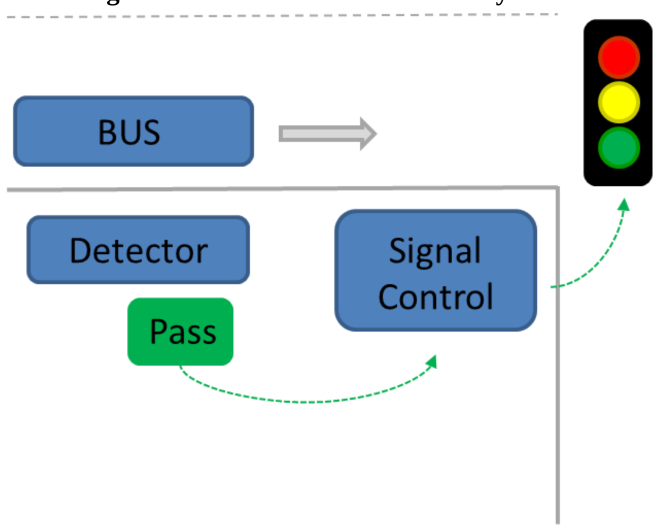
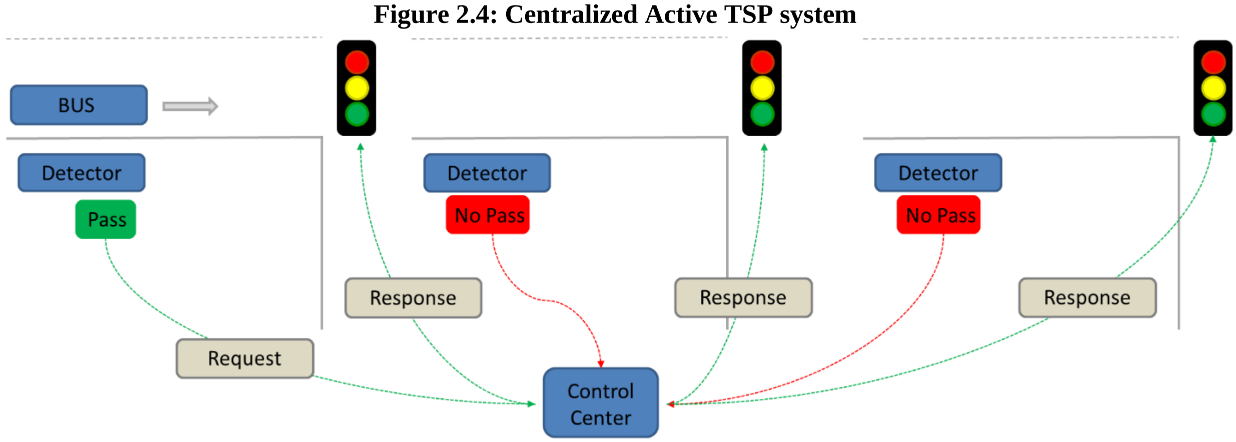



**Figure 2.4: Centralized Active TSP system**




The biggest issue with a simple active system is “false alarms”, where a false request is received from a bus because it is identified by detectors, but then stops for various reasons (bus stop, delay in traffic, queue) therefore preventing it from entering the intersection.

A major drawback for an active system is that it does not account for traffic conditions on its own. In other words, active systems will grant access to a requesting bus regardless of the how much delay might be added to automobiles in the intersection. The only way a bus request can be denied in an active system is if it is a conditional system and, for example, the traffic center makes the decision to deny.

Active systems can improve bus travel times but also introduce significant inconsistency in the impacts to cross-street traffic. Li et al (2011) discussed the reasons behind inconsistent impacts to cross-street traffic are 1) TSP benefits and negative impacts are not explicitly balanced and 2) instantaneous detection (which happens at the intersection level) is not ideal as it does not give enough time for the model to control green time in the most efficient way. This presented a new problem which requires an advanced system to take advantage of all wasted time down to the seconds.

#### 2.2.2.2. Adaptive TSP

Adaptive systems can account for impacts on overall intersection performance by monitoring traffic from all directions of travel and giving a response that minimizes overall delay. This type of monitoring will allow the system to respond to a bus request by minimizing negative impacts on traffic and/or maximizing flow for buses. Adaptive TSP systems generally attempt to account for these issues. Table 2.2 shows a list of existing adaptive systems that are used in the world.

**Table 2.2: Adaptive TSP System Used Worldwide**

| | Remarks | Best used |
|---|---|---|
| BIPS | Consider buses in both directions | In low-medium congestion |
| MOVA | Flexibility in types of priority (Green extension, red truncation, queue jump, left turn or any special case) | Where bus passage is the goal and impact on general traffic is not important |
| SCOOT | Gives great balance between bus and automobile | Where bus passage is the goal and impact on general traffic is important |
| SPOT | Decentralized system that uses traffic average speed | Where bus passage is the goal and impact on general traffic is not important |
| SPRINT | Most advanced, decentralized system | To reduce delay on non-transit vehicles |
| | | References: Chada et. Al (2002) |

Active/Adaptive system responses are not limited to green extension or red truncation. Queue jump and phase insertion are considered active system special cases as they require bus detection to operate more effectively. In order for TSP to work successfully, there needs to be assurance that transit vehicles will get to enter the intersection. In severe congestion, giving priority to traffic traveling in the same direction as the bus might not guarantee that the bus will make it through the intersection, therefore defeating the purpose of TSP. Ways to help overcome this issue include giving the bus the “first seat” in the intersection by adding a bus lane and/or giving the bus priority via a transit queue jump light. A white bar light instead of the traditional green light is the most common way to communicate with bus drivers to enter the intersection.

Zlatkovic et al (2013) tested the effectiveness of queue jump and TSP at a single intersection in Utah. The study consisted of four VISSIM models: control (base case), queue jump only, TSP only, and TSP and Queue jump. The TSP method either provided buses with 10 seconds of either additional green time or red truncation. The results yielded a 22% reduction of bus travel time for TSP with queue jump in comparison to 12% and 15% for TSP only and queue jump only, respectively. The study also reported that traffic on cross-streets was affected and delays increased on average by 15% for passenger vehicles. Another special case investigated by Zlatkovic is adding a protected left turn phase, to the existing cycle without changing the cycle length (the 2070 controller can do this). When a bus approaches an intersection that doesn't usually have a protected left turn phase, a request is sent to the system that responds by starting the protected green as a leading phase (before the arterial green phase) rather than a lagging phase or no phase at all.

## 2.6 Bus detection systems

Implementing an adaptive TSP system requires real-time bus position data provided by detection devices. Although many types of detection devices exist, inductance loop detectors are the most commonly used vehicle sensing device. While inductance loops can provide reliable sensing data for a dedicated bus lane, they cannot easily detect only buses in a mixed traffic stream. Infrared light detectors provide a better alternative to loop detectors as they only detect buses regardless of the existence of a bus lane. Global Positioning Systems (GPS) however, provide the most promise since they can provide real-time bus location and speed data wherever the bus may be operating. Bus detection is a crucial part to any TSP system. The more reliable the detection is, the better the system is going to be. A TSP system without real-time bus location data would omit confounding variables that must be included. Table 2.3 shows a breakdown of different types of detectors.

**Table 2.3: Comparison Between TSP Detectors**

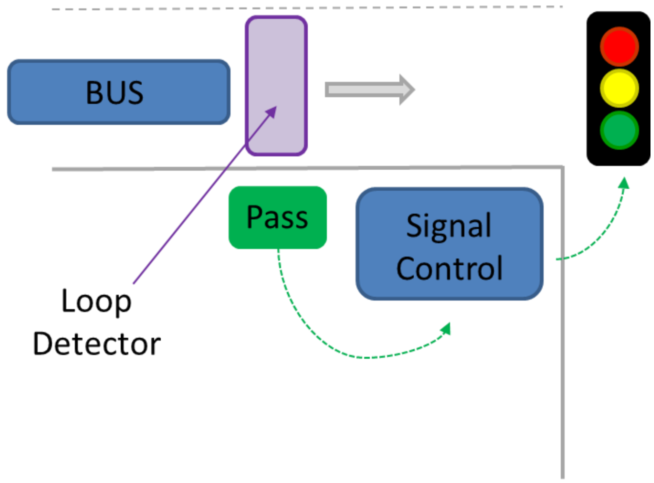
| System | Costs | | | Implementation | | Range |
|---|---|---|---|---|---|---|
| | Per Intersection | Per Bus | Operating | Bus Hardware ? | Intersection Hardware? | |
| Loop | $2,000 | $250 | Low | Transmitter | additional loop to check out | limited |
| Infrared Light | $10,000 | $3,000 | $2,000 | Emitter | Infrared detector | 2,500'* |
| GPS | $7,500 | $5,000 | No data available | GPS unit | Radio receiver | 2,500' |
| Wi-Fi | $5,000 | $5,000 | Low | Wireless transmitter | Wireless receiver | 1 Mile +/- |

Reference: Federal Transit Administration (2008)

### 2.6.1 Loop Detectors

Loop detectors are mainly used for active systems because these methods often detect bus presence at chosen locations close to intersections. A loop detector detection zone consists of the surface area of a coil of wire imbedded in the pavement and connected to a sensing device that provides a switch closure when the inductance of the coil changes due to a vehicle entering the detection zone. Figure 2.5 shows an example of how loop detectors work.

**Figure 2.5: Loop detector example**

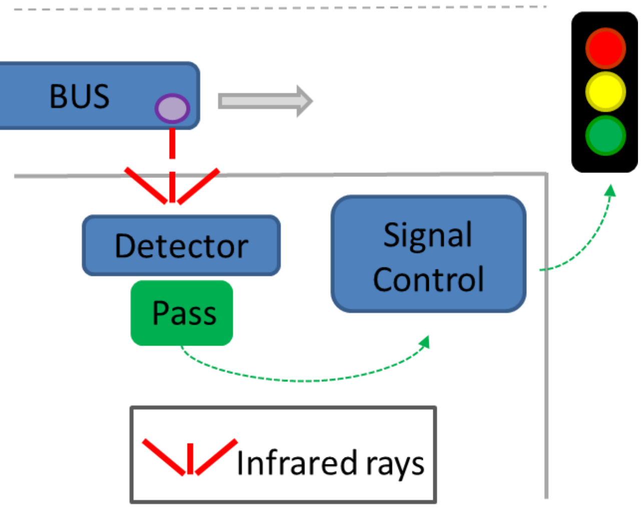



When the bus crosses a detector, the detector transmits the priority request to the signal controller, and the signal controller implements the priority strategies (Gardner et al., 2009). Loop detectors are inexpensive compared to other detection methods, but they are location specific meaning that the designer must decide where to install and how to configure the device. However, loop detectors might have some limitations since in a mixed traffic stream they cannot reliably identify buses, so they are only applicable in bus lanes. The duration of vehicle presence in the detection zone can be used to estimate vehicle length if vehicle speed is known but reliable speed estimation requires a loop detector pair. Since buses may not be the only long vehicles in a typical mixed traffic stream, their ability to identify or classify buses in a mixed traffic stream is not very robust. Classification can be prone to errors in congestion situations, since speeds vary significantly making estimated vehicle lengths unreliable. Also, loop detectors must be installed near intersections for best results since if a bus stop is between the intersection and the loop detector, stopping for passenger activity would cause buses to miss the implementation of their request and this would cause what was presented earlier as a “false alarm”.

### 2.6.2 Infrared Light

Another bus detection system is infrared light based. It is a system that is more advanced than loop detectors because this system can only sense buses when they arrive to an intersection. The infrared light detection system consists of a sender device installed near an intersection and a receiver installed on buses. Figure 2.6 shows an example of how infrared light detectors work.

**Figure 2.6: Infrared light detector example**

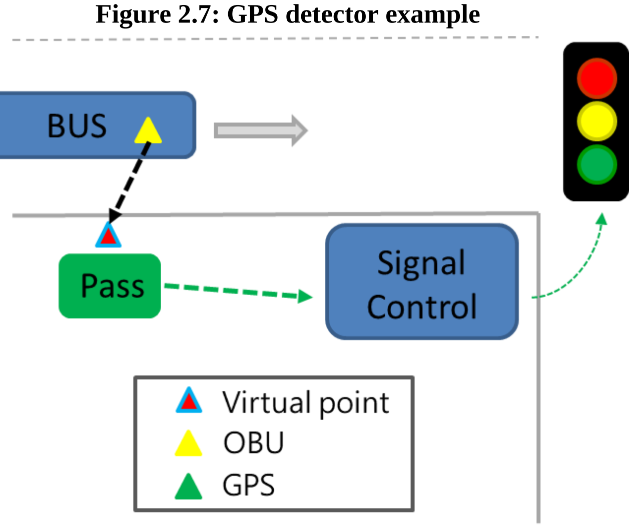



Once the bus passes, the sending device reads the receiver and then the bus is detected passing that point. One of the main disadvantages of this system is that it requires a clear line of sight between the sender and receiver to be able to communicate. In special cases that could be a problem, if the bus cannot align next to the curb side or if there is some object obstructing the line of sight.

2.6.3 GPS and Wi-Fi Detectors

The Global Positioning System also known as Navstar is a global navigation satellite system that provides geo-location and time information to a GPS receiver in all weather conditions, anywhere on or near the Earth where there is a steady signal to four or more GPS satellites. A GPS receiver on a bus can periodically transmit position data to a central computer that tracks the bus path. The computer can determine when the bus trajectory intersects chosen "detector" locations much like "virtual" loop detectors, however, such a system requires no field device installation. Figure 2.7 shows an example of how GPS detectors work.

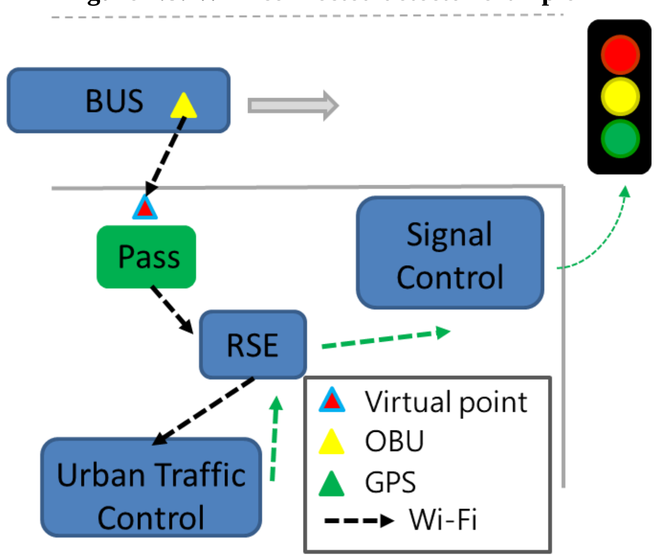
**Figure 2.7: GPS detector example**



The concept of GPS in TSP, which is known as “virtual loops” is similar to loop detectors. The GPS plays a crucial part of the success of TSP implementation as they are, by far, the most reliable detection method in terms of affordability and real-time updates. GPS detectors are not only used for TSP purposes, they also improve ridership as they can be used to predict bus arrival at bus stops. Bus stops with estimated bus arrival times significantly increase ridership as proved in the Tang and Thakuriah (2012) study in Chicago. They tested the effect of having the bus estimated arrival times for a certain bus route, the results showed an average increase of 126 passengers. Using such technologies is becoming more common as bus stops in the US equipped with electronic display of dynamic traveler information increased from 1% to 5% from 2007 to 2010 (USDOT, 2010) considering the enormous number of bus stops 5% is significant. GPS are also called AVL (Automatic Vehicle Location) systems which are widely used in buses in the United States, 66% of fixed route buses are equipped with AVL units (USDOT, 2010). This makes implementing a system that uses a GPS based approach for TSP affordable in comparison to other detection methods.

GPS detectors are virtual points that can be assigned at any location along bus routes. These virtual points provide bus position if a bus passes by. These virtual points are monitored by a roadside equipment device (RSE). Figure 2.8 shows an example of Wi-Fi detection.

**Figure 2.8: Wi-fi connected detector example**




Buses are provided with an On-Board Unit (OBU) that the virtual points can read along with a GPS device. Urban signal control centers usually build a network of several virtual points along bus routes. Passing buses’ positions are then transmitted to the control center. (Gardner et al., 2009; Hounsell et al., 2007). The transmission ways include 3G, Wi-Fi, or Dedicated Short Range Communications (DSRC). This method is simpler than monitoring bus locations by GPS only, as it will minimize complexity of the optimization process by assigning few bus locations that have an effect on the request for signal priority.

Some of the GPS detector advantages include that the detectors are applicable for buses traveling in any lane. GPS detectors obtain bus positions from the OBU, no other vehicles would be mistakenly read which provides location data with less errors. Also, the location of detectors is flexible. The only cost is to establish the network and bus equipment. There is no additional cost in terms of moving virtual locations or even adding more virtual points to the network. Adding more virtual points will enhance the accuracy of the bus position but also adds to the complexity of the optimization process. This also has an effect on bus routes. When bus routes change it is easier to change points on the virtual networks than changing field hardware like loop detectors. On the other hand, some of the disadvantages for GPS detectors include: the accuracy of GPS is dependent on uncertain variables. Tall buildings, trees or other physical obstructions between the device and satellite can have negative effects on the performance of GPS. GPS is also prone to errors in bad weather. These cases would result in a lack of bus position data. Similarly, the connection between bus and control system is less stable than loop detectors since an OBU and an RSE device transmit the data with 3G, Wi-Fi or DSRC, which might not be as stable as a traditionally hard wired loop detector connection. As Hounsell (2008) discussed in his London based TSP model, using an AVL method to determine bus location is less accurate than using a fixed infrastructure detection method. However, Hounsell & Shrestha (2012) discussed that this slight unreliability of AVL systems can be overcome by using the location between two buses, on the same routes, and evaluating the actual headway versus scheduled. This type of information is processed in their TSP model which takes advantage of the growing number of AVL based buses.

## 2.7 TSP Previous Studies

Transit Signal Priority systems has been a field of extensive study and research over the past 40 years. Studies used and tested many techniques ranging from something basic like extending the green signal time based on bus speed and distance from the intersection, to more advanced approaches like calculating the effect of bus green extensions on overall delay in the intersection to systems that maximize an objective function and minimize collateral negative impacts. In the next sections, the literature review examines various points of view on TSP and provides a summary to give a better overall look at current TSP approaches and practices.

### 2.7.1 TSP Evaluation Techniques

Most studies used computer simulators to analyze and evaluate their models. This comes from the nature of TSP being easier to test in simulation than the field where results will usually take longer to analyze, and modifications will be harder to implement. The two main methods of building models are analytical and empirical. Analytical models are theoretical models that follow specific mathematical formulations. While empirical methods use actual historic and/or field data as the basis. These methods help developers to decide if TSP is effective and worth installing. Analytical methods are most commonly used in the early stages of designing a system, while empirical methods can be used on both pre and post-implementation to give a real-time evaluation. Computer simulation models are divided into two subcategories based on the simulation technique, Micro and Macro.

One of the early studies that used computer simulation is Salter and Shahi (1979). They evaluated the effects of giving priority to buses on general traffic delays. Their goal was not to provide a new transit signal priority model but to show the relationship between decreasing bus delay that leads to an increase in traffic delay. With that study, the inverse relationship between bus delay and traffic delay was proven. This led to further research to study that relationship and try to find an equilibrium point where overall minimum delay is achieved. Four years later, Benevelli et al (1983) tried to build a TSP system that would minimize delays through better detecting buses and accounting for bus speed while deciding to extend the green light. NETSIM was used to simulate a corridor in Richmond, Virginia. The study used an algorithm that detected a bus approaching the intersection and gave the bus priority to pass into the intersection based on its speed and its location, ultimately giving a better approximation of bus passage. This study introduced the concept of detecting buses to improve TSP, therefore shifting the interest from Passive to Active TSP. Now detecting buses is an essential part of the success of any TSP system. Research continued on how to improve detection by introducing different gadgets and techniques like GPS and loop detection systems.

Micro simulation models are built on a network of links and nodes that usually represents an actual road segment, corridor or network. These links usually have specific entering flows that are taken from generated traffic counts. Nodes represent intersections which can be controlled by stops signs, pre-timed signals or other forms of signal control. Within the network drivers travel with randomly assigned driver characteristics and participate in traffic events like gap acceptance and turning movements. This series of events work as a replication of what is happening in real life. These models need to be calibrated to be a better descriptor of reality. Khasnabis et al (1996) used CORSIM to test the bus delay at the intersection level and also the route level. By using microsimulation, the authors were able to compare travel values at the corridor level to values for the cross-streets. This yielded a net savings in delay which leads to the success of the proposed TSP method.

Even though microsimulation is the best approach to test TSP, some of the studies were limited in exploring its potential due to the fact it required massive memory space. Chang and Ziliaskopoulos (2002) reported that micro-scopic simulation requires extensive PC computational memory and sometimes that limits models to have 15 intersections or less. In 2017 this is not the case as a corridor of 15 intersections simulation time in CORSIM would take less than 4 seconds.

Several studies used VISSIM or CORSIM as the simulation package for their model. Both VISSIM and CORSIM are micro-simulators that are designed for the analysis of streets, corridors or networks. The biggest two differences between VISSIM and CORSIM as Bloomberg and Dale (2000) reported, for the car-following model VISSIM uses a psycho-physical driver behavior model while CORSIM uses a model derived from experimental work by General Motors. The Second difference is that VISSIM reports travel time for routes between two-points in general, while CORSIM reports travel time for each link which can then be combined to find travel time for a specific route. These differences imply that VISSIM is closer to looking at the model in a broader way than CORSIM.

One of the easiest ways to evaluate TSP models is using the change in travel time for buses, after all the objective behind building any TSP model is to minimize bus travel time. Table 2.4 represents a summary of the studies included in this literature review that reported the bus PM travel time with the TSP type and location of the study.

**Table 2.4: Summary of TSP Studies Reporting Change in PM Time**

| | Year | Priority | Location | Field Test | Micro-simulation | Change in Bus PM Travel Time |
|---|---|---|---|---|---|---|
| Jepson et al | 1997 | Passive | Gold Coast, Australia | | ** | -36 seconds |
| Skabardonis | 2000 | Passive | San Franciscon, CA | | ** | -13% |
| Hounsell | 1990 | Active | London, U.K. | | ** | -9 sec/bus/junction |
| Zaworski | 1994 | Active | Portland, OR | ** | | -8% |
| Hunter-Zaworski | 1994 | Active | Portland, OR | ** | | -7.8% |
| Sunkari et al | 1995 | Active | College Station, TX | ** | | -10% |
| Ghali et al | 1995 | Active | York, U.K. | | ** | -14% |
| Mcleod | 1998 | Active | London, U.K. | | ** | -7.6% |
| Furth & Muller | 2000 | Active | Eindhoven, Netherlands | ** | | -52%* |
| Chang & Ziliaskopoulos | 2002 | Active | Chicago, IL | | ** | N/A |
| Lownes & Machemehl | 2005 | Active | Minneapolis, MN | ** | | -3% to -6% |
| Yagar & Han | 1994 | Adaptive | Toronto, Canada | | ** | -12.2%* |
| Mirchandani et al | 2001 | Adaptive | N/A | | ** | -13.4% |
| Duerr | 2002 | Adaptive | Wurzburg, Germany | | ** | -25% |
| Teng et al | 2003 | Adaptive | New York City, NY | ** | | Increased |
| Lee et al | 2005 | Adaptive | Toronto, Canada | | ** | -34.25% |
| Dion | 2005 | Adaptive | Arlington, VA | | ** | -2.6% |
| Li et al. | 2011 | Adaptive | Richmond, CA | | ** | -43% |
| Wu et al. | 2012 | Adaptive | San Diego, CA | ** | | -27.3% |
| Gu & Cao | 2013 | Adaptive | Dalian, China | | ** | -14.7%* |
| Li et al. | 2016 | Adaptive | Nanjing,China | ** | | -12%* |
| -Field tested models might include simulation but not the other way around | | | | | | *Delay |

### 2.7.2 Active TSP Studies

Yagar and Han (1994) introduced a model based on adding vehicle delay to calculate total delay. This model gives buses higher weight in the function and calculates total delay in each cycle. Once the calculations are done, the system chooses among cycles that are preset in the control box that would help minimize total delay. This study introduced a new method that allows real-time communication between vehicles, transit, and the signal controller. A few years later, Skabardonis (2000) expanded looking into the vehicle delay while deciding whether or not to give buses priority. His approach was that using active TSP will only be beneficial outside rush hour. However, a green light extension would be granted for TSP during rush hour only if there was sufficient spare green time in the cycle. Skabardoins tested and evaluated multiple passive and active systems in 21 intersections, and his results showed improvements without adverse impacts on general traffic. Active TSP proved to better, on average, than passive TSP during rush hours due to the fact that bus arrivals are affected by general traffic. His study was designed around low traffic volume cross-streets which ultimately led to minimum effects on general traffic. In TSP, the main objective is to minimize travel time for transit. Most studies successfully achieved that by simply giving priority to transit vehicles.

Fehon et al (2004) showed that most of the TSP systems in the United States utilize active strategies. Also, 6 years later Stevanovic (2010) reported that 80% of the 45 agencies that were surveyed reported deployment of some sort of an adaptive traffic control system with only 10% reporting using adaptive TSP. This is due to the fact that active systems are cheaper and easier to implement since they require less hardware and software.

### 2.7.3 Adaptive TSP Studies

Adaptive TSP systems work best if they are implemented in adaptive signal control systems which usually cover multiple intersection with system-wide real-time data. However, more than 90% of the signalized intersections in the United States are closed-loop actuated signals (Gettman et al. 2007). Smith (2002) discussed that implementation of adaptive systems on a wide-scale is financially difficult due to the high cost of changing existing signal control infrastructure.

Mirchandani (2001) used CORSIM to simulate an adaptive optimization-based TSP system. Their model included a traffic signal timing algorithm called RHODES which considers second-by-second loop detector readings to formulate signal phase responses. The model results showed improvement in bus travel time with a slight negative effect on cross-street traffic. Michandani's model lacked the randomness of bus arrivals since the simulation package assumed exact location for buses.

Dion and Helliga (2002) performed one of the early studies to develop a model that considers all the unique characteristics of transit vehicles, which are usually not accounted for in simulation packages. Some of these characteristics include the interference caused to traffic by bus stoppage in the right of way to board/alight passengers. Their model, called SPPORT, was tested in a single intersection and the results yielded overall delay increase for bus and general traffic (along bus direction and cross-street as well). Dion (2005) took that model and applied it to a corridor, which yielded a negative local impact on some intersections leading to an overall failure of the system. The reason behind this failure was the need to implement the adaptive system model on an adaptive traffic signal control system to eliminate negative impacts to the cross-streets.

Improving adaptive TSP requires a better estimate of the real-time location of buses. Nichols and Bullock (2004) introduced the use of GPS to improve bus detection accuracy for TSP. In comparison to loop detectors that only detect buses at certain locations, GPS detectors can report real-time locations of buses all the time.

With higher bus volumes comes higher chances that multiple bus requests would happen during one cycle, most of the literature prior to 2006 did not touch that topic until Head et al (2006) developed an advanced decision control model that has the potential to receive multiple requests in one cycle and prioritize responses based on a mixed integer formula. However, Li et al. 2011 did not use that method to test the multiple request case, in his study, he briefly discussed the low chances of multiple buses requesting priority, which is debatable. He tested adaptive TSP systems on actuated control systems which yielded a reduction of 36% for average passenger delay for both transit vehicles and general traffic. This model, again, did not account for multiple bus requests per cycle and only allowed TSP activation for up to three consecutive cycles. Also, this model was implemented in a high flow corridor with a very low volume cross-street traffic. Therefore, the potential detrimental effects on the cross-street were not observed.

Li et al (2016) looked even closer at passenger delay as the objective function. They developed a model with the objective of minimizing accessibility-based passenger delay at the intersection and also the waiting-delay time for buses downstream. This model looked at the total delay of bus passengers during a trip, starting from getting to the bus, riding the bus, and leaving the simulation scope. While Lin et al and Li et al looked at bus passenger delay, Gu and Cao (2013) proposed a bi-objective optimization model for signal timing that uses GPS data to minimize delay and stops at the intersection. Their model approached the TSP problem differently by looking at vehicle stops, was successful in minimizing transit delay and traffic delay as well.

2.7.4 Cycle Length optimization

Optimizing cycle length is an important part of the adaptive TSP mechanism. As soon as a priority request is received from a bus, the TSP system tries to respond with the best scenario to grant the bus a fast passage while also minimizing or holding the system wide delay numbers. However, calculating all parameters and trying to optimize cycle length has been proven to be challenging in the literature.

Zhou et al (2007) used VISSIM to optimize cycle length timings. The model used a parallel genetic algorithm (PGA) instead of a genetic algorithm (GA) because PGA provides faster convergence rates by dividing populations of interest into subpopulations to be calculated in parallel, saving simulation time. His approach focused on cycle length in TSP based intersections and tested benefits for passenger vehicle and bus travel times. The study concluded that TSP is effectively reducing delay while also doing small to no damage to overall delay compared to no TSP. With TSP overall delay is 18.2 in comparison to 17.5 without TSP, the difference between the two is close to 4%. However, bus delay with TSP is 8.7 while without TSP is 17.5 more than 100% difference (all units seconds/vehicle).

Stevanovic et al (2008) used Direct CORSIM optimization which is a feature of TRANSYT-7F software package and found similar results to Zhou et al. This tool is used to optimize traffic signal timings based on a combination between genetic algorithms and traffic microsimulation. Stevanovic et al built a model that optimizes four signal timing parameters: cycle length, green splits/offsets and phase sequences. The model is VISSIM based Genetic Algorithm Optimization of Signal Timings that is called VISGAOST. VISGAOST is built in C++ and uses VISSIM to run the simulation. Results from the model showed a 14% decrease in delay in a corridor without TSP. For a corridor with TSP, the simulation tested optimizing the signals with TSP and without TSP in the same corridor and showed a decrease of 5% without TSP and 4% with TSP being implemented. The small percentage decrease could be due to the added parameters when dealing with TSP which introduce more constraints and a higher variability. Stevanovic's optimized solution used 10 computers, and more than 7000 iterations that took around 90 hours to converge. This long convergence time is expected due to the complexity of combining TSP and cycle length optimization together. However, signal control optimization can also be used for objectives other than TSP. Looking also at emissions, Stevanovic et al (2009) simulated a 14-

interesection network in Park City, Utah. Their objective was to minimize fuel consumption which they successfully did by a 1.5% decrease.

## 2.8 Parameters affecting TSP performance

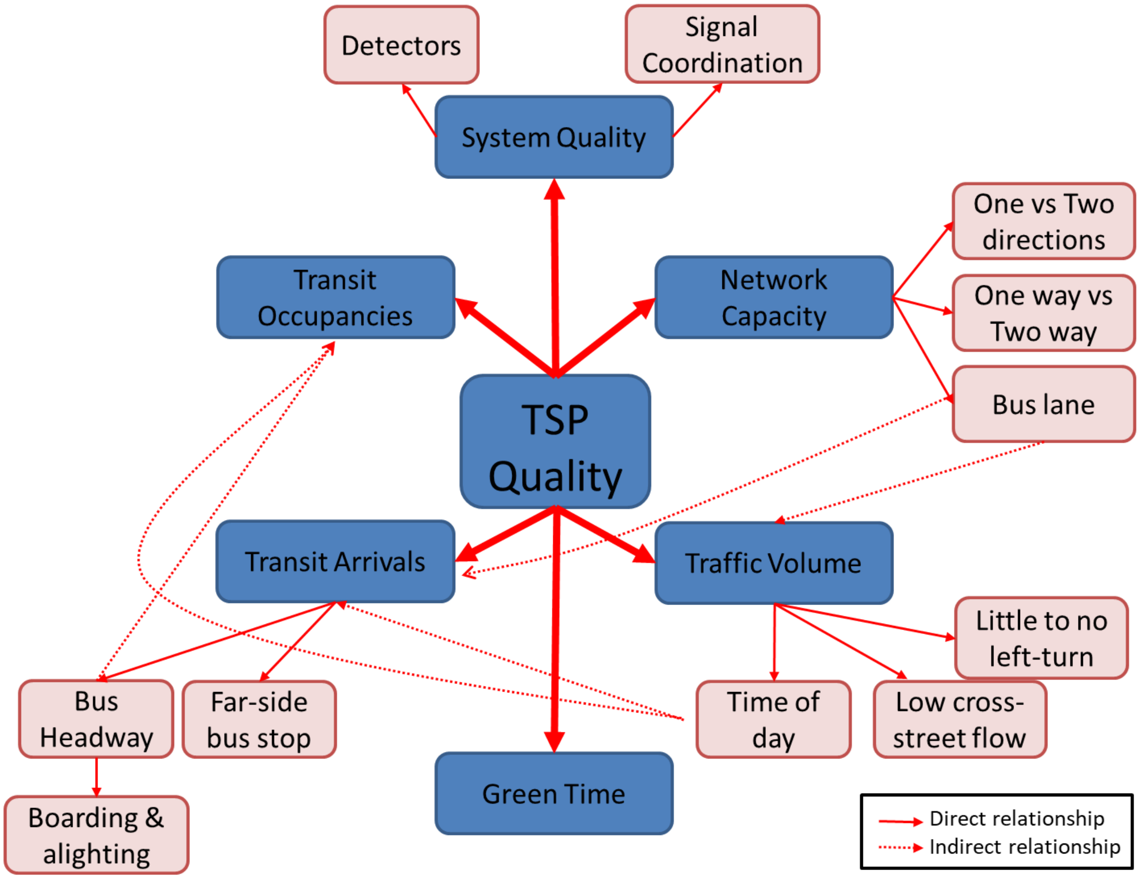
A Transit Signal Priority system gives priority to buses to provide better reliability and shorter travel time for passengers. By increasing bus ridership, emissions are reduced, and congestion is lessened. The TSP system is effective but needs to be improved. The traditional system cannot handle multiple bus requests, heavy traffic conditions, or uncertain bus arrival times. In order to measure TSP effectiveness, we need to understand what variables or factors are accounted for in the system. TSP impacts can be measured in different ways. However, these measures are affected by certain variables. Garrow (1997) summarized the parameters affecting TSP success in 5 components:

1. Transit arrivals,
2. Transit occupancies,
3. Traffic volume,
4. network capacity, and
5. Intelligent transportation systems quality.

These parameters need to be closely studied to determine their impact on the quality of TSP. Another potential negative impact of TSP is disruption of signal coordination. That is, if one signal along a signalized corridor has a TSP timing change, movement of platoons along the corridor can be disrupted. These negative impacts of TSP result in an understanding that when developing TSP systems both positive and negative impacts should be accounted for. Minimizing bus delay is not the only objective of TSP as different factors are included to ensure a net positive outcome, or an overall improvement.

Figure 2.9 shows the summarized parameters affecting TSP implementation quality.

**Figure 2.9: TSP quality factors and variables network**




As discussed earlier, TSP quality depends on five main factors (in blue), these factors have relationships with certain variables (shown in the red boxes). A direct relationship has a direct impact on the factor to which it is related, meanwhile some of these variables overlap in dependencies with other variables. For example, high bus traffic flow is going to affect traffic volume directly and also has an effect on transit arrivals. To minimize confusion and to make the graph easier to read, direct relationships were assigned solid red arrows while indirect relationships between factors/variables are shown with dotted red arrows. Following is a brief summary of why each factor is important.

### 2.8.1 Transit Arrivals

#### 2.2.2.3. Bus headway

Bus headway will affect the frequency of bus arrivals at the intersection. In passive TSP systems, changes in bus headways may mean reprogramming TSP to enable bus progression. Adaptive systems have the flexibility of working with random bus arrivals, but too frequent arrivals can lead to more harm than good in TSP performance. The logic behind this comes from learning that each bus entering the intersection will send a request to have priority in passing. The more buses arriving the more requests are going to be honored. Mcleod (1998) developed a model that tackled that issue of frequent requests by prioritizing bus requests based on their headway. His model, called “Headway Algorithm”, grants priority to buses based on the ratio of their headway to the scheduled headway. However, this increases the amount of green time taken away from cross-streets which may ultimately lead to more overall delay in the network. In this case TSP may be doing more damage than benefits for the corridor.

Bus load factor is another variable that affects TSP. The main purpose of TSP is to grant priority for Transit vehicles. As mentioned earlier, 1.3 car passengers compared to 10 bus passengers experiencing the same delay is not fair. Transit vehicles with more passengers need TSP more than other vehicles because the person-delay is going to be significantly higher when more people are on board. So, in order for TSP to be more effective the logical objective would be maximizing load ratios to minimize person-delay in the network. However, heavy loaded buses tend to stop more frequently for passenger boarding/alighting. The increased number of bus stops will lead to more variation in bus arrivals, and this could lead to the bus missing the progression bandwidth and ultimately requesting more green time at each intersection.

Bus stop frequency will have a significant effect on the outcome of TSP when testing on a network level. This can be noticed as commuters who travel more than 15 minutes tend to choose rapid buses since they stop less frequently than local buses. That sort of behavior indicates that when traveling at a network level (long path) buses with less stops travel faster. Another factor that affects bus travel time is dwelling times. Multiple studies confirmed that dwelling times depend on number of passengers, these studies developed similar models that predict dwelling times, 5 seconds to 75, seconds using the total number of passengers (boarding + alighting) to be from 1 passenger to 20 respectively. (Levinson 1983, Guenther and Hamat 1988, Dueker 2004). Also, Transit Cooperative Research Program (TCRP) reported that on average dwelling time at busy stops can be 60 seconds, major stops 30 seconds and typical stops have 15 seconds. These values can add up with multiple bus stops for multiple buses traveling through TSP based intersections. One way to prevent these values from adversely affecting TSP is to minimize wasted time caused in bus stops. The process of boarding/alighting can be improved by various methods. One of these methods is implementing a magnetic stripe reader to speed up the process of passenger boarding. The percentage of buses having this technology in 2000 was only 5%, this percentage increased significantly to 40% in 2009. (USDOT, 2010) This change has a direct impact on the results of a lot of field-based TSP studies as buses will travel faster now due to the reduction of boarding/alighting time. Another method is to implement systems for passengers to pay bus fares faster. In 2009, 80% of buses accept electronic fare payment and this number is rapidly increasing to ensure faster payment methods.

Since some TSP models assume bus arrival time there has to be a solution to the additional uncertainty. Zeng et al (2014) introduced a stochastic mixed-integer nonlinear model (SMINP) which accounts for the uncertainty in bus arrival time. This model was created and tested in VISSIM and gives green time whenever the bus actually arrives while factoring in green time, split phase, deviation of green time and saturation flow. This model was compared to a standard TSP model which gives the green light to the bus based on the bus arrival. The model results showed a 30% improvement of bus delay compared to the basic model in low to medium traffic flow. In cases like several bus lines in the same intersection a “rolling optimization scheme” to control which bus needs access first was implemented. In high congestion, the model will automatically give less priority for buses and operate on normal pre-timed settings as giving priority might cause more delay in the intersection.

#### 2.2.2.4. Far-side bus stop

Bus stop locations are an important part of TSP effectiveness as most of the literature shows that far side bus stops improve the likelihood of buses traveling through intersections: **(**Sayed and Abdelfatah 2004, Sundstrom 2008 and Smith 2005). When a bus approaches an intersection and a request is made, stopping at a nearside bus stop (before the intersection) will prevent the TSP system from completing its purpose by allowing the bus to travel, this kind of missed communication between buses and TSP affects the performance of TSP greatly.

### 2.8.2 Transit Occupancies

In the case of transit occupancies, multiple variables are indirectly related to this factor. Time of day, bus headway and high bus traffic flow are all indications that transit occupancies might be high or low. The fundamental use of TSP is to make buses travel faster, but if bus occupancies are low then that may defeat the purpose of shifting delay from buses to general traffic. Most studies in the literature approached this very carefully with almost all case studies (specially the recent studies) being built in an urban environment during peak hours to assume higher rates of bus occupancies, which ultimately will affect the quality of the TSP contribution.

Several studies looked at TSP during rush/peak hours which implied that buses are used more than average. In that case, priority should be provided to medium to high occupancy buses. Ngan (2002) studied the benefit-cost ratio for adding a TSP system in a specific intersection. He used values from multiple studies to develop a table that shows the effect of passenger occupancy and bus volume on the benefit-cost ratio. His table shows that buses with higher occupancies are the best clients for the TSP and the more frequent the buses, the higher the benefit-cost ratio.

Higher passenger occupancy might impact TSP negatively in terms of buses stopping more frequently for alighting/boarding. However, Diab and El-Geneidy (2012) reported that for each additional passenger on board, bus travel time is reduced by 0.3 to 2.3 seconds, on average. This might be due to the fact that late buses usually travel faster to catch up to the schedule (Figliozzi and Feng 2012)

### 2.8.3 System Quality

TSP outcomes are not always positive. Some studies concluded that TSP actually worsens the overall system. Garrow (1997) used the TRAF-Netsim micro-simulator to test TSP effectiveness on the Guadalupe-N Lamar corridor in Austin, TX. Thirty bus stops were tested in three models: peak and off-peak periods for local bus and off-peak period for express bus. In his results, using an active priority system for local bus off peak showed a reduction of travel time by 11%. He also tested split phasing that showed little significant success in reducing bus travel time in the corridor in general. For express bus off-peak, he used an unconditional “preemption” system that resulted in a decrease in travel time by 19% on average but he also mentioned that using preemption caused disruption for cross-street traffic. For local bus peak hours, results showed when saturation occurs in cross-streets it is not recommended to give a green light to the transit vehicle as it does have a negative impact on the overall intersection delay. Moreover, testing the overall TSP impact on the corridor and cross-streets resulted in failure of TSP as it increased person minutes travel time even while buses are assumed to have 50 person and autos

Another Active TSP study that resulted in negative results was Sundstrom (2008), as he compared TSP versus no TSP for buses in a corridor in Portland, OR using an Automatic Vehicle Location (AVL) system. AVL is a device installed on all buses in his study corridor to monitor all bus movements and send/receive data from a bus dispatch system. His results showed that there was no significant difference in overall travel time or schedule adherence between using TSP or no TSP for that 2 mile corridor. Some of the factors affecting this failure can be that 63% of bus stops were placed nearside intersections instead of far side. Another reason could be heavy traffic on cross-streets which might negatively affect TSP effectiveness.

#### 2.2.2.5. Detectors

The quality of detectors will greatly affect TSP performance. As discussed earlier, Loop detectors are the most commonly used detectors currently. However, loop detectors can be prone to failure for multiple reasons like reading a truck as a bus, or reading a slow-moving bus entering the interest zone but not leaving, causing the TSP to perform poorly by making false assumptions about bus movements.

#### 2.2.2.6. Signal Coordination

Signal coordination is an important factor not only in passive TSP systems but also in both active and adaptive. Connected intersections rely very heavily on the advantage of platoon progression going through multiple intersections without stopping. The better the coordination to achieve progression the better the quality of TSP. Also, coordinating with single or multiple buses can also minimize the conflict of buses having to be screened and processed at each intersection.

In developing TSP systems, early studies focused on isolated intersections to optimize bus movement in that specific intersection. These models lacked coordination among multiple intersections to take advantage of TSP. However, Duerr (2002) developed a TSP system that approaches the problem of coordination among intersections in a unique way. His system dynamically changes the coordination between signal timings to try to keep a progression coordination in place. His model introduced a mathematical way to adjust and modify connected intersections, this approach can be applied on a bigger scale to coordinate more than multiple signals on a single corridor. Approaching the network based problem requires dynamic changes that can be dealt with by using Dynamic Traffic Assignment (DTA). Chang and Ziliaskopoulos (2002) explored DTA methods when applied in TSP systems. They argued that DTA models implemented in smaller size networks can be sufficient to validate algorithm effectiveness in solving TSP problems. However, applying these algorithms will have impacts on a large scale network. These impacts usually aren’t captured in the validation process due to the lack of data sets of large networks. Chang and Ziliaskopoulos used VISTA and ROUTESIM (simulator used to assign vehicles on shortest routes), their model used datasets that were used for forecasting purposes which lead to issues in terms of signal timings or/and signal locations. To improve their model quality, they added 2115 nodes with signal data. Their model successfully captured the impacts of TSP on a network level consisting of highways and some major streets in the Chicago area. These impacts were limited to only the changes of traffic flow due to the TSP implementation. One major drawback in this study was the effect on cross-streets. Chang and Ziliaskopoulos did not include minor streets due to a lack of detailed turning movement counts.

### 2.8.4 Network Capacity

#### 2.2.2.7. Bus lane

Adding a bus lane as part of a TSP study was rarely found in the literature. Adding a bus lane changes the capacity of the corridor/network which will change driver behavior and may change traffic demand. Several studies tested the impact of adding a reserved bus lane in general. One study estimated that the time savings due to implementation of reserved lane ranged between 1.2% and 2.3% of total running time with no significant impact on trip time variation or headway variation (Surprenant-Legault and El-Geneidy, 2011)

#### 2.2.2.8. One Direction Versus Two Directions:

Christofa and Skabardonis (2011) developed and implemented an adaptive TSP system in a single intersection in Greece. Their location was chosen based on the complexity of the intersection as it does serve multiple bus routes traveling in different directions. Their results showed that their model was successful in decreasing both bus and car passenger delay. He et al (2003) also developed a similar model but with an active system with similar results. This shows that TSP has the potential of being applied in intersections with transit traveling in either one or two directions of travel.

#### 2.2.2.9. One-Way versus Two-Way

One-way TSP systems are generally easier to develop and monitor. However, if the network capacity is high then the chances of having buses traveling in both directions are high too. Most studies have only tested one-way systems. However, Bagherian et al (2015) study was one of the most advanced that touched on TSP at the network level. They tested TSP effectiveness on a small network with 9 intersections (Buses traveling in N/S and W/E bounds). They used VISSIM to simulate bus and automobile travel times with TSP (Green extension, red truncation) along with a C++ code to optimize TSP. Five objective functions were generated, minimizing total travel time had the biggest impact on bus travel time with a 4.7% reduction. When testing for car travel time it was found that TSP at the network level has a small impact +0.6% and -0.3% in best and worst cases, respectively. Their results were not appealing but their model was not built on a realistic scenario, chances of having 9 intersections with bus routes in all directions are slim. Kimpel (2005) found positive results on the route level. However, when evaluated on the system network level, TSP failed to show significant improvements. The reason behind this could be that TSP in one direction has less variation in the impacts, negative or positive. While having two directional TSP increases the variability of bus arrivals, the variability of delay on both sides ultimately leads to higher variation in results. Also, TSP applied on a network level can severely affect progression in both travel directions.

### 2.8.5 Traffic Volume

This factor is directly related to all other factors, and it summarizes the importance of TSP. TSP was created as a solution to reduce transit stops at intersections. With higher volumes, chances are higher that transit will eventually stop at intersections in order for traffic to flow from other directions. Traffic volume, affects the system quality, the transit occupancies, the transit arrivals and network capacity.

#### 2.2.2.10. Little to no left turn

For situations where there is little to no left turn traffic demand, TSP would work best as there is no conflict in turning vehicles nor is there a left turn queue that will affect the bus direction of travel.

#### 2.2.2.11. Low cross-street flow

As discussed earlier, some studies neglected the fact that some cross-street flows might actually be higher than their models. This factor, if not assumed conservatively will ultimately give false hopes about the success of TSP. By nature, TSP takes green time from cross-streets by extending green signal time or starting a new green light phase for the bus travel direction, this will increase delay values on the cross-street which can be severe if higher volumes exist.

#### 2.2.2.12. Time of day

TSP can be effective depending on time of day, most TSP systems are designed to work explicitly when volume to capacity ratios (V/C) are high. V/C ratios are higher during peak hours when streets may be congested. Another case in which TSP might be effective is when high congestion occurs during special occasions outside of peak hours, like an event that might attract more than usual traffic to a specific destination. Kimpel (2005) used a regression model to analyze TSP effects on bus running time and concluded that there was a statistically significant improvement in bus running time in general. However, TSP primary benefits were limited to the PM peak hour only.

High congestion might not be the ideal implementation scenario for TSP. Congested intersections are no longer able to give up green time in order to minimize delay and buses requesting access to the intersection in high V/C cases might not be able to enter due to standing queues. This would eventually lead to a defeat of the TSP purpose. In other cases where V/C is smaller (off-peak) transit vehicles have the liberty to travel smoothly with minimal impacts on cross-streets. However, Garrow’s thesis showed that using TSP during off-peak hours could actually increase overall delay.

### 2.8.6 Green Time

The remaining green time when a bus is approaching an intersection has an effect in most advanced TSP systems. These systems will incorporate the remaining green time and if feasible add more green time or switch to another response, like red truncation or split phase. Also, green extension is often limited to 10% of the green time available in the green phase (Smith 2005. Chen et al (2017) introduced a model that uses cross-street remaining green time as a factor in the TSP model. They looked at gaps in cross-street traffic flow, and if there was a gap of more than 5 seconds then the corridor red was truncated to allow the bus to pass the intersection. This concept introduced a way to optimize traffic flow in the intersection and also in the corridor by minimizing green time waste.

In addition to the previous parameters there are other parameters that might affect the performance of TSP and the coordination between intersections (in case of TSP implemented in corridors). One of these parameters can be other transport routes intersecting the coordinated corridor. An example of that special case is a rail grade crossing that intersects the direction of travel in a corridor. Wu et al (2012) tested that case in San Diego, CA by developing a model that consists of buses traveling in the corridor, general traffic and the arrivals of trains. Their model demonstrated positive results by minimizing bus travel time without affecting general traffic. This model was not successful in minimizing cross-street delay but that might be expected as more variables usually add more strain on the optimization process.

## 2.9 Ideal Candidate Locations for TSP Implementation

TSP in general is a response to a problem as it serves to improve transit ridership or get the passengers to their destinations on time. It is ideal to implement it in high to medium congestion areas where it can improve the quality of travel for commuters. Rural areas usually don’t have congestion so implementation of TSP would not be ideal. Some of the positive impacts of TSP are: Improved schedule adherence as buses would be able to keep up with the schedule. Keeping up with the schedule leads to higher reliability. Increasing reliability will ultimately increase the quality of transit service which is the main goal for all MPOs. Not only does TSP have an impact on transit, it also can reduce costs for drivers by reducing fuel consumption and emissions. TSP can also have a positive impact on the environment by helping change mode choices to bus from automobile. Many more positive outcomes can come with TSP, but as mentioned earlier TSP can be seen as both positive and negative at the same time. Negative impacts of TSP can be increased delay on cross-streets which might not be acceptable to some drivers. TSP might improve delay times for some cross-streets and also for the bus travel time but this could lead to an overall delay increase in the corridor or even the network. This could happen when drivers shift their travel behavior by changing travel paths which leads to more pressure on other links of the network, as was captured by Agrawal et al (2002) in their study on the impacts of implementing a TSP system in a Chicago sub-network, which led to drivers choosing different routes and putting pressure on other links in the network.

Sayed and Abdelfatah (2004) used Vissim to simulate bus volume, traffic of cross-streets, bus headways and stop locations, bus detectors, and signal coordination. After simulating all the field gathered data and implementing different scenarios in the system, they recommended that a TSP implementation is most effective under these conditions:

1. Moderate to heavy bus volume in the corridor
2. Little or no left turning traffic
3. Slight to moderate v/c on cross-streets
4. Far-side bus stops

5. Signal priority given to traffic in peak direction.

Their findings also included, a lower average travel time when using TSP for buses, less delay if bus stops were far sided, and the overall delay for all vehicles was lower when using TSP.

## 2.10 TSP effectiveness OR Performance Measures

In order to characterize TSP a set measures of effectiveness must be established to study impacts of TSP and maximize overall performance. TSP systems have been used in the US since the 1980s. With a large number of variables and different implementation approaches, comes a great amount of variation in results too. How do we interpret these results? There is no single measure that can adequately address this. Improving reliability of TSP could potentially be the best measure to test and evaluate TSP models as it directly relates to transit travel time.

TSP implementation has proven to be a substantial improvement in some cities and a complete failure in others. Implementation of TSP is usually done to increase ridership of public transit. As Currie (2008) reports that the highest increase in ridership was accounted for by MPOs investing in projects targeting reliability. This shows that reliability is a major factor in increasing ridership. To increase bus reliability, the existing number of buses should operate according to the schedule.

Several studies suggested strategies to improve transit reliability. Bus rapid transit (BRT) is one of the ways to improve reliability by introducing faster service for commuters with less frequent stops. Bus stop relocation can be beneficial for transit service as described in the Li and Bertini (2009) study in Portland, Oregon. Their study suggested a new bus stop structure that reduced annual operational cost by $60,000. Other strategies like a smart card payment system saved time and therefore increased reliability (Tirachini 2013). A number of other studies approached this issue of increasing transit reliability, however, TSP still provides a comparatively inexpensive tool to increase reliability and also improve traffic travel time and delay.

Albright and Filiozzi (2012) studied the significance of TSP at the intersection level on bus schedule adherence. Their study used regression analysis for bus scheduling lateness, passenger flow behaviors, and bus locations to determine the factors affecting bus travel times. Their results showed that TSP is more effective for buses having severe delays and that "TSP is a significant factor in determining travel time for the corridor". TSP promotes schedule adherence but also works best if buses are having severe delays. This concept proves that TSP is not always needed but it is a tool that helps transit to keep up with the schedule. As Chang and Ziliaskopoulos (2002) discussed, TSP can be used to add more control over transit travel time. As TSP can help late buses to pass through intersections and save lost time it can also stop buses running-early. Bus schedule adherence is a major factor in commuters deciding whether to take the bus or drive to work. Also, schedule adherence can provide bus operational savings by preventing MPOs from adding more buses to the network. This is because buses are able to keep their headway and move passengers more efficiently. Savings can also be reflected on passengers as well, as Oshyani and Cats (2016) evaluated the societal savings associated with improving travel time on a bus route in Sweden and estimated a savings of  approximately 5 million Euro per year.

Before we discuss cities that experienced TSP implementation and their results. We should mention that results being positive or negative may be dependent on perspectives and goals. TSP can indeed be negative and positive at the same time. An example of that could be a preemption system that gives priority to buses regardless of any other variable. This will definitely decrease the bus travel time but will also negatively affect travel time on cross-streets by increasing their delay.

TSP systems have a direct effect on schedule adherence as they can improve bus travel time. However, buses excessive use of TSP might have undesirable effects as Kimpel (2005) found that TSP affected negatively some bus routes as most buses arrived early instead of on-time or late. Another example is taken from McGowan (1975) which tested TSP in Washington DC. The results of the study were a huge reduction in bus travel time which led to bus early arrivals. This affect can be seen as positive since passenger travel times are reduced but also negative as bus reliability was reduced as well. Furth and Muller (2000) solved that dilemma by developing a conditional TSP system that only works when buses are late. This TSP system is conditional on the need of the bus to travel faster than other vehicles without traveling faster than scheduled. Frurth and Muller found that their TSP model did not significantly improve overall delay in the network but also successfully decreased bus travel time. Several other studies developed conditional TSP models like Satiennam et al (2005) which developed a model in Japan with results that significantly decreased overall traffic time including bus travel time. Ma and Bai (2007) also successfully decreased overall travel time in the system while also introducing a new concept for conditional priority. Ma and Bai developed their model based on Chang et al (2003) late buses only concept; which gives priority for late buses only. Ma and Bai added another condition by also prioritizing red lights for early buses to force them to stop.

Several cities look at on-time performance instead of schedule adherence as it is defined as the percentages of buses that arrive/depart from a specific location in a specific time window (Kittelson and associates, Inc. 2013). This approach will help to only look at buses who are on-time instead of late/early.

Looking at previous studies, TSP systems have a set of measure of effectiveness that include, not limited to, minimizing bus travel time by reducing stop/signal delay, minimizing general traffic flow delays and when working with networks/corridors minimizing overall travel time. Some intersections would experience delay that can be negligible when compared to the benefits of the overall corridor/network. Using these measures of effectiveness we can compare TSP performance in different forms and systems. Table 2.5 summarizes studies that used these three main measures of effectiveness. Other measures were found in the literature as Cisco and Khasnabis (1994) used queue length to measure the effectiveness of TSP by using average vehicle/person delay as a unit of measurement. However, this measure was not common.

## 2.11 Costs of delay

Cost is another approach to see the effectiveness of TSP. In 1997, an FHWA study reported that the congestion delay cost for each mile traveled is $0.128 for buses and $0.062 for passenger vehicles in urban highways. This shows that buses are at least twice as important as passenger vehicles, not to mention that buses can hold up to 50 passengers, while passenger vehicles on average have approximately one passenger. There is a relationship between vehicle delay and passenger delay. Studying the passenger delay would give more importance to buses, especially during peak hours in urban areas, where bus ridership is at the maximum. These passenger delay values can be quantified using the CORSIM simulation and applied with congestion delay cost per mile.

Not only does TSP affect delay in terms of money and time, it can also have a huge impact on the environment. The USDOT (2005) estimated air pollution damage costs in the Highway Economic Requirement System-State Version technical report. The study has many important tables that can be beneficial to expand the scope of this study, especially in terms of emissions cost values. These values will be used in measuring emissions' cost on the CORSIM outputs. Carbon monoxide (CO) emissions cost $100 per ton and Nitrogen Oxide (NOx) emissions cost $3,625 per ton (in 2000 dollars). Comparing emissions before and after TSP, or after altering TSP would be also beneficial.

**Table 2.5: Summary of studies using Person Delay Versus Vehicle/Transit Delay**

| | Person Delay | Vehicle and Transit Delay |
|---|---|---|
| Furth and Muller (2000) | ** | |
| Mirchandani et al. (2001) | ** | |
| Christofa & Skabardonis (2011) | ** | |
| Duerr (2002) | | ** |
| Dion and Hellinga (2002) | | ** |
| He et al. (2003) | | ** |
| Vasudevan (2005) | | ** |
| Li et al. (2011) | | ** |
| Wu et al. (2012) | | ** |

## 2.12 TSP Implementation in the United States

Table 2.6 shows five cities in the US that used TSP and a comparison between cost of implementing TSP and the travel time improvement.

**Table 2.6: Five US Cities Experiences with TSP Implementation**

| | Portland, OR | Oakland, CA | Seattle, WA | Los Angeles, CA | Chicago, IL |
|---|---|---|---|---|---|
| # Corridors | 5 | 1 | 3 | 9 | 1 |
| # Intersections | 60 | 62 | 28 | 654 | 15 |
| # Busses | 775 | 21 | 1400 | 283 | 125 |
| System Setup | Centralized | Decentralized | Distributed | Centralized | Decentralized |
| Controller Type | 2070 | 170 | NEMA & 170 | NEMA & 2070 | NEMA & 2070 |
| Detection Technology | Optical Detectors | Encoded Infrared | Passive RF | Loop Detection | Loop Detection |
| Capital Cost | $5,000,000 | $300,000 | $2,500,000 | $10,000,000 | $732,000 |
| Cost per Bus/Intersection | $108 | $230 | $64 | $54 | $390 |
| Impcat on crossing streets | Not mentioned | Very minimum | Minimum | Minimum | Very minimum |
| Travel Time Improvement | 10% | 9% | 5.5-8% | 19-25% | 15% |

In Portland, positive improvement was shown and the best outcome from TSP was at afternoon. The Portland TSP experience led to savings not only in time but also in cash as the MPO was successful in eliminating the need to buy an additional bus (Kimpel 2005). Oakland, CA experienced an increase in ridership of 25% in 18 months. Also, the Oakland MPO noted that to help improve TSP they moved 37 bus stops to far-side instead of nearside. Seattle had the most buses in this comparison and it is the only city that had maintenance cost data which is equal to $1,000 per intersection per year. Their result showed a massive increase for trip delay up to 34% and 40% reduction in trip travel time variability. Los Angeles had the most expensive TSP system due to the high number of intersections (654). They experienced a reduction of 19-25% in travel time, 1/3 of that is accounted for by TSP and 2/3 by their headway based stops system. One remarkable result by implementing TSP is that before TSP they received 100 bus complaints per month, and this was reduced to 12 after implementing TSP. Out of these 5 cities, Seattle had the most vehicles in its TSP based fleet, however, Houston has the most signalized intersections with 1563 in a TSP system with up to 80 TSP operationally linked intersections. (Smith 2005). Table 2.7 summarizes the difference between the controller types used in those 5 cities.

**Table 2.7: Traffic Controller Types**

| | NEMA | 170 | 2070 |
|---|---|---|---|
| Remarks | 2 to 8 actuated phases | 2 to 8 actuated phases | Combination of NEMA & 170 + 6 overaly dual-ring traffic controller |
| Best used | Basic use any type of TSP | Short term memory needs, Changeable lane control, Ramp metering control | Most advance device that is in use |
| Refrences: University of Utah | | | |

# Chapter 3. Single Intersection Model

In order to improve TSP one must look at previous research and existing TSP practices. Once a general understanding of the state-of-practice is perceived, several points of interest to test and tackle are naturally going to be revealed. Through extensive literature review, TSP was found to be extremely versatile and different in almost every city. The ultimate goal is to test all variables and factors listed in the TSP quality network. These factors and variables are:

1. Network capacity:
    a. One-way versus two-way of traffic.
    b. Bus lane.
    c. Buses in One versus two directions.
2. Green Time
3. Traffic Volume:
    a. Cross-street flow
    b. Left-turns
4. Transit Arrivals
    a. Bus Stop location
    b. Bus Headway
5. Transit Occupancies
6. System Quality
    a. Detectors
    b. Signal Coordination (Progression)

Different studies highlighted different aspects of TSP in order to elevate the quality by minimizing weaknesses in the system. The first step in general, is to build a model that is going to be a representation of real life intersections, corridors or networks. The most important part of any model is to ensure that the data reflects reality as accurately as possible. In this study, CORSIM is going to be used to build a micro-simulation model to generate scenarios where TSP can be tested and evaluated. However, CORSIM capabilities are limited in terms of building a TSP system, an external code has to be created in order to modify CORSIM to be able to simulate TSP. This external code is called the Run Time Extension (RTE), which helps developers/engineers to use any command outside of the traditional CORSIM commands to change and modify the simulated environment. The decision of using CORSIM and RTE came after an extensive review of the existing methods with a careful consideration of using minimal coding to generate faster and easier-to-approach results.

CORSIM comes with different pre-coded RTEs that the user can use as a base for future modifications. Unfortunately, CORSIM does not come with any TSP code. However, emergency vehicles preemption code that gives priority to emergency vehicles by extending green or truncating red on cross-streets with no regard to any other factor other than the vehicle arrival, is provided. This code was used as the base to further code buses instead of emergency vehicles.

In order to be able to change the signal states from an RTE without using the EV transmitter and without passing special files to CORSIM to change the current timing scheme, the signal controllers of the nodes must be configured as pre-timed and externally-controlled. This needs to be done so that the signals are completely controlled by the RTE. C++ is used to classify and modify the files controlled by the RTE.

All results from the simulation are an average of running 25 different random number seeds producing 25 replicate runs. Using 25 samples comes from the central limit theorem, which states that as the sample size increases the probability of normality increases. If a normal distribution is achieved, it is safe to say the mean of the sample is a good representation of the population mean.

Most studies agree that TSP can save traveler time on a specific corridor, but the hidden impact that needs further investigation is what's the TSP impact on the less-traveled cross-streets. Certain variables are going to be tested to see the impact of changing those variables on both the bus delay/speed and all traffic delay/speed values.

## 3.1 Model 1: One-way Corridor Single Intersection

The first step of exploring TSP is to set up a single isolated intersection in CORSIM, the case with minimum variables would be ideal to start with. Looking at different cases, one-way streets are the easiest to implement and adopt a TSP system due to the fact that buses traveling in one direction will never have opposing left-turning traffic, also instead of having traffic coming from 4 directions, 3 directions would be simpler. The first step in this model is to explore a one-way single intersection with a main corridor traveling north and a two-way local street intersecting that corridor. Figure 3.1 shows the case that was built in CORSIM. In order to predict reality as close as possible, certain assumptions were made for the simulation and Table 3.1 shows those assumptions.

**Figure 3.1: Model 1 CORSIM configuration**

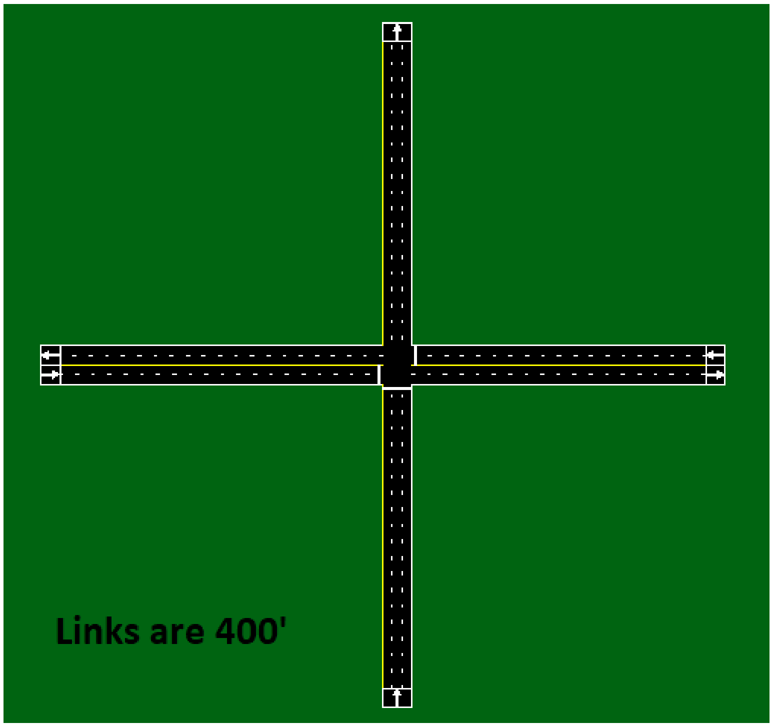



**Table 3.1: Model 1 Assumptions**

| Direction | Lanes | Turning | | | Green time | Cycle length | G/C ratio | Capacity per hour | Volume | V/C |
|---|---|---|---|---|---|---|---|---|---|---|
| | | Left | Thru | Right | | | | | | |
| **NB** | **3** | 15 | 70 | 15 | 55 | 90 | 0.61 | 3483 | 1500 | 0.431 |
| **EB** | **2** | 70 | 30 | 0 | 25 | | 0.28 | 1056 | 500 | 0.474 |
| **WB** | **2** | 0 | 30 | 70 | | | | | 500 | 0.474 |

A few runs were made without implementing any sort of TSP just to get an idea of what delays and average speeds to expect, the following table summarizes the average results for 25 runs. The only difference between the three runs is the bus headway, very minimal delay changes occurred. Table 3.2 shows the results of running Model 1 with no TSP.

**Table 3.2: Model 1 No TSP Results**

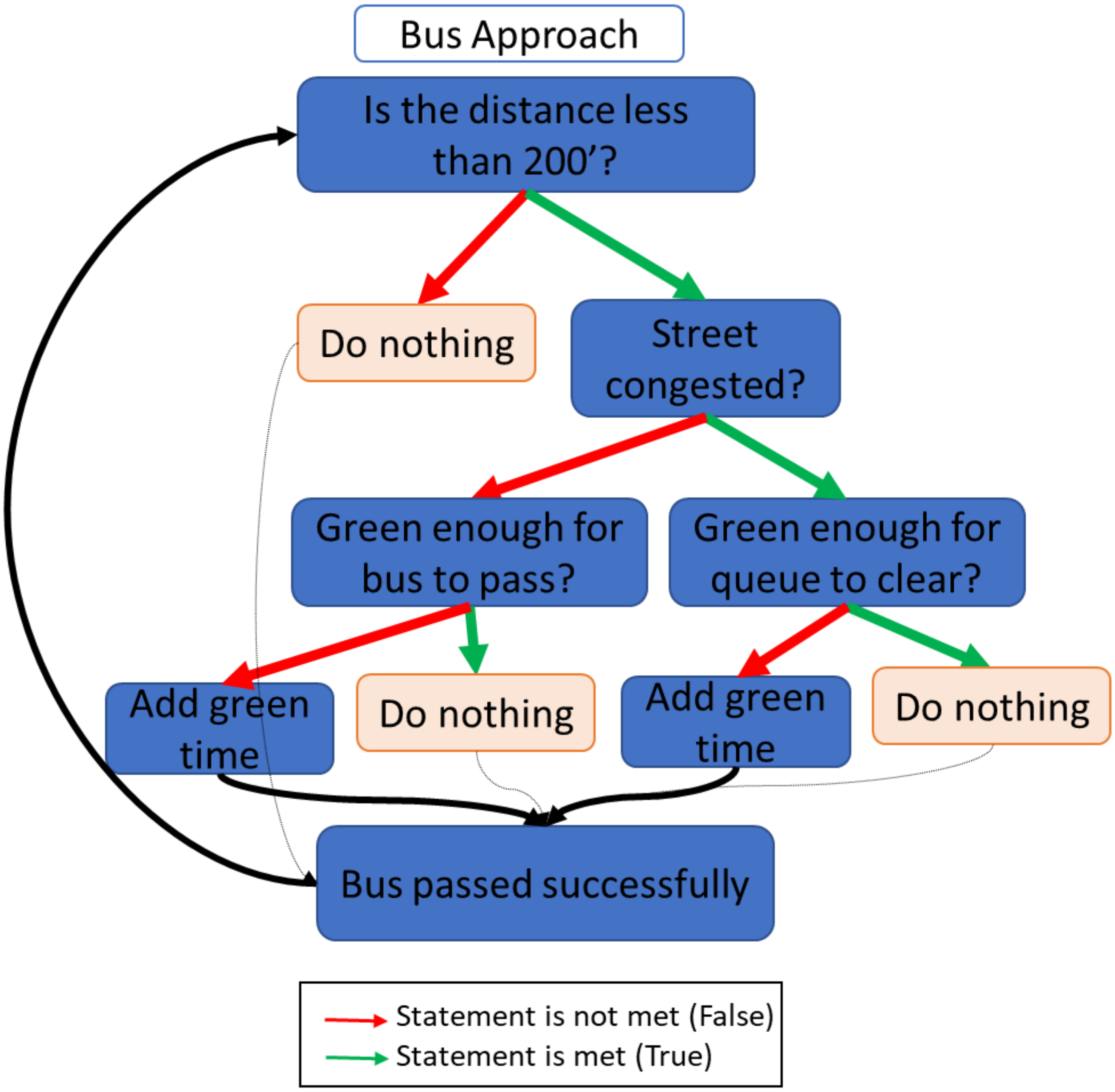
| Bus Headway 7 | | | | | | | |
|---|---|---|---|---|---|---|---|
| | N/S | E/W | Bus | | N/S | E/W | Bus |
| Delay | 6.59 | 28.52 | 1.70 | Speed | 18.68 | 7.59 | 16.20 |
| SD Delay | 0.38 | 12.57 | 0.16 | SD Speed | 0.56 | 2.38 | 0.89 |
| Bus Headway 5 | | | | | | | |
| | N/S | E/W | Bus | | N/S | E/W | Bus |
| Delay | 6.53 | 27.45 | 2.34 | Speed | 18.76 | 7.81 | 15.91 |
| SD Delay | 0.35 | 12.24 | 0.12 | SD Speed | 0.51 | 2.48 | 0.55 |
| Bus Headway 3 | | | | | | | |
| | N/S | E/W | Bus | | N/S | E/W | Bus |
| Delay | 6.52 | 27.20 | 2.22 | Speed | 18.72 | 7.80 | 22.50 |
| SD Delay | 0.26 | 11.54 | 0.16 | SD Speed | 0.42 | 2.35 | 0.88 |
| Delay= Seconds/Vehicle, Speed= Miles/Hour, SD= Standard Deviation | | | | | | | |

Delay values represent the average control delay per vehicle per direction of travel, these values are reported as seconds while speed is reported in miles per hour. Results show that the less frequent buses come, the less delay they would experience. This could be due to the fact that with frequent buses the probability of a bus stopping at a red light is higher. Here it is also noted that E/W delay variation is really high due to the fact that 70% of East bound traffic going North has to stop and wait for a gap to turn left. The delay numbers on these cases are as high as 40 for East bound and as low as 15 for West bound. These results will be used as a benchmark to compare to the results of implementing different types of TSP.

### 3.1.1 Scenario 1

The first TSP action to explore is adding extra green time. The point of this TSP is to grant additional green time for buses approaching the intersection when the green signal is close to runout and before the traffic signal turns red. The reason why this was the first approach, is to avoid red truncating and causing damages to cross-street traffic while also trying, with minimum changes, to let buses travel through the intersection. After running multiple runs, a basic TSP system was created. Also, to make the scenario more versatile and applicable to different situations, stopped queues were added to the set of scenario constraints. In the case of waiting queues, the scenario takes account of the time it will take to discharge the queue and for the bus to successfully pass the intersection. The Scenario 1 TSP system design is explained in Figure 3.2.

**Figure 3.2: Scenario 1 steps**




A virtual point was placed 200' south of the intersection (200' before the intersection on the bus route). This virtual point works as a detector for the bus, for each second in the simulation, the detector will check if there is a bus anywhere between the point and the intersection, meaning that if the distance between a bus and the intersection is less than 200' then the next question will ask if there is congestion on that 200' or not. If no, then it will check to see if the remaining green time is enough for the bus to pass based on this equation: 200'/(bus speed)=required green time to pass, by checking if the remaining green time is larger than this or not, if yes then do nothing, if not then add one second of green time and back again to the same process. Now if the street is in fact congested, the way congestion was calculated is by taking the number of non-moving vehicles that are in a queue on the right lane (the lane the bus is assigned to travel on) and plugging that number into this equation: 3.7+2.1*(non-moving vehicles) which represents Greenshields model. This equation will yield seconds which takes us to the next question, is the green enough for the queue to clear and the bus to pass? If yes, do nothing. If not, then add 1 second of green time then go back again to the same process. This approach is to try to provide priority green time to buses only if they are near an intersection that is already green. This is the simplest way to provide additional green time with minimum damage to the cross-street.

### 3.1.2 Scenario 1 Code Breakdown

The Run Time Extension (RTE) constructs the list of signal states for each link in the CLink::m_SignalStates member. Each element of the list represents the signal state for one consecutive second of simulation. The CLink object maintains a pointer to the current signal state in the list and moves that pointer one item forward in the list each call of CLink::SetSignalState(). Also, CLink::SetSignalState() calls CORSIM's SetSignal() API call to actually set the signal state. The call order for CLink::SetSignalState() looks as follows. CLink::SetSignalState() is called by CNode::SetSignalState(), which is called by CNetwork::UpdateNodeSignalStates(), which in turn is called by the EVPreemtion_PreNetsimSignal() callback each simulation iteration. The bus tracking and preemption is implemented in the CNetwork::TraceBUSLocation() method, which gets called every simulation iteration by the EVPreemtion_PreNetsimSignal() callback.

#### 2.2.2.13. CNode class changes

Adding an extra second for a green light is not possible through an RTE. Instead, holding the existing green light for an additional second was successfully implemented. In order to hold the current signal state of a node, a new property m_holdSignals was added to the CNode class. This property serves as a flag to indicate whether to hold the current signal states of the node during the next simulation iteration. The property is private, so two access methods were added: GetHoldSignals() to get the property value and SetHoldSignals() to set the value.

#### 2.2.2.14. CLink class changes

The CLink::SetSignalState() method was modified to accept the hold signal flag as the bHoldSignals parameter. Also, a small change to the method's logic was made. When the bHoldSignals flag is set to true, the pointer to the current signal state is not moved, so the previous state is used for the current simulation iteration. CORSIM does not provide a possibility to change the remaining green time. Instead, having the signal states list for the node, and knowing that each item in the list represents the signal state during one second, the software starts from the current state and counts the number of green states starting from the current state to determine an accurate remaining green time. That logic is implemented in the CLink::GetRemainingGreenTime() method.

For a better understanding of the approach to hold signals or forcing the green signal this paragraph explains how an externally controlled signal works in the RTE:

Once the simulation starts, the pointer to the current signal state is maintained inside the link object to keep track of the signal states. Each simulation cycle, the EVPreemption_PreNetsimSignal() callback executes the CNetwork::UpdateNodeSignalStates() method:

```
//*this is for controlling signal time*//
```

```
  pNetwork->UpdateNodeSignalStates();
```

which calls the CNode::SetSignalState() for each externally controlled node in the network:

```
    if( pNode->GetControlType() == CString("external") )
    {
      // Node is not controlled by CORSIM.
      pNode->SetSignalState();
    }
```

CNode::SetSignalState() in turn calls the CLink::SetSignalState() for each approach link:

```
        for( int iApproach=0; iApproach<maxApproaches; iApproach++ )
        {
                pApproach = m_pApproaches[iApproach];
                if( pApproach != NULL ) pApproach->SetSignalState(bHold);
        }
```

CLink::SetSignalState() actually reads the current signal states for the downlink node signals and moves the current signal state pointer one position forward in the states list:

```
void CLink::SetSignalState( bool bHoldSignals )
{  // Set the CORSIM signal state for this link.
  int nTime = sclock + giEndOfInit;
  // At the start of the simulation OR at the end of the signal
  // state list; so go back to the beginning of the list.
  if( nTime == 0 || m_SigListPos == NULL )
  {    m_SigListPos = m_SignalStates.GetHeadPosition();   }
  // Send the signal state for this link to CORSIM.
  if( m_SigListPos != NULL )
  {         CSignalState* pSignalState = NULL;
            POSITION pos = m_SigListPos;
            CSignalState *curState = m_SignalStates.GetPrev(pos);
            if (pos == NULL) pos = m_SignalStates.GetTailPosition();
            curState = m_SignalStates.GetAt(pos);
            CSignalState::SignalStateCode initialSignal = curState->GetThrough();
            if(bHoldSignals) pSignalState = m_SignalStates.GetAt(m_SigListPos);
            else pSignalState = m_SignalStates.GetNext(m_SigListPos);
    if( pSignalState != NULL )
    {       CSignalState::SignalStateCode nextCode = pSignalState->GetThrough();
                    if ( nextCode == CSignalState::S_GREEN) {
                            m_forcedGreen = false;
                            m_pDnNode->SetForceGreen(false);
                            if (initialSignal != CSignalState::S_GREEN) {
                                    m_pDnNode->SetPhaseStart(true);     }         }
      SetSignal( m_pUpNode->GetID(), m_pDnNode->GetID(),
            pSignalState->GetLeft(),
            pSignalState->GetThrough(),
            pSignalState->GetRight(),
            pSignalState->GetLeftDiag() );     } }}
```

Scenario 1 “Add Green Time” condition is implemented by holding the current signal states on a node for one simulation cycle. Meaning that the green phase will go for one additional second. For example, in the case of a bus approaching a green signal, the code holds the current signal states for all approach links to the bus's downlink node. In order to do that, the CNode class has the m_nHoldSignals member flag, which controls whether to hold the signal states during the current simulation cycle, or not. The flag is controlled by the CNode::SetHoldSignals(bool) method. The flag is turned on for required nodes inside the CNetwork::TraceBusLocation() method. When the flag is on, the CNode::SetSignalStates() method calls the CLink::SetSignalState() for each approach link with the input parameter set to "true", which tells the method not to move the current state pointer one position forward after retrieving and setting the current signal states

2.2.2.15. Congestion analysis

For the queue length, CORSIM only provides statistical average of the queue. In order to get the real queue length for the current moment, the CLink::GetQueueLength() method performs the following calculations.

Distance to the downlink node is calculated. For each vehicle that is currently in the system:

- Get the link the vehicle is currently on. Skip if it is on a different link than the bus.
- Calculate the vehicle's distance to the downlink node.
- Skip the vehicle if the distance is larger than the bus's.
- Skip the vehicle if it is on a different lane.
- Skip the vehicle if it's moving (i.e. its speed > 0).
- Otherwise, increase the queue length.
- Return the queue length

2.2.2.16. Tracing Bus Location

CNetwork::TraceBUSLocation() method: At the beginning, the function cleans up the signal hold flags for all of the nodes:

```
"       pos = m_LinkList.GetHeadPosition();
while (pos != NULL)
{       pLink = m_LinkList.GetNext(pos);
        if(pLink) pLink->SetDnNodeSignalHold(false);        }"
```

Then, it loops through all the vehicles in the network looking for buses (vehicle type 3) and for each bus the following steps are performed:

Vehicle ID (vehID), link ID (LinkID), downlink node (bus_dnode), uplink node (bus_unode), bus ID (busid), bus speed (busSpeed) are retrieved from CORSIM. The following values are calculated:

-Dis2Sig – Distance to the signal. Calculated as link length minus distance to the uplink.

-ttime – Travel time. Calculated as current clock time minus bus entry time into the system.

-pLink – pointer to the CLink object for the current link gets retrieved from the link objects list.

-timeToPass – Time to pass the signal with the current speed. Calculated as distance to the signal divided by the bus speed.

-greenTime – Green signal time remaining. Calculated in the CLink::GetRemainingGreenTime() method of the link object. Described in the CALCULATING REMAINING GREEN TIME section.

-If analyzeQueue flag is turned on, the queue length (queueLength) and queueClearTime is calculated according to the formula from the requirements. The queue length calculation is described in the calculating the queue length section.

If the distance to the signal (Dis2Sig) is less than 200 feet, then, according to the current code, timeToPass or queueClearTime is checked to see if it is larger than current greenTime. If it is less, then the downlink node's signal hold flag is set by calling pLink->SetDnNodeSignalHold(true). At the end of the loop iteration, a CSV record is added to the file by calling the AddCSVRecord() method. This file was used to inspect the specific results to make sure the code is working as desired. This file helped a lot in finding glitches and understanding why some numbers did not come as expected.

### 3.1.3 Scenario 1 Results

The results for Scenario 1 are described in Table 3.3. They show a very small increase in bus delay instead of a decrease. It also shows that the standard deviation is very high compared to the basic case standard deviations. This is due to the fact that buses that are taking advantage of TSP travel faster while others that depended on progression are now being affected because of the extra green time that threw the progression off. However, none of these values are significantly different than the base case. Sixteen two-way independent t tests were performed with alpha level of 0.05. None of the 6 variables that were compared (3 delay values and 3 speed values) for each headway timing (3, 5 and 7) was significantly different. In summary, adding green light only will not benefit the system but on average makes conditions worse, not significantly worse but it might have the potential to do so in the long run. This shows that only adding green time will not make significant changes to the system, which leads us to the next scenario.

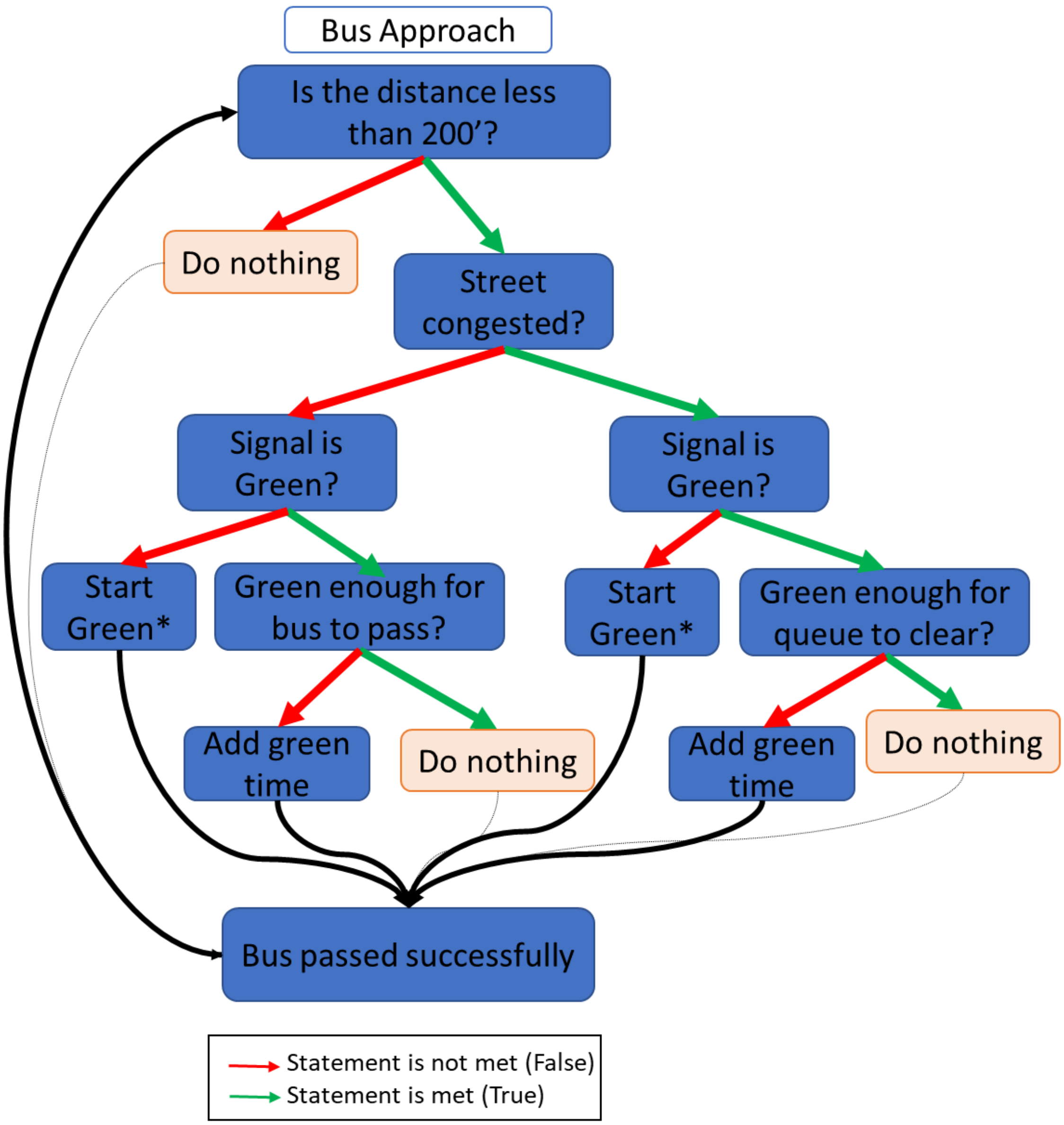
**Table 3.3: Model 1 Scenario 1 Results**

| NOTSP Bus Headway of 7 | | | | | | | |
|---|---|---|---|---|---|---|---|
| | N/S | E/W | Bus | | N/S | E/W | Bus |
| Delay | 6.59 | 28.52 | 1.70 | Speed | 18.68 | 7.59 | 16.20 |
| SD Delay | 0.38 | 12.57 | 0.16 | SD Speed | 0.56 | 2.38 | 0.89 |
| TSP Bus Headway of 7 | | | | | | | |
| | N/S | E/W | Bus | | N/S | E/W | Bus |
| Delay | 6.54 | 28.24 | 1.82 | Speed | 18.74 | 7.66 | 15.54 |
| SD Delay | 0.36 | 12.65 | 0.20 | SD Speed | 0.53 | 2.45 | 1.17 |
| TSP Impact | | | | | | | |
| | -0.78% | -1.00% | 7.05% | | 0.31% | 1.03% | -4.06% |
| Sig Dif? | NO | NO | NO | Sig Dif? | NO | NO | NO |
| | | | | | | | |
| NOTSP Bus Headway of 5 | | | | | | | |
| | N/S | E/W | Bus | | N/S | E/W | Bus |
| Delay | 6.53 | 27.45 | 2.34 | Speed | 18.76 | 7.81 | 15.91 |
| SD Delay | 0.35 | 12.24 | 0.12 | SD Speed | 0.51 | 2.48 | 0.55 |
| TSP Bus Headway of 5 | | | | | | | |
| | N/S | E/W | Bus | | N/S | E/W | Bus |
| Delay | 6.51 | 29.10 | 2.45 | Speed | 18.75 | 7.63 | 15.51 |
| SD Delay | 0.20 | 14.08 | 0.32 | SD Speed | 0.31 | 2.59 | 1.48 |
| Impact | | | | | | | |
| | -0.37% | 5.99% | 4.79% | | -0.07% | -2.28% | -2.49% |
| Sig Dif? | NO | NO | NO | Sig Dif? | NO | NO | NO |
| | | | | | | | |
| NO TSP Bus Headway of 3 | | | | | | | |
| | N/S | E/W | Bus | | N/S | E/W | Bus |
| Delay | 6.52 | 27.20 | 2.22 | Speed | 18.72 | 7.80 | 22.50 |
| SD Delay | 0.26 | 11.54 | 0.16 | SD Speed | 0.42 | 2.35 | 0.88 |
| TSP Bus Headway of 3 | | | | | | | |
| | N/S | E/W | Bus | | N/S | E/W | Bus |
| Delay | 6.50 | 28.07 | 2.44 | Speed | 18.71 | 7.75 | 21.74 |
| SD Delay | 0.30 | 13.21 | 0.74 | SD Speed | 0.45 | 2.51 | 2.76 |
| Impact | | | | | | | |
| | -0.31% | 3.20% | 10.08% | | -0.06% | -0.69% | -3.38% |
| Sig Dif? | NO | NO | NO | Sig Dif? | NO | NO | NO |
| Delay= Seconds/Vehicle, Speed= Miles/Hour, Sig Dif= Significant Difference | | | | | | | |

### 3.1.4 Scenario 2

The next action to test is red truncation. This scenario is going to respond to buses approaching in a red light phase by ending the green light on the crossing-street and starting a new green phase for the bus direction of travel. The previous scenario was only applied when buses approached the intersection in the last few seconds of green time. So, in that scenario a bus approaching an intersection on the arterial street with a cycle of 90 seconds, with 55 seconds of arterial green and 25 seconds for the crossing direction will only be able to pass if arrival occurs in the 55 seconds of arterial green, leaving buses who come in the other 25 seconds completely out of the picture. This scenario will treat any bus any time. The Scenario 2 system design is explained in Figure 3.3.

**Figure 3.3: Scenario 2 steps**




This scenario is built based on the previous scenario with a few modifications or additions. A new step to check the state of the signal is added. If the signal is green, the code will continue to work just like the first scenario, if not it will start green based on a few assumptions depending on the street congestion:

Congestion: the signal will start green as soon as the bus is less than 200' from the intersection.

No congestion: the signal will not start until the bus starts slowing down. The trigger for the start of a new green phase is the bus speed decreases. The reason for that is to make sure that not a single second of green time is wasted. If there is no congestion then we anticipate that the bus will travel smoothly, starting the green phase earlier than needed is a waste of green time. Here it should be noted that in the code, the transition time for 3 seconds of yellow clearance time and 2 seconds of all red is also accounted for.

### 3.1.5 Scenario 2 Code Breakdown

In an effort to increase efficiency and versatility of any code built in this study a configuration file was added to modify the code with desired values and inputs, it also works as a switch to turn on or off certain changes in the code. In other words, in order to be able to change the code scenarios and scenario parameters without having to rebuild the RTE plugin, all parameters are can be modified from the configuration file. To implement that, the ConfigFile class was added. The class accepts the config file name as the constructor's parameter. The class contains two methods – ConfigFile::LoadFile() and ConfigFile::GetOption(const string&). These two methods work as follows:

LoadFile() method reads the config file, analyzes each line assuming the line is in "key = value" format, where "key" is the configuration option name and "value" is its value. Each key-value pair gets added to the std::map<string,string> member, which is named "cfg". So after the file is loaded, the "cfg" member contains a map with option names as the map key.

The GetOption(const string&) method gets the value of the key, specified in the parameter, from the configuration map "cfg". If the key is not found, an empty string is returned.

Once the new parameters are loaded and saved, CNetwork class is extended with the LoadConfig() method, which accepts the config file path. Also the new private "cfg" pointer to the ConfigFile type was added, to hold the configuration. The LoadConfig() method allocates the ConfigFile object and loads the configuration. Then, it reads the config options and sets defaults for the options which were not found in the config. The options and their defaults are as follows (Table 3.4):

**Table 3.4: Scenario 2 Configuration Default Values**

| Option name | Description | Default value |
|---|---|---|
| **analyze_queue** | Perform queue (congestion) analysis. "true" or "false" | TRUE |
| **enable_preemption** | Enable or disable the preemption algorithm. "true" or "false" | TRUE |

These default values can be switched on in order to activate Scenario 2 by changing the values in the configuration file to True for both, or simply turning both values to False will switch off these algorithms and the code will work just as Scenario 1. Once the configuration file is ready, The LoadConfig() method sets appropriate member values according to the loaded configuration. The CNetwork::LoadConfig() method gets called once, at the beginning of the simulation, and at the end of the EVPreemption_INIT() function in opcntrl.cpp as follows:

```
"pNetwork->LoadConfigFile("C:\\Temp\\bus.cfg");"
```

Analyze_queue is explained in the previous scenario when looking at the queues formed on the bus's link. Enable_preemption controls what happens when buses arrive during a red phase. When a bus approaches a downstream link on red, the code forces switching the signals on the bus's link to green. In order to do that safely, the cross-street signals have to switch to the end of their green phase, yellow and all red first. For the purposes of programming, the yellow and red phases will be called Amber phases. When the "Set Green" procedure is initiated, the CNetwork::TraceBusLocation() finds the pointers to the CLink objects of the cross-street:

```
"leftNode = pLink->GetLeftNode();
rightNode = pLink->GetRightNode();
dNode = pLink->GetDnNode();
if (leftNode) leftLink = FindLink(leftNode->GetID(), dNode->GetID());
if (rightNode) rightLink = FindLink(rightNode->GetID(), dNode->GetID());"
```

TraceBusLocation() calculates how many seconds are left to switch from green to amber. That is performed in the CLink::GetCyclesToNextAmber() call on the cross-street object:

```
"if (forceGreen) {
        CLink *crossLink = leftLink;
        if (crossLink == NULL) crossLink = rightLink;
        if (crossLink) {
                int skipCnt = crossLink->GetCyclesToNextAmber();
                if (skipCnt > 0) {
                        dNode->SkipSignalCycles(skipCnt, pLink);}}}"
```

The CLink::GetCyclesToNextAmber() walks through the signal states list starting from the current state, while it is green, and maintains a counter, returning the result at the end:

```
        "int CLink::GetCyclesToNextAmber() {
        POSITION pos = m_SigListPos;
        int cnt = 0;
        if (pos == NULL) pos = m_SignalStates.GetHeadPosition();
        if (pos != NULL) {
                CSignalState *currState = m_SignalStates.GetAt(pos);
                while (currState && (currState->GetThrough() == CSignalState::S_GREEN)) {
                        currState = m_SignalStates.GetNext(pos);
                        if (pos == NULL) pos = m_SignalStates.GetHeadPosition();
                        cnt++;
                        if (pos == m_SigListPos) {cnt = 0;      break;  }}}
//      sprintf(gsOutput, "Amber state in %d cycles", cnt);
//      OutputString(gsOutput, strlen(gsOutput), SIM_COLOR_RGB, RTE_MESSAGE_RGB);
        return cnt;}"
```

Having the amount of time to switch to the amber read from the cross-street, the TraceBusLocation() routine calls the CNode::SkipSignalCycles() on the downlink node. The CNode::SkipSignalCycles(int) in return calls the CLink::SkipSignalCycles(int) for each approach link, which moves the current state pointer for the specified number of positions, effectively putting the cross-street to the end of the green phase and moving the bus's link to the end of the red phase minus the amount of the amber plus all-red time on the cross-street:

```
"void CLink::SkipSignalCycles(int cnt) {          POSITION pos = m_SigListPos;
if (pos == NULL) pos = m_SignalStates.GetHeadPosition();
if (pos != NULL) {
        do {    CSignalState* currState = m_SignalStates.GetNext(pos);
                if (pos == NULL) pos = m_SignalStates.GetHeadPosition();
                cnt--;          } while (cnt > 0);
                        if(pos) m_SigListPos = pos;      }}"
```

3.1.6 Scenario 2 Results

Results of Scenario 2 are shown in Table 3.5. With 3 minute headways, bus delay/speed did not change much, due to the high frequency of buses. However, now the standard deviation is no longer higher than the base case. This means that this scenario is capturing more bus requests but not significantly affecting their delay/speed values. Here it should be noted that in real life, buses with 3 minutes headways is nearly an impossible situation. Twenty buses an hour is more than a conservative assumption, however for the purposes of having more results and comparisons, we will continue to test buses with 3-minute headways. In the case of 5 and 7-minute headways, which is ideal, the bus delay and speed are significantly different. The values reflect that using red truncation and green extension at the same time significantly decreases delay and increases speed. It is also important to make sure that no damages are being made to the cross-street, in this case delay values increase, and speed decreased, which means that TSP affected the cross-street in a negative way. However, due to the fact that EB and WB values differ as discussed earlier, determining whether those changes are significant is still difficult.

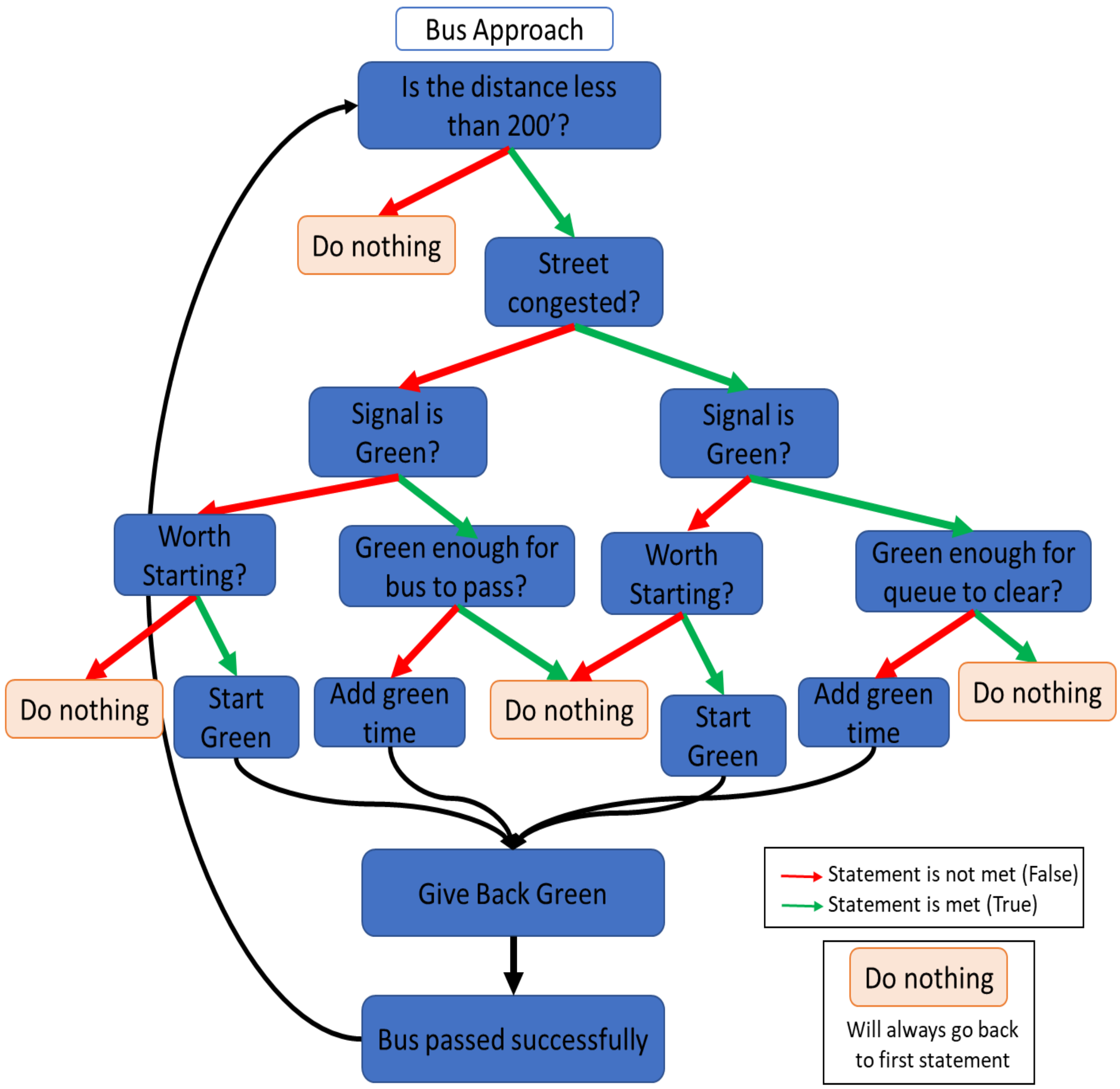
**Table 3.5: Model 1 Scenario 2 Results**

| NOTSP Bus Headway of 7 | | | | | | | |
|---|---|---|---|---|---|---|---|
| | N/S | E/W | Bus | | N/S | E/W | Bus |
| Delay | 6.59 | 28.52 | 1.70 | Speed | 18.68 | 7.59 | 16.20 |
| SD Delay | 0.38 | 12.57 | 0.16 | SD Speed | 0.56 | 2.38 | 0.89 |
| TSP Bus Headway of 7 | | | | | | | |
| | N/S | E/W | Bus | | N/S | E/W | Bus |
| Delay | 6.30 | 31.49 | 0.87 | Speed | 19.15 | 7.18 | 25.11 |
| SD Delay | 0.35 | 14.75 | 0.37 | SD Speed | 0.61 | 2.48 | 4.43 |
| TSP Impact | | | | | | | |
| | -4.33% | 10.41% | -49.03% | | 2.49% | -5.32% | 54.98% |
| Sig Dif? | NO | NO | YES | Sig Dif? | NO | NO | YES |
| | | | | | | | |
| NOTSP Bus Headway of 5 | | | | | | | |
| | N/S | E/W | Bus | | N/S | E/W | Bus |
| Delay | 6.53 | 27.45 | 2.34 | Speed | 18.76 | 7.81 | 15.91 |
| SD Delay | 0.35 | 12.24 | 0.12 | SD Speed | 0.51 | 2.48 | 0.55 |
| TSP Bus Headway of 5 | | | | | | | |
| | N/S | E/W | Bus | | N/S | E/W | Bus |
| Delay | 6.21 | 32.86 | 0.91 | Speed | 19.25 | 7.10 | 28.25 |
| SD Delay | 0.35 | 16.36 | 0.43 | SD Speed | 0.51 | 2.65 | 5.10 |
| Impact | | | | | | | |
| | -4.91% | 19.71% | -61.20% | | 2.60% | -9.07% | 77.59% |
| Sig Dif? | NO | NO | YES | Sig Dif? | NO | NO | YES |
| | | | | | | | |
| NO TSP Bus Headway of 3 | | | | | | | |
| | N/S | E/W | Bus | | N/S | E/W | Bus |
| Delay | 6.52 | 27.20 | 2.22 | Speed | 18.72 | 7.80 | 22.50 |
| SD Delay | 0.26 | 11.54 | 0.16 | SD Speed | 0.42 | 2.35 | 0.88 |
| TSP Bus Headway of 3 | | | | | | | |
| | N/S | E/W | Bus | | N/S | E/W | Bus |
| Delay | 6.35 | 29.26 | 2.24 | Speed | 18.92 | 7.59 | 22.40 |
| SD Delay | 0.27 | 13.77 | 0.20 | SD Speed | 0.40 | 2.60 | 1.08 |
| Impact | | | | | | | |
| | -2.57% | 7.57% | 0.96% | | 1.05% | -2.71% | -0.44% |
| Sig Dif? | NO | NO | NO | Sig Dif? | NO | NO | NO |
| Delay= Seconds/Vehicle, Speed= Miles/Hour, Sig Dif= Significant Difference | | | | | | | |

### 3.1.7 Scenario 3

Adding green time and red truncation all the time is highly beneficial to buses approaching intersections, since it provides access to the intersection every time a bus approaches. Now that we succeeded in granting significantly better conditions for buses, how can we make sure that cross-street traffic impacts are minimized? Also, how can we modify the code so that it only gives access to the bus when it is beneficial? Scenario 3 was built on the same logic as Scenario 2 but with a few more modifications/additions to make sure that buses who are granted access will have minimum effect on the cross-street. Figure 3.4 shows the system design of Scenario 3.

**Figure 3.4: Scenario 3 steps**




The main two elements that were added are: "Worth Starting?" and "Give Back Green". "Worth Starting?" works when buses approach a red phase, before starting green, the code will check if there is on average 2 or more non-moving vehicles on the cross-street before truncating red and starting green for the bus. The number of non-moving cross street vehicles was chosen as 2 as a safe assumption to reflect if there are any vehicles experiencing stopped delay while their light is green. The other addition to the code is "Give Back Green", GBG works after a green light is added or started for the bus and counts the green light seconds for the remaining phase before it ends (the crossing street green that was "stolen" or taken away in order to make the bus pass). It counts these remaining green seconds and would give it back to the cross-street on the next signal cycle. For Example, a bus approaches an intersection with a red signal, and the cross-street is 12 seconds into its 25 second green. The code will start green for bus, now the cross-street has 13 remaining green seconds. The code will only give back 10 seconds, meaning that once the 55 seconds for the bus direction ends, the next phase would have 35 instead of 25 seconds. (Assuming that the N/S direction has 55 seconds, and E/W has 25 seconds). GBG works under one condition: green given back has to be under 10 seconds. Again, this is another assumption to be on the safe side when green time is given back, the 2 non-moving vehicles condition along with max green of 10 will be furtherly explored in this report later.

### 3.1.8 Scenario 3 Code Breakdown

In order to adapt the code to the new changes and still make it more flexible, a new configuration table was created. Table 3.6 shows the new table which represents all parameters across the three scenarios with the ability to easily modify and change all the added factors and variables.

**Table 3.6: Scenario 3 Configuration Default Values**

| Option name | Description | Default value |
|---|---|---|
| **analyze_queue** | Perform queue (congestion) analysis. “true” or “false” | TRUE |
| **enable_preemption** | Enable or disable the preemption algorithm. “true” or “false” | TRUE |
| **set_green_threshold** | Threshold of amount of the non-moving vehicles on the cross-link for the “Start Green” feature. | 2 |
| **enable_green_giveback** | Enable or disable giving back the green time that was previously held. “true” or “false”. | TRUE |

#### 2.2.2.17. Worth Starting

The “Worth Starting” option is now added. If the set_green_threshold configuration option is set to -1, the worthStarting flag is set to “true” meaning that the option is satisfied. If the threshold is non-negative, the TraceBusLocation() method calculates the number of non-moving vehicles on the cross-street by calling the CLink::GetNonMovingCount() method:

```
“bool worthStarting = true;
if (threshold >= 0) {
        int cntLeft = 0, cntRight = 0;
        if (leftLink) cntLeft = leftLink->GetNonMovingCount();
        if (rightLink) cntRight = rightLink->GetNonMovingCount();
        if ((cntLeft > threshold) || (cntRight > threshold)) {
                worthStarting = false;          }          }”
```

The CLink::GetNonMovingCount() method checks the speed of each vehicle on the current link and counts them:

```
"int CLink::GetNonMovingCount()
{         int cnt = 0;
for (int iv = 0; iv < ttlveh; iv++) {
          int link = nvhlnk[iv];
          if (link != m_nCorsimId) continue; // This vehicle is on another link. Skip.
          int speed = spdln[iv];
          if (speed == 0) {
                    cnt++; // This vehicle is not moving             }         }
return cnt;}"
```

If the number of non-moving vehicles on the cross-streets exceeds the threshold, then the worthStarting flag is set to "false" meaning that the option is not satisfied. The code will keep looping until the "Worth Starting" option is satisfied.

Give Back Green "GBG":

This functionality is set to TRUE in Scenario 3 while in Scenario 2 it should be FALSE, the "enable_green_giveback" parameter from the config file is used. The value of the parameter is assigned to the value of the CNetwork::enableGreenGiveback member flag in the CNetwork::LoadConfigFile():

```
"val = cfg->GetOption("enable_green_giveback");
if (!val.compare("")) val = "true";
if (!val.compare("false")) SetGreenGivebackEnable(false);
else SetGreenGivebackEnable(true);"
```

Eventually, that flag is assigned to the CNode::enableGreenGiveback flag when creating nodes during initialization in the CNetwork::GetNodes() method:

```
pNode->SetGivebackGreenEnable(enableGreenGiveback);
```

As described in the previous sections, the CNode::skipCycles counter contains the number of seconds, called cycles here, currently held on a node. Now the general definition of a cycle in traffic is the time for a signal controller to display all signal phases one time. But in this case, cycle means the number of seconds that was held on a specific node. When a cycle is held, or skipped, a pointer to the link which held the cycle is also stored. When the hold flag for the node is turned off, the CNode::SetSignalState() method checks if the skipCycles counter is larger than zero. If it is, it checks if the approach links that are cross-street which held cycles just started a green phase. If they did, and the enableGreenGiveback flag is turned on, then the give back counter (CNode::giveBack) is set to 10 if the skipCycles is larger than 10, and to skipCycles otherwise:

```
"if (enableGreenGiveback && (skipCycles > 0)) {
          // Give back green if enabled
          if (skipCycles <= 10) {
                    giveBack = skipCycles;
          }                   else {
```

```
                giveBack = 10;
}       }”
```

Then, each call of CNode::SetSignalState(), if the giveBack counter is larger than 0, the counter decrements by 1 and signals are held on all approaches, giving back the green seconds to the cross-street from which the green seconds were taken previously.

### 3.1.9 Scenario 3 Results

Results for Scenario 3 are shown in Table 3.7. By comparing Scenario 3 TSP with no TSP we find that the scenario is effective for both 5 and 7-minute headways. While still not being able to capture any significant changes in the 3-minute headway category. Here it should be noted that changes between Scenario 2 and Scenario 3 are obvious in terms of effect on cross-streets. Table 3.8 compares results from Scenario 2 and Scenario 3.

**Table 3.7: Model 1 Scenario 3 Results**

| | | | | | | | |
|---|---|---|---|---|---|---|---|
| NOTSP Bus Headway of 7 | | | | | | | |
| | N/S | E/W | Bus | | N/S | E/W | Bus |
| Delay | 6.59 | 28.52 | 1.70 | Speed | 18.68 | 7.59 | 16.20 |
| SD Delay | 0.38 | 12.57 | 0.16 | SD Speed | 0.56 | 2.38 | 0.89 |
| TSP Bus Headway of 7 | | | | | | | |
| | N/S | E/W | Bus | | N/S | E/W | Bus |
| Delay | 6.31 | 30.05 | 0.94 | Speed | 19.15 | 7.43 | 24.12 |
| SD Delay | 0.39 | 13.99 | 0.37 | SD Speed | 0.56 | 2.51 | 4.66 |
| TSP Impact | | | | | | | |
| | -4.30% | 5.36% | -44.91% | | 2.48% | -2.06% | 48.86% |
| Sig Dif? | NO | NO | YES | Sig Dif? | NO | NO | YES |
| | | | | | | | |
| NOTSP Bus Headway of 5 | | | | | | | |
| | N/S | E/W | Bus | | N/S | E/W | Bus |
| Delay | 6.53 | 27.45 | 2.34 | Speed | 18.76 | 7.81 | 15.91 |
| SD Delay | 0.35 | 12.24 | 0.12 | SD Speed | 0.51 | 2.48 | 0.55 |
| TSP Bus Headway of 5 | | | | | | | |
| | N/S | E/W | Bus | | N/S | E/W | Bus |
| Delay | 6.34 | 30.64 | 1.20 | Speed | 19.05 | 7.32 | 24.59 |
| SD Delay | 0.28 | 14.23 | 0.45 | SD Speed | 0.39 | 2.51 | 4.69 |
| Impact | | | | | | | |
| | -3.00% | 11.61% | -48.59% | | 1.55% | -6.32% | 54.59% |
| Sig Dif? | NO | NO | YES | Sig Dif? | NO | NO | YES |
| | | | | | | | |
| NO TSP Bus Headway of 3 | | | | | | | |
| | N/S | E/W | Bus | | N/S | E/W | Bus |
| Delay | 6.52 | 27.20 | 2.22 | Speed | 18.72 | 7.80 | 22.50 |
| SD Delay | 0.26 | 11.54 | 0.16 | SD Speed | 0.42 | 2.35 | 0.88 |
| TSP Bus Headway of 3 | | | | | | | |
| | N/S | E/W | Bus | | N/S | E/W | Bus |
| Delay | 6.38 | 28.61 | 2.29 | Speed | 18.93 | 7.65 | 22.22 |
| SD Delay | 0.28 | 13.16 | 0.36 | SD Speed | 0.40 | 2.53 | 1.68 |
| Impact | | | | | | | |
| | -2.16% | 5.17% | 3.12% | | 1.12% | -1.96% | -1.21% |
| Sig Dif? | NO | NO | NO | Sig Dif? | NO | NO | NO |

Delay= Seconds/Vehicle, Speed= Miles/Hour, Sig Dif= Significant Difference

**Table 3.8: Model 1 Scenario 2 Versus Scenario 3 Results**

| Scenario #2 TSP (Headway 7 Minutes) | | | | | | | |
|---|---|---|---|---|---|---|---|
| | N/S | E/W | Bus | | N/S | E/W | Bus |
| Delay | 6.30 | 31.49 | 0.87 | Speed | 19.15 | 7.18 | 25.11 |
| SD Delay | 0.35 | 14.75 | 0.37 | SD Speed | 0.61 | 2.48 | 4.43 |
| Scenario #3 TSP (Headway 7 Minutes) | | | | | | | |
| | N/S | E/W | Bus | | N/S | E/W | Bus |
| Delay | 6.31 | 30.05 | 0.94 | Speed | 19.15 | 7.43 | 24.12 |
| SD Delay | 0.39 | 13.99 | 0.37 | SD Speed | 0.56 | 2.51 | 4.66 |
| TSP Impact | | | | | | | |
| | 0.03% | -4.57% | 8.09% | | -0.01% | 3.44% | -3.95% |
| Sig Dif? | NO | NO | NO | Sig Dif? | NO | NO | NO |
| | | | | | | | |
| Scenario #2 TSP (Headway 5 Minutes) | | | | | | | |
| | N/S | E/W | Bus | | N/S | E/W | Bus |
| Delay | 6.21 | 32.86 | 0.91 | Speed | 19.25 | 7.10 | 28.25 |
| SD Delay | 0.35 | 16.36 | 0.43 | SD Speed | 0.51 | 2.65 | 5.10 |
| Scenario #3 TSP (Headway 5 Minutes) | | | | | | | |
| | N/S | E/W | Bus | | N/S | E/W | Bus |
| Delay | 6.34 | 30.64 | 1.20 | Speed | 19.05 | 7.32 | 24.59 |
| SD Delay | 0.28 | 14.23 | 0.45 | SD Speed | 0.39 | 2.51 | 4.69 |
| Impact | | | | | | | |
| | 2.01% | -6.77% | 32.51% | | -1.03% | 3.02% | -12.95% |
| Sig Dif? | NO | NO | NO | Sig Dif? | NO | NO | NO |
| | | | | | | | |
| Scenario #2 TSP (Headway 3 Minutes) | | | | | | | |
| | N/S | E/W | Bus | | N/S | E/W | Bus |
| Delay | 6.35 | 29.26 | 2.24 | Speed | 18.92 | 7.59 | 22.40 |
| SD Delay | 0.27 | 13.77 | 0.20 | SD Speed | 0.40 | 2.60 | 1.08 |
| Scenario #3 TSP (Headway 3 Minutes) | | | | | | | |
| | N/S | E/W | Bus | | N/S | E/W | Bus |
| Delay | 6.38 | 28.61 | 2.29 | Speed | 18.93 | 7.65 | 22.22 |
| SD Delay | 0.28 | 13.16 | 0.36 | SD Speed | 0.40 | 2.53 | 1.68 |
| Impact | | | | | | | |
| | 0.43% | -2.23% | 2.14% | | 0.07% | 0.77% | -0.77% |
| Sig Dif? | NO | NO | NO | Sig Dif? | NO | NO | NO |
| Delay= Seconds/Vehicle, Speed= Miles/Hour, Sig Dif= Significant Difference | | | | | | | |

Although none of these results (Table 3.8) are statistically significant, Scenario 2 was better in handling bus delay and on average it moved buses faster with less delays. However, Scenario 3 had smaller effects on cross-streets in all cases, due to the fact cross-street values are high in variations, the results are still not clear on which scenario is best in minimizing bus delay with minimum effect on cross-streets.

## 3.2 Model 2: Two-way Corridor Single Intersection

One-way corridors are ideal to implement TSP, but it is hard to gauge the effect of modifying different factors. Also, in real life many intersections have 4 directions of travel. Building another model, that is based on a two-way corridor will add to the versatility of this study and also touches on another variable namely the network capacity factor. Figure 3.5 shows a CORSIM screenshot of the model.

**Figure 3.5: Model 2 CORSIM configuration**

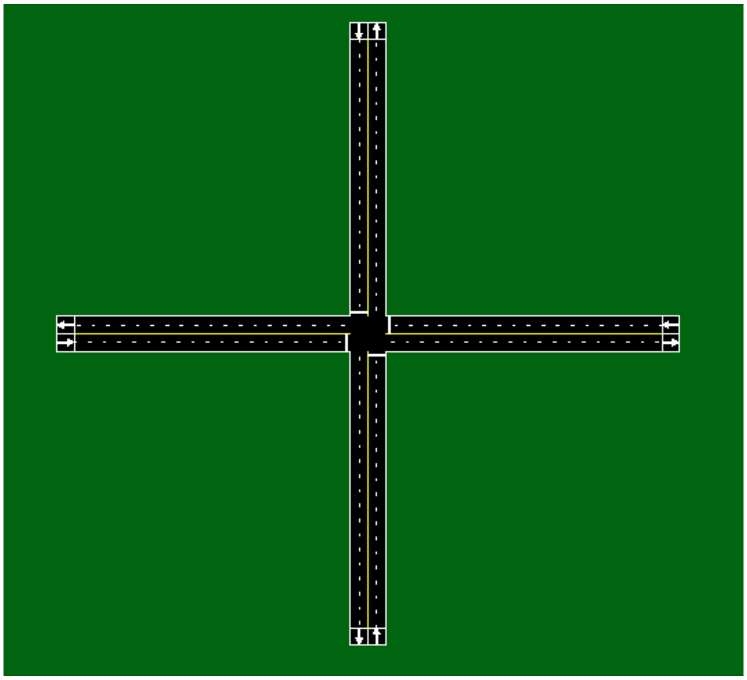


Table 3.9 shows the assumption that were used in this model, in order to be consistent with Model 1 some of these values like cycle length and phases were not changed.

**Table 3.9: Model 2 Assumptions**

| Direction | Lanes | Turning | | | Green time | Cycle length | G/C ratio | Capacity per hour | Volume | V/C |
|---|---|---|---|---|---|---|---|---|---|---|
| | | Left | Thru | Right | | | | | | |
| **NB** | **2** | 15 | 70 | 15 | 55 | 90 | 0.61 | 2322 | 1000 | 0.431 |
| **SB** | **2** | 15 | 70 | 15 | | | | | 1000 | 0.431 |
| **EB** | **2** | 40 | 20 | 40 | 25 | | 0.28 | 1056 | 500 | 0.474 |
| **WB** | **2** | 40 | 20 | 40 | | | | | 500 | 0.474 |

The same three scenarios will be applied to this model in order to evaluate TSP. No TSP base case results will be used as a benchmark. Table 3.10 summarizes the effects of TSP, each will be briefly discussed.

**Table 3.10: Model 2 Scenario 1 Results**

| NOTSP Bus Headway of 7 | | | | | | | |
|---|---|---|---|---|---|---|---|
| | N/S | E/W | Bus | | N/S | E/W | Bus |
| Delay | 8.93 | 21.79 | 2.09 | Speed | 15.38 | 8.36 | 13.95 |
| SD Delay | 0.57 | 1.33 | 0.23 | SD Speed | 0.58 | 0.35 | 1.06 |
| TSP Bus Headway of 7 | | | | | | | |
| | N/S | E/W | Bus | | N/S | E/W | Bus |
| Delay | 8.92 | 21.45 | 2.07 | Speed | 15.40 | 8.45 | 14.30 |
| SD Delay | 0.51 | 1.20 | 0.33 | SD Speed | 0.55 | 0.34 | 1.70 |
| TSP Impact | | | | | | | |
| | -0.19% | -1.60% | -1.03% | | 0.17% | 1.14% | 2.49% |
| Sig Dif? | NO | NO | NO | Sig Dif? | NO | NO | NO |
| | | | | | | | |
| NOTSP Bus Headway of 5 | | | | | | | |
| | N/S | E/W | Bus | | N/S | E/W | Bus |
| Delay | 9.03 | 21.86 | 2.82 | Speed | 15.27 | 8.35 | 14.01 |
| SD Delay | 0.67 | 1.29 | 0.28 | SD Speed | 0.68 | 0.33 | 0.96 |
| TSP Bus Headway of 5 | | | | | | | |
| | N/S | E/W | Bus | | N/S | E/W | Bus |
| Delay | 8.91 | 21.69 | 2.61 | Speed | 15.39 | 8.36 | 14.82 |
| SD Delay | 0.54 | 1.34 | 0.32 | SD Speed | 0.56 | 0.36 | 1.39 |
| Impact | | | | | | | |
| | -1.34% | -0.75% | -7.24% | | 0.80% | 0.21% | 5.81% |
| Sig Dif? | NO | NO | NO | Sig Dif? | NO | NO | NO |
| | | | | | | | |
| NO TSP Bus Headway of 3 | | | | | | | |
| | N/S | E/W | Bus | | N/S | E/W | Bus |
| Delay | 9.04 | 22.04 | 3.42 | Speed | 15.25 | 8.30 | 17.41 |
| SD Delay | 0.60 | 1.38 | 0.35 | SD Speed | 0.62 | 0.36 | 1.20 |
| TSP Bus Headway of 3 | | | | | | | |
| | N/S | E/W | Bus | | N/S | E/W | Bus |
| Delay | 9.09 | 22.22 | 6.26 | Speed | 15.16 | 8.22 | 11.62 |
| SD Delay | 0.57 | 1.27 | 1.57 | SD Speed | 0.60 | 0.31 | 2.11 |
| Impact | | | | | | | |
| | 0.61% | 0.82% | 83.21% | | -0.57% | -1.00% | -33.23% |
| Sig Dif? | NO | NO | YES | Sig Dif? | NO | NO | YES |

Delay= Seconds/Vehicle, Speed= Miles/Hour, Sig Dif= Significant Difference

Here the results show that using TSP with bus headway of 3 mins actually increases the delay and decrease the speed for buses. This could be due to excessive use of TSP, every 180 seconds will destroy progression, meaning that the chances of buses approaching an intersection while it is red are now higher which eventually will increase bus delay. By looking at the detailed output for one simulation run that reports each time a bus is less than 200' from the intersection over 3600 seconds, it was noticed that in the case without TSP, none of 22 buses arrived at the intersection during the red signal. Five buses arrived at the beginning of the green phase, so they waited for a few seconds each for the queue to discharge. The cumulative stop time was 28 seconds. For the case with TSP, 12 out of 22 buses arrived at the intersection, stopped at the end of the queue, and had to wait for the green, and then wait for the queue to discharge. Total wait time on red was 110 seconds and wait for discharge was 50 seconds. Also, 4 buses arrived at the beginning of the green phase and had to wait for the queue to discharge. Wait time for those 4 buses was 20 seconds. So total wait time in the case with TSP was 180 seconds. In comparison to 28 seconds without TSP, leading to very different average wait times per vehicle which are 28/22= 1.27 for no TSP versus 180/22=8.18 with TSP. This is a single case out of the 25 cases, but it might be a good explanation as to why TSP is not helpful in the case of 3-minute bus headways.

Results for Model 2 Scenario 2 are provided in Table 3.11. Bus delay for 3-minute headways is still significantly larger than the other two headways examined, however, bus delay for 5 and 7 minute headways is now significantly less. The model also showed increased delay on cross-streets, but no statistically significant results were found.

**Table 3.11: Model 2 Scenario 2 Results**

| NOTSP Bus Headway of 7 | | | | | | | |
|---|---|---|---|---|---|---|---|
| | N/S | E/W | Bus | | N/S | E/W | Bus |
| Delay | 8.93 | 21.79 | 2.09 | Speed | 15.38 | 8.36 | 13.95 |
| SD Delay | 0.57 | 1.33 | 0.23 | SD Speed | 0.58 | 0.35 | 1.06 |
| TSP Bus Headway of 7 | | | | | | | |
| | N/S | E/W | Bus | | N/S | E/W | Bus |
| Delay | 9.32 | 22.70 | 1.25 | Speed | 15.03 | 8.12 | 19.87 |
| SD Delay | 0.66 | 1.40 | 0.28 | SD Speed | 0.64 | 0.34 | 2.62 |
| TSP Impact | | | | | | | |
| | 4.34% | 4.15% | -40.28% | | -2.25% | -2.82% | 42.42% |
| Sig Dif? | NO | NO | YES | Sig Dif? | NO | NO | YES |
| | | | | | | | |
| NOTSP Bus Headway of 5 | | | | | | | |
| | N/S | E/W | Bus | | N/S | E/W | Bus |
| Delay | 9.03 | 21.86 | 2.82 | Speed | 15.27 | 8.35 | 14.01 |
| SD Delay | 0.67 | 1.29 | 0.28 | SD Speed | 0.68 | 0.33 | 0.96 |
| TSP Bus Headway of 5 | | | | | | | |
| | N/S | E/W | Bus | | N/S | E/W | Bus |
| Delay | 9.52 | 23.24 | 1.50 | Speed | 14.84 | 8.01 | 21.31 |
| SD Delay | 0.79 | 1.75 | 0.31 | SD Speed | 0.76 | 0.40 | 2.49 |
| Impact | | | | | | | |
| | 5.49% | 6.33% | -46.80% | | -2.84% | -4.02% | 52.15% |
| Sig Dif? | NO | NO | YES | Sig Dif? | NO | NO | YES |
| | | | | | | | |
| NO TSP Bus Headway of 3 | | | | | | | |
| | N/S | E/W | Bus | | N/S | E/W | Bus |
| Delay | 9.04 | 22.04 | 3.42 | Speed | 15.25 | 8.30 | 17.41 |
| SD Delay | 0.60 | 1.38 | 0.35 | SD Speed | 0.62 | 0.36 | 1.20 |
| TSP Bus Headway of 3 | | | | | | | |
| | N/S | E/W | Bus | | N/S | E/W | Bus |
| Delay | 9.36 | 23.39 | 4.15 | Speed | 15.02 | 7.99 | 15.27 |
| SD Delay | 0.64 | 1.91 | 0.34 | SD Speed | 0.62 | 0.44 | 0.84 |
| Impact | | | | | | | |
| | 3.54% | 6.10% | 21.30% | | -1.49% | -3.80% | -12.31% |
| Sig Dif? | NO | NO | YES | Sig Dif? | NO | NO | YES |

Delay= Seconds/Vehicle, Speed= Miles/Hour, Sig Dif= Significant Difference

Results for Model 2 Scenario 3 are provided in Table 3.12. Scenario 3 was successful in decreasing delay significantly for 5 and 7-minute headways without significantly increasing delay in the case of 3-minute headways. Also, even though E/W and N/S delays were increased none were significantly different from the base case.

**Table 3.12: Model 2 Scenario 3 Results**

| NOTSP Bus Headway of 7 | | | | | | | |
|---|---|---|---|---|---|---|---|
| | N/S | E/W | Bus | | N/S | E/W | Bus |
| Delay | 8.93 | 21.79 | 2.09 | Speed | 15.38 | 8.36 | 13.95 |
| SD Delay | 0.57 | 1.33 | 0.23 | SD Speed | 0.58 | 0.35 | 1.06 |
| TSP Bus Headway of 7 | | | | | | | |
| | N/S | E/W | Bus | | N/S | E/W | Bus |
| Delay | 9.43 | 22.78 | 1.15 | Speed | 14.90 | 8.13 | 21.10 |
| SD Delay | 0.68 | 1.50 | 0.29 | SD Speed | 0.67 | 0.36 | 3.02 |
| TSP Impact | | | | | | | |
| | 5.52% | 4.53% | -45.10% | | -3.07% | -2.75% | 51.23% |
| Sig Dif? | NO | NO | YES | Sig Dif? | NO | NO | YES |
| | | | | | | | |
| NOTSP Bus Headway of 5 | | | | | | | |
| | N/S | E/W | Bus | | N/S | E/W | Bus |
| Delay | 9.03 | 21.86 | 2.82 | Speed | 15.27 | 8.35 | 14.01 |
| SD Delay | 0.67 | 1.29 | 0.28 | SD Speed | 0.68 | 0.33 | 0.96 |
| TSP Bus Headway of 5 | | | | | | | |
| | N/S | E/W | Bus | | N/S | E/W | Bus |
| Delay | 9.55 | 22.80 | 1.68 | Speed | 14.79 | 8.12 | 20.01 |
| SD Delay | 0.77 | 2.00 | 0.39 | SD Speed | 0.71 | 0.47 | 2.87 |
| Impact | | | | | | | |
| | 5.73% | 4.32% | -40.20% | | -3.14% | -2.71% | 42.81% |
| Sig Dif? | NO | NO | YES | Sig Dif? | NO | NO | YES |
| | | | | | | | |
| NO TSP Bus Headway of 3 | | | | | | | |
| | N/S | E/W | Bus | | N/S | E/W | Bus |
| Delay | 9.04 | 22.04 | 3.42 | Speed | 15.25 | 8.30 | 17.41 |
| SD Delay | 0.60 | 1.38 | 0.35 | SD Speed | 0.62 | 0.36 | 1.20 |
| TSP Bus Headway of 3 | | | | | | | |
| | N/S | E/W | Bus | | N/S | E/W | Bus |
| Delay | 9.47 | 23.55 | 4.01 | Speed | 14.87 | 7.94 | 15.71 |
| SD Delay | 0.74 | 1.95 | 0.51 | SD Speed | 0.65 | 0.46 | 1.64 |
| Impact | | | | | | | |
| | 4.79% | 6.81% | 17.28% | | -2.44% | -4.39% | -9.74% |
| Sig Dif? | NO | NO | YES | Sig Dif? | NO | NO | YES |

Delay= Seconds/Vehicle, Speed= Miles/Hour, Sig Dif= Significant Difference

### 3.2.1 Max Green

At this point, it is safe to say that scenario 3 works best in both one-way corridors and two-way corridors. With the option to add green back, our model is now flexible in being used in bus headways ranging from 3 to 7 minutes. The next step to further investigate what is the ideal max green for GBG. In order to do that, simulation runs with max green time ranging from 0 to

20 seconds were further analyzed. Table 3.13 shows the summary of the average results for each of 25 runs.

**Table 3.13: Model 2 Max Green Analysis**

| Max Green | N/S Delay | E/W Delay | Bus Delay | | N/S Speed | E/W Speed | Bus Speed |
|---|---|---|---|---|---|---|---|
| **NO TSP** | 9.03 | 21.86 | 2.82 | | 15.27 | 8.35 | 14.01 |
| **20** | 9.65 | 22.95 | 1.57 | | 14.69 | 8.06 | 21.00 |
| **15** | 9.58 | 22.81 | 1.55 | | 14.74 | 8.11 | 21.05 |
| **10** | 9.62 | 23.07 | 1.55 | | 14.77 | 8.04 | 21.19 |
| **9** | 9.66 | 23.09 | 1.66 | | 14.73 | 8.03 | 20.11 |
| **8** | 9.63 | 23.45 | 1.67 | | 14.75 | 7.95 | 20.06 |
| **7** | 9.50 | 23.26 | 1.69 | | 14.87 | 8.01 | 19.96 |
| **6** | 9.25 | 22.97 | 1.61 | | 15.11 | 8.08 | 20.63 |
| **5** | 9.45 | 23.45 | 1.53 | | 14.91 | 7.97 | 21.46 |
| **4** | 9.31 | 23.23 | 1.51 | | 14.99 | 8.02 | 21.48 |
| **3** | 9.58 | 23.14 | 1.45 | | 14.72 | 8.01 | 22.43 |
| **2** | 9.10 | 23.28 | ***1.04*** | | 15.23 | 8.00 | 26.30 |
| **1** | 8.92 | 22.32 | ***1.05*** | | 15.41 | 8.23 | 25.71 |
| **0** | 8.49 | 22.90 | 1.40 | | 15.83 | 8.08 | 22.52 |

The results show that Cases 1 and 2 in the max green column of the table produced least bus delay. A one-factor ANOVA test was performed to see if any means significantly differed. The null hypothesis states that all means are equal with the alternative stating at least one mean is different than the others. The ANOVA results are shown in Table 3.14.

Table 3.14: Model 2 Max Green ALL ANOVA Results

| ALL Bus Delay ANOVA Results | | | | |
|---|---|---|---|---|
| *Groups* | *Count* | *Sum* | *Average* | *Variance* |
| 0 | 25 | 35.08 | 1.40 | 0.23 |
| 1 | 25 | 26.27 | 1.05 | 0.06 |
| 2 | 25 | 25.97 | 1.04 | 0.19 |
| 3 | 25 | 36.32 | 1.45 | 0.33 |
| 4 | 25 | 37.80 | 1.51 | 0.20 |
| 5 | 25 | 38.25 | 1.53 | 0.27 |
| 6 | 25 | 40.20 | 1.61 | 0.18 |
| 7 | 25 | 42.17 | 1.69 | 0.16 |
| 8 | 25 | 41.67 | 1.67 | 0.13 |
| 9 | 25 | 41.52 | 1.66 | 0.13 |
| 10 | 25 | 38.85 | 1.55 | 0.21 |
| 15 | 25 | 38.67 | 1.55 | 0.16 |
| 20 | 25 | 39.13 | 1.57 | 0.19 |
| ANOVA | | | | |
| *Source of Variation* | *SS* | *df* | *MS* | *F* |
| Between Groups | 13.32 | 12 | 1.11 | 5.89 |
| Within Groups | 58.80 | 312 | 0.19 | |
| | | | *P-value* | *F crit* |
| Total | 72.12 | 324 | 0.00 | 1.78 |
| ALL E/W Delay ANOVA Results | | | | |
| *Groups* | *Count* | *Sum* | *Average* | *Variance* |
| 0 | 25 | 582.31 | 23.29 | 3.40 |
| 1 | 25 | 560.32 | 22.41 | 1.22 |
| 2 | 25 | 595.93 | 23.84 | 2.51 |
| 3 | 25 | 589.27 | 23.57 | 2.20 |
| 4 | 25 | 592.19 | 23.69 | 2.30 |
| 5 | 25 | 602.49 | 24.10 | 3.72 |
| 6 | 25 | 585.78 | 23.43 | 2.42 |
| 7 | 25 | 595.29 | 23.81 | 4.18 |
| 8 | 25 | 602.46 | 24.10 | 3.64 |
| 9 | 25 | 601.74 | 24.07 | 2.70 |
| 10 | 25 | 591.72 | 23.67 | 3.88 |
| 15 | 25 | 575.50 | 23.02 | 1.42 |
| 20 | 25 | 580.60 | 23.22 | 2.41 |
| ANOVA | | | | |
| *Source of Variation* | *SS* | *df* | *MS* | *F* |
| Between Groups | 70.45 | 12 | 5.87 | 2.12 |
| Within Groups | 864.18 | 312 | 2.77 | |
| | | | *P-value* | *F crit* |
| Total | 934.64 | 324 | 0.02 | 1.78 |

We reject the null that says all means are equal and found evidence that at least one mean is different than others based on a low p-value. It is suspected that cases 1 and 2 are different, so those two values were taken out and ANOVA was performed again (Table 3.15) only to find that p-value is high now which means we fail to reject the null hypothesis that says all means are equal.

**Table 3.15: Model 2 Max Green partial ANOVA Results**

| Bus Delay ANOVA Results (without 1 and 2) | | | | |
|---|---|---|---|---|
| *Groups* | *Count* | *Sum* | *Average* | *Variance* |
| 0 | 25 | 35.08 | 1.40 | 0.23 |
| 3 | 25 | 36.32 | 1.45 | 0.33 |
| 4 | 25 | 37.80 | 1.51 | 0.20 |
| 5 | 25 | 38.25 | 1.53 | 0.27 |
| 6 | 25 | 40.20 | 1.61 | 0.18 |
| 7 | 25 | 42.17 | 1.69 | 0.16 |
| 8 | 25 | 41.67 | 1.67 | 0.13 |
| 9 | 25 | 41.52 | 1.66 | 0.13 |
| 10 | 25 | 38.85 | 1.55 | 0.21 |
| 15 | 25 | 38.67 | 1.55 | 0.16 |
| 20 | 25 | 39.13 | 1.57 | 0.19 |
| ANOVA | | | | |
| *Source of Variation* | *SS* | *df* | *MS* | *F* |
| Between Groups | 1.98 | 10 | 0.20 | 0.99 |
| Within Groups | 52.81 | 264 | 0.20 | |
| | | | *P-value* | *F crit* |
| Total | 54.79 | 274 | 0.45 | 1.87 |
| E/W Delay ANOVA Results (without 1 and 2) | | | | |
| *Groups* | *Count* | *Sum* | *Average* | *Variance* |
| 0 | 25 | 582.31 | 23.29 | 3.40 |
| 3 | 25 | 589.27 | 23.57 | 2.20 |
| 4 | 25 | 592.19 | 23.69 | 2.30 |
| 5 | 25 | 602.49 | 24.10 | 3.72 |
| 6 | 25 | 585.78 | 23.43 | 2.42 |
| 7 | 25 | 595.29 | 23.81 | 4.18 |
| 8 | 25 | 602.46 | 24.10 | 3.64 |
| 9 | 25 | 601.74 | 24.07 | 2.70 |
| 10 | 25 | 591.72 | 23.67 | 3.88 |
| 15 | 25 | 575.50 | 23.02 | 1.42 |
| 20 | 25 | 580.60 | 23.22 | 2.41 |
| ANOVA | | | | |
| *Source of Variation* | *SS* | *df* | *MS* | *F* |
| Between Groups | 34.12 | 10 | 3.41 | 1.16 |
| Within Groups | 774.53 | 264 | 2.93 | |
| | | | *P-value* | *F crit* |
| Total | 808.65 | 274 | 0.32 | 1.87 |

To further investigate the values for Cases 1 and 2, and to decide which value is better, we ran a two-way independent t test (post-hoc) to determine if the two are different (See Table 3.16).

**Table 3.16: Model 2 Max Green 1 and 2 comparisons**

| Bus Delay Two-sample Independent T test | | |
|---|---|---|
| | *1* | *2* |
| Mean | 1.05 | 1.04 |
| Variance | 0.06 | 0.19 |
| Observations | 25 | 25 |
| Hypothesized Mean Difference | | 0 |
| df | 37 | |
| t Stat | 0.12 | |
| P(T<=t) one-tail | 0.45 | |
| t Critical one-tail | 1.69 | |
| P(T<=t) two-tail | 0.90 | |
| t Critical two-tail | 2.03 | |
| E/W Delay Two-sample Independent T test | | |
| | *1* | *2* |
| Mean | 22.41 | 23.84 |
| Variance | 1.22 | 2.51 |
| Observations | 25 | 25 |
| Hypothesized Mean Difference | | 0 |
| df | 43 | |
| t Stat | -3.68 | |
| P(T<=t) one-tail | 0.00 | |
| t Critical one-tail | 1.68 | |
| P(T<=t) two-tail | 0.00 | |
| t Critical two-tail | 2.02 | |

Results show that Cases 1 and 2 do not differ in bus delay. However, in E/W delay (cross street delay) they do significantly differ and giving back green time of 1 second causes less delay in E/W and causes minimum bus delay as well.

### 3.2.2 Non-Moving Vehicles

The other assumption to be inspected is the number of non-moving vehicles that is the threshold for activating “Worth Starting?”. In the previous runs, 2 non-moving vehicles was used as a safe assumption. Runs with number of non-moving vehicles ranging from 0 to 10 were recorded and Table 3.17 shows the average results for the runs.

**Table 3.17: Model 2 Non-Moving Vehicles Analysis**

| Non-moving cars | Delays | | | | Speed | | |
|---|---|---|---|---|---|---|---|
| | N/S | E/W | Bus | | N/S | E/W | Bus |
| **10** | 9.09 | 23.70 | 0.96 | | 15.22 | 7.90 | 26.72 |
| **5** | 9.30 | 24.14 | 0.94 | | 15.03 | 7.79 | 27.21 |
| **4** | 9.25 | 23.50 | 0.99 | | 15.06 | 7.94 | 26.60 |
| **3** | 9.11 | 23.38 | 0.95 | | 15.20 | 7.98 | 27.13 |
| **2** | 9.16 | 23.22 | 1.11 | | 15.16 | 8.01 | 25.15 |
| **1** | 9.10 | 22.96 | 1.08 | | 15.21 | 8.08 | 25.45 |
| **0** | 9.17 | 23.01 | 1.26 | | 15.17 | 8.04 | 23.65 |

Results show the more non-moving vehicles we have as a condition the less bus delay we will get. ANOVA results () show that the p-value is low, rejecting the null hypothesis and finding evidence that at least one mean is different than the others. Looking at the average bus delays, we suspect that zero might be the one different mean, since it is 1.26 compared to all others ranging from 1.11 to 0.96. Running ANOVA again without zero, we get a p-value of 0.09 which is higher than alpha level of 0.05, failing to reject the null and concluding that there is no evidence that at least one mean is significantly different than the others. Finding that zero is the only condition were delays will be higher than other conditions. ANOVA results for E/W were run and no significant difference was found for any variables.

**Table 3.18: Model 2 Non-Moving Vehicles ANOVA Results**

| ALL Bus Delay ANOVA Results | | | | |
|---|---|---|---|---|
| *Groups* | *Count* | *Sum* | *Average* | *Variance* |
| 10 | 25 | 23.97 | 0.96 | 0.03 |
| 5 | 25 | 23.40 | 0.94 | 0.06 |
| 4 | 25 | 24.68 | 0.99 | 0.08 |
| 3 | 25 | 23.70 | 0.95 | 0.08 |
| 2 | 25 | 27.75 | 1.11 | 0.10 |
| 1 | 25 | 27.05 | 1.08 | 0.09 |
| 0 | 25 | 31.55 | 1.26 | 0.13 |
| ANOVA | | | | |
| *Source of Variation* | *SS* | *df* | *MS* | *F* |
| Between Groups | 2.11 | 6 | 0.35 | 4.44 |
| Within Groups | 13.33 | 168 | 0.08 | |
| | | | *P-value* | *F crit* |
| Total | 15.44 | 174 | 0.00 | 2.15 |

| Bus Delay ANOVA Results (without 0) | | | | |
|---|---|---|---|---|
| *Groups* | *Count* | *Sum* | *Average* | *Variance* |
| 10 | 25 | 23.97 | 0.96 | 0.03 |
| 5 | 25 | 23.40 | 0.94 | 0.06 |
| 4 | 25 | 24.68 | 0.99 | 0.08 |
| 3 | 25 | 23.70 | 0.95 | 0.08 |
| 2 | 25 | 27.75 | 1.11 | 0.10 |
| 1 | 25 | 27.05 | 1.08 | 0.09 |
| ANOVA | | | | |
| *Source of Variation* | *SS* | *df* | *MS* | *F* |
| Between Groups | 0.69 | 5 | 0.14 | 1.92 |
| Within Groups | 10.30 | 144 | 0.07 | |
| | | | *P-value* | *F crit* |
| Total | 10.99 | 149 | 0.10 | 2.28 |

In summary, Model 2 Scenario 3 successfully lowered delay values for 5 and 7-minute headways without significant affects to E/W and N/S traffic. Scenario 3 did not negatively affect bus delays for 3-minute headway conditions as seen in Scenario 1 and Scenario 2. If maximum green to be given back to cross-streets is 1 second, that value still has a significant effect on lowering bus delay in comparison to other conditions. Any number, other than zero, for the non-moving vehicles conditions will lower bus delays and will not affect cross street delays (E/W).

### 3.2.3 Cross-Street Volume Analysis

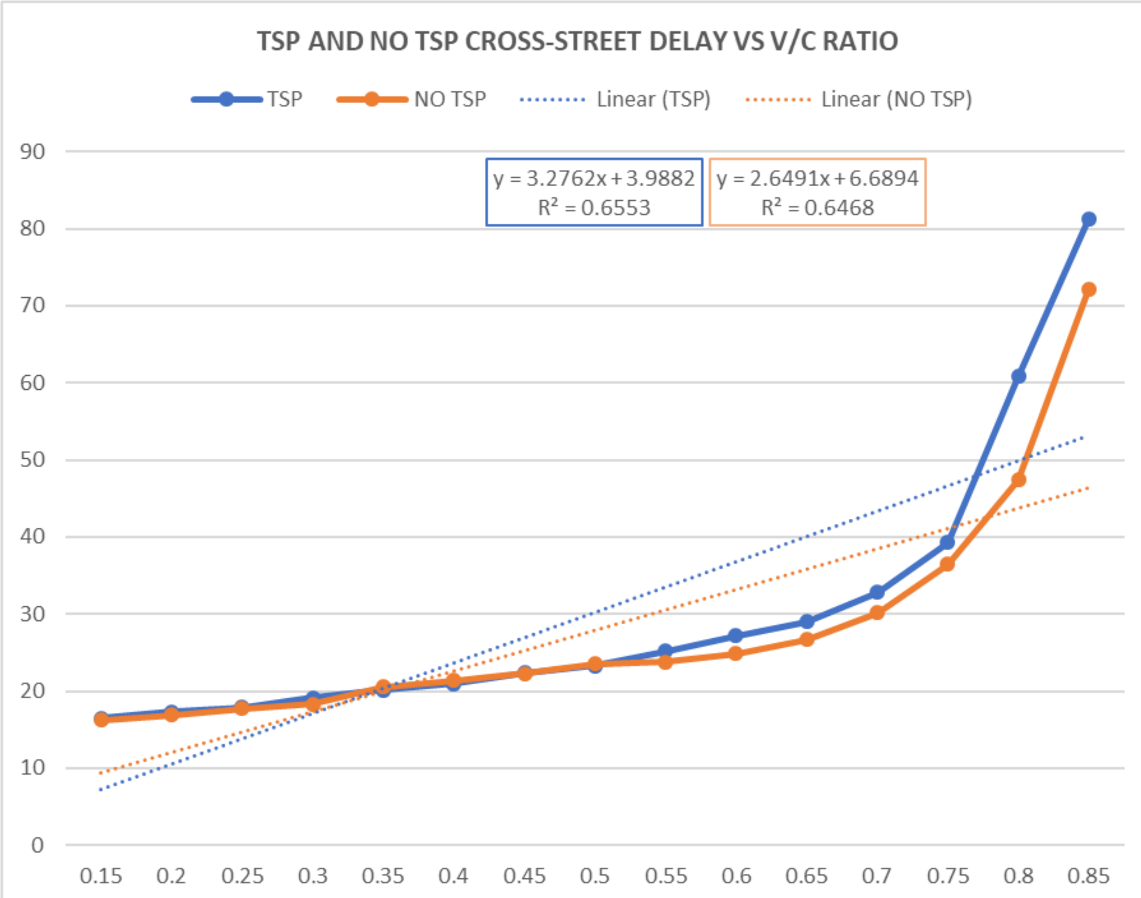
Now we established a TSP that is successful in decreasing bus delay and flexible with different bus headways and works with One-way and Two-way streets. The next step is to analyze the effect of cross-street traffic on the TSP quality. Runs for 5 minute bus headways with a corridor volume to capacity ratio (V/C ratio) of 0.43 with cross-street V/C ranging from 0.15 to 0.85 were recorded. Table 3.19 shows the averages for these runs.

**Table 3.19: Cross-Street V/C Analysis**

| TSP | | NO TSP | | V/C Ratio | Flow |
|---|---|---|---|---|---|
| Cross-Street Delay | Bus Delay | Cross-Street Delay | Bus Delay | | |
| 16.47 | 1.04 | 16.23 | 2.74 | 0.15 | 158.33 |
| 17.32 | 1.01 | 16.92 | 2.80 | 0.20 | 211.11 |
| 17.88 | 1.08 | 17.68 | 2.75 | 0.25 | 263.89 |
| 19.10 | 1.02 | 18.33 | 2.80 | 0.30 | 316.67 |
| 20.14 | 1.02 | 20.58 | 2.76 | 0.35 | 369.45 |
| 20.99 | 1.08 | 21.34 | 2.75 | 0.40 | 422.22 |
| 22.40 | 1.03 | 22.25 | 2.75 | 0.45 | 475.00 |
| 23.28 | 1.09 | 23.51 | 2.82 | 0.50 | 527.78 |
| 25.18 | 1.07 | 23.81 | 2.71 | 0.55 | 580.56 |
| 27.16 | 1.06 | 24.81 | 2.71 | 0.60 | 633.34 |
| 29.01 | 1.09 | 26.70 | 2.78 | 0.65 | 686.11 |
| 32.78 | 1.32 | 30.14 | 2.70 | 0.70 | 738.89 |
| 39.24 | 1.22 | 36.49 | 2.81 | 0.75 | 791.67 |
| 60.81 | 1.47 | 47.36 | 2.85 | 0.80 | 844.45 |
| 81.20 | 1.55 | 72.09 | 2.86 | 0.85 | 897.23 |

Cross-street delay values are similar for V/C less than 0.55, however once the V/C exceeds 0.55 those values begin to differ with TSP having higher values. Further analysis of the means and standard deviations of the samples V/C 0.50 to 0.65 showed that a V/C ratio starting at 0.63 would cause significantly more delays for TSP in comparison to No TSP. Figure 3.6 shows the plot of TSP and NO TSP cross-street delay versus V/C ratio. TSP has a slightly higher R-squared value. For each one unit increase in V/C for TSP there will be a 3.27 seconds increase in delay in comparison to only a 2.49 increase for No TSP, meaning that TSP cross-street delay gets larger faster than No TSP with larger V/C ratios.

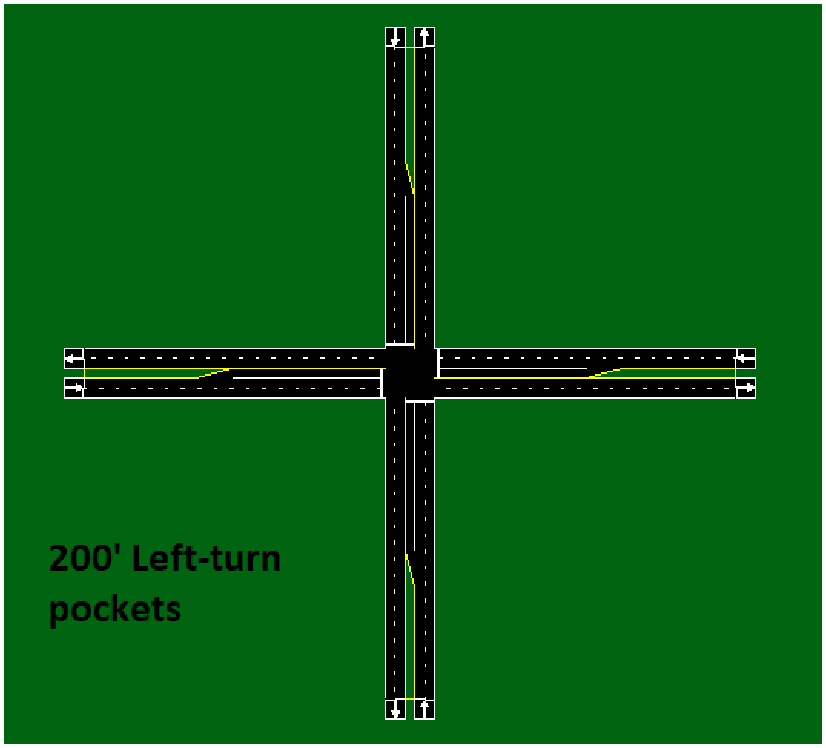
**Figure 3.6: Cross-street delay analysis**




## 3.3 Model 3: Left-Turn Pockets for Two-way Corridor Single Intersection

This model is the same as Model 2 with the addition of 200 feet left turn pockets on all directions of travel to test that effect on TSP quality. Figure 3.7 shows a CORSIM screenshot of the model.

**Figure 3.7: Model 3 CORSIM configuration**




No changes were made on the code or the assumptions from Model 2, the simple purpose of this model is to test the effect of left-turn pockets on the three TSP scenarios.

The results in Table 3.20 show that no significant changes were found including the Scenario 1 effect for no left-turn pockets that had significant negative effects for buses with 3-minute headways. This explains the confusion that was found when trying to analyze the results. Having left-turn pockets will move left-turn queues outside of the bus path traveling north. These results show that left-turn pockets can be an important part of TSP quality. To make sure that left turn pockets not only impact Scenario 1 with 3-minute bus headways, Scenario 2 (Table 3.21) and Scenario 3 (Table 3.22), experiments were performed to see if left turn pockets would also have a positive effect on bus delays without damaging cross-street traffic.

**Table 3.20: Left-Turn Pocket Scenario 1 Results**

| NOTSP Bus Headway of 7 | | | | | | | |
|---|---|---|---|---|---|---|---|
| | N/S | E/W | Bus | | N/S | E/W | Bus |
| Delay | 7.70 | 20.01 | 1.61 | Speed | 17.70 | 8.90 | 16.63 |
| SD Delay | 0.42 | 1.09 | 0.22 | SD Speed | 0.49 | 0.33 | 1.13 |
| TSP Bus Headway of 7 | | | | | | | |
| | N/S | E/W | Bus | | N/S | E/W | Bus |
| Delay | 7.58 | 20.26 | 1.74 | Speed | 17.81 | 8.83 | 15.99 |
| SD Delay | 0.45 | 1.26 | 0.15 | SD Speed | 0.57 | 0.36 | 0.86 |
| TSP Impact | | | | | | | |
| | -1.49% | 1.28% | 7.80% | | 0.64% | -0.81% | -3.81% |
| Sig Dif? | NO | NO | NO | Sig Dif? | NO | NO | NO |
| | | | | | | | |
| NOTSP Bus Headway of 5 | | | | | | | |
| | N/S | E/W | Bus | | N/S | E/W | Bus |
| Delay | 7.67 | 20.11 | 2.34 | Speed | 17.65 | 8.86 | 15.92 |
| SD Delay | 0.40 | 1.10 | 0.12 | SD Speed | 0.49 | 0.32 | 0.57 |
| TSP Bus Headway of 5 | | | | | | | |
| | N/S | E/W | Bus | | N/S | E/W | Bus |
| Delay | 7.68 | 20.34 | 2.39 | Speed | 17.63 | 8.78 | 15.71 |
| SD Delay | 0.39 | 1.17 | 0.25 | SD Speed | 0.51 | 0.35 | 1.14 |
| Impact | | | | | | | |
| | 0.12% | 1.17% | 2.51% | | -0.12% | -0.89% | -1.31% |
| Sig Dif? | NO | NO | NO | Sig Dif? | NO | NO | NO |
| | | | | | | | |
| NO TSP Bus Headway of 3 | | | | | | | |
| | N/S | E/W | Bus | | N/S | E/W | Bus |
| Delay | 7.54 | 20.12 | 2.20 | Speed | 17.79 | 8.89 | 22.61 |
| SD Delay | 0.53 | 1.21 | 0.18 | SD Speed | 0.61 | 0.35 | 1.01 |
| TSP Bus Headway of 3 | | | | | | | |
| | N/S | E/W | Bus | | N/S | E/W | Bus |
| Delay | 7.72 | 20.05 | 2.71 | Speed | 17.59 | 8.87 | 20.98 |
| SD Delay | 0.54 | 1.21 | 1.11 | SD Speed | 0.65 | 0.37 | 4.11 |
| Impact | | | | | | | |
| | 2.37% | -0.36% | 23.13% | | -1.13% | -0.17% | -7.21% |
| Sig Dif? | NO | NO | NO | Sig Dif? | NO | NO | NO |

Delay= Seconds/Vehicle, Speed= Miles/Hour, Sig Dif= Significant Difference

**Table 3.21: Left-Turn Pocket Scenario 2 Results**

| NOTSP Bus Headway of 7 | | | | | | | |
|---|---|---|---|---|---|---|---|
| | N/S | E/W | Bus | | N/S | E/W | Bus |
| Delay | 7.70 | 20.01 | 1.61 | Speed | 17.70 | 8.90 | 16.63 |
| SD Delay | 0.42 | 1.09 | 0.22 | SD Speed | 0.49 | 0.33 | 1.13 |
| TSP Bus Headway of 7 | | | | | | | |
| | N/S | E/W | Bus | | N/S | E/W | Bus |
| Delay | 7.75 | 20.66 | 0.93 | Speed | 17.62 | 8.70 | 23.95 |
| SD Delay | 0.40 | 1.06 | 0.35 | SD Speed | 0.48 | 0.31 | 4.21 |
| TSP Impact | | | | | | | |
| | 0.71% | 3.27% | -41.97% | | -0.42% | -2.22% | 44.04% |
| Sig Dif? | NO | NO | YES | Sig Dif? | NO | NO | YES |
| | | | | | | | |
| NOTSP Bus Headway of 5 | | | | | | | |
| | N/S | E/W | Bus | | N/S | E/W | Bus |
| Delay | 7.67 | 20.11 | 2.34 | Speed | 17.65 | 8.86 | 15.92 |
| SD Delay | 0.40 | 1.10 | 0.12 | SD Speed | 0.49 | 0.32 | 0.57 |
| TSP Bus Headway of 5 | | | | | | | |
| | N/S | E/W | Bus | | N/S | E/W | Bus |
| Delay | 8.12 | 20.95 | 1.33 | Speed | 17.18 | 8.62 | 23.22 |
| SD Delay | 0.52 | 1.48 | 0.45 | SD Speed | 0.63 | 0.40 | 4.01 |
| Impact | | | | | | | |
| | 5.89% | 4.21% | -43.25% | | -2.69% | -2.65% | 45.92% |
| Sig Dif? | NO | NO | YES | Sig Dif? | NO | NO | YES |
| | | | | | | | |
| NO TSP Bus Headway of 3 | | | | | | | |
| | N/S | E/W | Bus | | N/S | E/W | Bus |
| Delay | 7.54 | 20.12 | 2.20 | Speed | 17.79 | 8.89 | 22.61 |
| SD Delay | 0.53 | 1.21 | 0.18 | SD Speed | 0.61 | 0.35 | 1.01 |
| TSP Bus Headway of 3 | | | | | | | |
| | N/S | E/W | Bus | | N/S | E/W | Bus |
| Delay | 7.78 | 20.35 | 2.64 | Speed | 17.56 | 8.81 | 20.72 |
| SD Delay | 0.59 | 1.37 | 0.59 | SD Speed | 0.73 | 0.39 | 2.76 |
| Impact | | | | | | | |
| | 3.26% | 1.13% | 19.67% | | -1.30% | -0.91% | -8.34% |
| Sig Dif? | NO | NO | NO | Sig Dif? | NO | NO | NO |

Delay= Seconds/Vehicle, Speed= Miles/Hour, Sig Dif= Significant Difference

As expected, Scenario 2 with left turn pockets is successful in decreasing bus delay, without affecting cross-street traffic.

**Table 3.22: Left-Turn Pocket Scenario 3 Results**

| NOTSP Bus Headway of 7 | | | | | | | |
|---|---|---|---|---|---|---|---|
| | N/S | E/W | Bus | | N/S | E/W | Bus |
| Delay | 7.70 | 20.01 | 1.61 | Speed | 17.70 | 8.90 | 16.63 |
| SD Delay | 0.42 | 1.09 | 0.22 | SD Speed | 0.49 | 0.33 | 1.13 |
| TSP Bus Headway of 7 | | | | | | | |
| | N/S | E/W | Bus | | N/S | E/W | Bus |
| Delay | 7.73 | 20.89 | 0.53 | Speed | 17.61 | 8.65 | 30.61 |
| SD Delay | 0.42 | 1.55 | 0.15 | SD Speed | 0.53 | 0.43 | 3.23 |
| TSP Impact | | | | | | | |
| | 0.46% | 4.40% | -67.14% | | -0.52% | -2.76% | 84.11% |
| Sig Dif? | NO | NO | YES | Sig Dif? | NO | NO | YES |
| | | | | | | | |
| NOTSP Bus Headway of 5 | | | | | | | |
| | N/S | E/W | Bus | | N/S | E/W | Bus |
| Delay | 7.67 | 20.11 | 2.34 | Speed | 17.65 | 8.86 | 15.92 |
| SD Delay | 0.40 | 1.10 | 0.12 | SD Speed | 0.49 | 0.32 | 0.57 |
| TSP Bus Headway of 5 | | | | | | | |
| | N/S | E/W | Bus | | N/S | E/W | Bus |
| Delay | 7.64 | 20.52 | 0.64 | Speed | 17.72 | 8.74 | 31.53 |
| SD Delay | 0.54 | 1.10 | 0.12 | SD Speed | 0.64 | 0.30 | 2.22 |
| Impact | | | | | | | |
| | -0.37% | 2.08% | -72.48% | | 0.36% | -1.33% | 98.08% |
| Sig Dif? | NO | NO | YES | Sig Dif? | NO | NO | YES |
| | | | | | | | |
| NO TSP Bus Headway of 3 | | | | | | | |
| | N/S | E/W | Bus | | N/S | E/W | Bus |
| Delay | 7.54 | 20.12 | 2.20 | Speed | 17.79 | 8.89 | 22.61 |
| SD Delay | 0.53 | 1.21 | 0.18 | SD Speed | 0.61 | 0.35 | 1.01 |
| TSP Bus Headway of 3 | | | | | | | |
| | N/S | E/W | Bus | | N/S | E/W | Bus |
| Delay | 7.53 | 20.30 | 2.74 | Speed | 17.85 | 8.82 | 20.57 |
| SD Delay | 0.40 | 1.24 | 0.87 | SD Speed | 0.53 | 0.36 | 3.67 |
| Impact | | | | | | | |
| | -0.13% | 0.88% | 24.52% | | 0.33% | -0.73% | -9.03% |
| Sig Dif? | NO | NO | NO | Sig Dif? | NO | NO | NO |
| Delay= Seconds/Vehicle, Speed= Miles/Hour, Sig Dif= Significant Difference | | | | | | | |

The bus delay value of 0.53 seconds is by far the smallest value in all scenarios. Comparing this value to the model 2 Scenario 3 results the minimum value of 1.15 with 0.29 standard deviation shows that TSP with no left turn interference is significantly better than left turn interference with no TSP and it is also significantly better than no left turn with TSP. Meaning that providing left turn pockets for left turn traffic significantly improves TSP overall effectiveness.

## 3.4 Model 4: Bus Lane Effect

The next variable to test is the effect of adding a bus lane. Most previous studies concluded that a bus lane would benefit buses and would not severely affect traffic in general, since buses are no longer sharing lanes with vehicles and vice versa. The biggest difference in this case is that buses are not going to have to wait for queues to clear when they request green time. In theory, some vehicles rely on buses to request green time and pass with the bus if they are lucky, otherwise they might be stuck in a red light situation. Testing this variable would show us what relationship exists, if any, between traffic and buses in situations when they do not share a lane. To approach this variable, we need to test adding a bus lane to the existing, slightly modified, three scenarios we tested before: 1) One-way traffic, 2) Two-way traffic and 3) Left-turn pockets. From this analysis forward, we will only test 5-minute headways as the best representations of average bus headways and also due to the fact that buses with a headway of 3 or 7 minutes are not as common in real life. The same assumptions in those previous models are kept and the only difference is adding an additional lane to each, so the total number of lanes is going to be 4 lanes for the One-way model, while the other two models have 3 lanes. This additional lane will be used in three ways to generate three scenarios: 1) Unrestricted lane, to test how traffic flows and record a base case for no bus lane and no TSP. 2) Bus only lane, capturing the effect of traffic losing one lane and buses being able to have a dedicated lane. 3) Bus only lane with TSP, here the effect of both TSP and bus only will be best observed. Table 3.23 shows the assumptions that were made in this model.

**Table 3.23: Model 4 Simulation Assumptions**

| One-way Traffic | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| Direction | Lanes | Turning | | | Green time | Cycle length | G/C ratio | Capacity per hour | Volume | V/C |
| | | Left | Thru | Right | | | | | | |
| NB | 4 | 15 | 70 | 15 | 55 | 90 | 0.61 | 4644 | 2000 | 0.431 |
| EB | 2 | 70 | 30 | 0 | 25 | | 0.28 | 1056 | 500 | 0.474 |
| WB | 2 | 0 | 30 | 70 | | | | | 500 | 0.474 |
| **Two-way Traffic** | | | | | | | | | | |
| Direction | Lanes | Turning | | | Green time | Cycle length | G/C ratio | Capacity per hour | Volume | V/C |
| | | Left | Thru | Right | | | | | | |
| NB | 3 | 15 | 70 | 15 | 55 | 90 | 0.61 | 3483 | 1500 | 0.431 |
| SB | 2 | 15 | 70 | 15 | | | | 2322 | 1000 | 0.431 |
| EB | 2 | 40 | 20 | 40 | 25 | | 0.28 | 1056 | 500 | 0.474 |
| WB | 2 | 40 | 20 | 40 | | | | | 500 | 0.474 |

The following the three different cases comprise the bus lane tests:

3.4.1 One-way traffic single intersection

Table 3.24 summarizes results of the three different cases in a one-way traffic simulation which was built on a one-way 4 lane corridor intersecting with a two-way 2 lane cross street.

**Table 3.24: Scenario 1 One-way traffic Bus Lane Effect**

| 1- NOTSP & No Bus Lane | | | | | | | |
|---|---|---|---|---|---|---|---|
| | N/S | E/W | Bus | | N/S | E/W | Bus |
| Delay | 6.49 | 28.06 | 2.28 | Speed | 18.79 | 7.77 | 16.15 |
| SD Delay | 0.24 | 12.94 | 0.09 | SD Speed | 0.33 | 2.55 | 0.43 |
| 2- Bus Lane Only | | | | | | | |
| | N/S | E/W | Bus | | N/S | E/W | Bus |
| Delay | 6.45 | 27.88 | 2.20 | Speed | 18.94 | 7.97 | 16.60 |
| SD Delay | 0.28 | 13.92 | 0.17 | SD Speed | 0.44 | 2.84 | 0.90 |
| 3- TSP & Bus Lane | | | | | | | |
| | N/S | E/W | Bus | | N/S | E/W | Bus |
| Delay | 6.57 | 28.45 | 2.37 | Speed | 18.84 | 7.86 | 15.82 |
| SD Delay | 0.25 | 14.44 | 0.26 | SD Speed | 0.32 | 2.75 | 1.15 |
| 1 VS 2 Impact | | | | | | | |
| | -0.57% | -0.66% | -3.76% | | 0.84% | 2.52% | 2.82% |
| Sig Dif? | NO | NO | NO | Sig Dif? | NO | NO | NO |
| 1 VS 3 Impact | | | | | | | |
| | 1.16% | 1.39% | 3.67% | | 0.31% | 1.06% | -1.99% |
| Sig Dif? | NO | NO | NO | Sig Dif? | NO | NO | NO |
| 2 VS 3 Impact | | | | | | | |
| | 1.74% | 2.06% | 7.73% | | -0.53% | -1.42% | -4.68% |
| Sig Dif? | NO | NO | NO | Sig Dif? | NO | NO | NO |
| Delay= Seconds/Vehicle, Speed= Miles/Hour, Sig Dif= Significant Difference | | | | | | | |

The first box, (1-NOTSP & No Bus Lane) summarizes the simulation results for a base case model with no TSP and no bus lane. The next box (2-Bus Lane Only) describes results for changing the 4th lane to a bus only lane. The last box (3-TSP & Bus Lane) contains simulation results with a bus lane and the first scenario of TSP. The first scenario only extends green time when possible. In summary:

- Base case without TSP or a bus lane
- Bus lane in the right lane (which is also used for right turning vehicles)
- Bus lane and activating TSP

Comparing all results, 1 versus 2, 1 versus 3 and 2 versus 3 shows that in the case of one-way travel, neither adding a bus lane nor activating TSP with a bus lane provides any significant improvement to the intersection travel time. The next step is to test scenario 2, which extends green and truncates red. Table 3.25 summarizes the simulation results.

**Table 3.25: Scenario 2 One-way Traffic Bus Lane Effect**

| 1- NOTSP & No Bus Lane | | | | | | | |
|---|---|---|---|---|---|---|---|
| | N/S | E/W | Bus | | N/S | E/W | Bus |
| Delay | 6.49 | 28.06 | 2.28 | Speed | 18.79 | 7.77 | 16.15 |
| SD Delay | 0.24 | 12.94 | 0.09 | SD Speed | 0.33 | 2.55 | 0.43 |
| 2- Bus Lane Only | | | | | | | |
| | N/S | E/W | Bus | | N/S | E/W | Bus |
| Delay | 6.45 | 27.88 | 2.20 | Speed | 18.94 | 7.97 | 16.60 |
| SD Delay | 0.28 | 13.92 | 0.17 | SD Speed | 0.44 | 2.84 | 0.90 |
| 3- TSP & Bus Lane | | | | | | | |
| | N/S | E/W | Bus | | N/S | E/W | Bus |
| Delay | 6.29 | 30.41 | 1.20 | Speed | 19.25 | 7.56 | 24.36 |
| SD Delay | 0.28 | 15.74 | 0.36 | SD Speed | 0.46 | 2.82 | 3.96 |
| 1 VS 3 Impact | | | | | | | |
| | -3.14% | 8.36% | -47.51% | | 2.48% | -2.67% | 50.84% |
| Sig Dif? | NO | NO | YES | Sig Dif? | NO | NO | YES |
| 2 VS 3 Impact | | | | | | | |
| | -2.59% | 9.08% | -45.45% | | 1.62% | -5.06% | 46.71% |
| Sig Dif? | NO | NO | YES | Sig Dif? | NO | NO | YES |

Delay= Seconds/Vehicle, Speed= Miles/Hour, Sig Dif= Significant Difference

Results here show that TSP significantly affects bus delays and speed. In both cases, no bus lane and also with a bus lane, TSP was successful in improving bus delays and speed. The last step in the one-way case is testing Scenario 3, which checks if it is worth starting and also gives back green time. Table 3.26 shows scenario 3 simulation results.

**Table 3.26: Scenario 3 One-way Traffic Bus Lane Effect**

| 1- NOTSP & No Bus Lane | | | | | | | |
|---|---|---|---|---|---|---|---|
| | N/S | E/W | Bus | | N/S | E/W | Bus |
| Delay | 6.49 | 28.06 | 2.28 | Speed | 18.79 | 7.77 | 16.15 |
| SD Delay | 0.24 | 12.94 | 0.09 | SD Speed | 0.33 | 2.55 | 0.43 |
| 2- Bus Lane Only | | | | | | | |
| | N/S | E/W | Bus | | N/S | E/W | Bus |
| Delay | 6.45 | 27.88 | 2.20 | Speed | 18.94 | 7.97 | 16.60 |
| SD Delay | 0.28 | 13.92 | 0.17 | SD Speed | 0.44 | 2.84 | 0.90 |
| 3- TSP & Bus Lane | | | | | | | |
| | N/S | E/W | Bus | | N/S | E/W | Bus |
| Delay | 6.19 | 33.09 | 0.82 | Speed | 19.45 | 7.16 | 29.26 |
| SD Delay | 0.26 | 17.35 | 0.33 | SD Speed | 0.44 | 2.76 | 4.60 |
| 1 VS 3 Impact | | | | | | | |
| | -4.63% | 17.91% | -64.25% | | 3.54% | -7.91% | 81.24% |
| Sig Dif? | NO | NO | YES | Sig Dif? | NO | NO | YES |
| 2 VS 3 Impact | | | | | | | |
| | -4.09% | 18.69% | -62.85% | | 2.68% | -10.17% | 76.27% |
| Sig Dif? | NO | NO | YES | Sig Dif? | NO | NO | YES |

Delay= Seconds/Vehicle, Speed= Miles/Hour, Sig Dif= Significant Difference

Again, scenario 3 is the best scenario with significant improvement around 62-64% in comparison to scenario 2 which had improvements of 45-47% for bus delays.

### 3.4.2 Two-way traffic single intersection

In this step, a two-way traffic scenario is tested. The same conditions as the previous case were applied with the additional lane being used in 2 different ways and TSP is applied in the last case. Starting with scenario 1, results are shown in Table 3.27 below.

**Table 3.27: Scenario 1 Two-way Traffic Bus Lane Effect**

| 1- NOTSP & No Bus Lane | | | | | | | |
|---|---|---|---|---|---|---|---|
| | N/S | E/W | Bus | | N/S | E/W | Bus |
| Delay | 11.42 | 21.47 | 2.61 | Speed | 13.50 | 8.45 | 14.79 |
| SD Delay | 2.24 | 1.09 | 0.22 | SD Speed | 1.72 | 0.29 | 0.87 |
| 2- Bus Lane Only | | | | | | | |
| | N/S | E/W | Bus | | N/S | E/W | Bus |
| Delay | 13.23 | 21.79 | 2.29 | Speed | 12.48 | 8.38 | 16.14 |
| SD Delay | 3.82 | 1.47 | 0.19 | SD Speed | 2.18 | 0.38 | 0.89 |
| 3- TSP & Bus Lane | | | | | | | |
| | N/S | E/W | Bus | | N/S | E/W | Bus |
| Delay | 13.50 | 21.58 | 2.39 | Speed | 12.33 | 8.45 | 15.69 |
| SD Delay | 3.75 | 1.44 | 0.19 | SD Speed | 2.23 | 0.37 | 0.87 |
| 1 VS 2 Impact | | | | | | | |
| | 15.88% | 1.49% | -11.98% | | -7.51% | -0.81% | 9.16% |
| Sig Dif? | NO | NO | NO | Sig Dif? | NO | NO | NO |
| 1 VS 3 Impact | | | | | | | |
| | 18.21% | 0.54% | -8.26% | | -8.68% | -0.02% | 6.13% |
| Sig Dif? | NO | NO | NO | Sig Dif? | NO | NO | NO |
| 2 VS 3 Impact | | | | | | | |
| | 2.02% | -0.93% | 4.22% | | -1.27% | 0.80% | -2.78% |
| Sig Dif? | NO | NO | NO | Sig Dif? | NO | NO | NO |

Delay= Seconds/Vehicle, Speed= Miles/Hour, Sig Dif= Significant Difference

Adding a bus lane here improved bus delays up to 12%, this improvement however, is not statistically significant. Here it can also be noted that scenario 1 slightly increased delays, which was also observed in Model 2 when scenario 1 was used in two-way traffic. The next step is testing scenario 2 and scenario 3. Table 3.28 combines both scenario results.

**Table 3.28: Scenario 2 & Scenario 3 Two-way Traffic Bus Lane Effect**

| 1- NOTSP & No Bus Lane | | | | | | | |
|---|---|---|---|---|---|---|---|
| | N/S | E/W | Bus | | N/S | E/W | Bus |
| Delay | 11.42 | 21.47 | 2.61 | Speed | 13.50 | 8.45 | 14.79 |
| SD Delay | 2.24 | 1.09 | 0.22 | SD Speed | 1.72 | 0.29 | 0.87 |
| 2- Bus Lane Only | | | | | | | |
| | N/S | E/W | Bus | | N/S | E/W | Bus |
| Delay | 13.23 | 21.79 | 2.29 | Speed | 12.48 | 8.38 | 16.14 |
| SD Delay | 3.82 | 1.47 | 0.19 | SD Speed | 2.18 | 0.38 | 0.89 |
| Scenario#2: TSP & Bus Lane | | | | | | | |
| | N/S | E/W | Bus | | N/S | E/W | Bus |
| Delay | 13.71 | 23.01 | 1.14 | Speed | 12.16 | 8.08 | 24.93 |
| SD Delay | 3.53 | 1.66 | 0.35 | SD Speed | 2.07 | 0.41 | 3.55 |
| Scenario#2: 1 VS 3 Impact | | | | | | | |
| | 20.05% | 7.19% | -56.27% | | -9.88% | -4.37% | 68.61% |
| Sig Dif? | NO | NO | YES | Sig Dif? | NO | NO | YES |
| Scenario#2: 2 VS 3 Impact | | | | | | | |
| | 3.60% | 5.62% | -50.32% | | -2.56% | -3.58% | 54.46% |
| Sig Dif? | NO | NO | YES | Sig Dif? | NO | NO | YES |
| Scenario#3: TSP & Bus Lane | | | | | | | |
| | N/S | E/W | Bus | | N/S | E/W | Bus |
| Delay | 13.41 | 22.35 | 0.68 | Speed | 12.35 | 8.23 | 31.07 |
| SD Delay | 3.77 | 1.37 | 0.19 | SD Speed | 2.14 | 0.36 | 3.26 |
| Scenario#3: 1 VS 3 Impact | | | | | | | |
| | 17.47% | 4.12% | -73.95% | | -8.50% | -2.56% | 110.16% |
| Sig Dif? | NO | NO | YES | Sig Dif? | NO | NO | YES |
| Scenario#3: 2 VS 3 Impact | | | | | | | |
| | 1.37% | 2.59% | -70.40% | | -1.07% | -1.76% | 92.52% |
| Sig Dif? | NO | NO | YES | Sig Dif? | NO | NO | YES |
| Delay= Seconds/Vehicle, Speed= Miles/Hour, Sig Dif= Significant Difference | | | | | | | |

Going along with results from the previous case, one-way traffic, the two-way traffic case proved that TSP is effective in improving delays even better with bus lanes. The last step is to measure the effect with left-turn pockets.

### 3.4.3 Two-way traffic with Left-turn pockets single intersection

Table 3.29 shows that Scenario 1 did not have an increase in delays, in contrast to what happened in the two-way traffic case. The effect of having left-turn pockets is again proven to be significant. Adding a bus lane or/and TSP are still not significant in scenario 1.

**Table 3.29: Scenario 1 Left-turn Pockets Bus Lane Effect**

| | | | | | | | |
|---|---|---|---|---|---|---|---|
| 1- NOTSP & No Bus Lane | | | | | | | |
| | N/S | E/W | Bus | | N/S | E/W | Bus |
| Delay | 9.17 | 19.90 | 2.33 | Speed | 16.10 | 8.93 | 15.97 |
| SD Delay | 1.32 | 1.16 | 0.14 | SD Speed | 1.12 | 0.33 | 0.66 |
| 2- Bus Lane Only | | | | | | | |
| | N/S | E/W | Bus | | N/S | E/W | Bus |
| Delay | 9.53 | 19.94 | 2.32 | Speed | 15.89 | 8.93 | 16.00 |
| SD Delay | 1.70 | 0.92 | 0.17 | SD Speed | 1.55 | 0.26 | 0.81 |
| 3- TSP & Bus Lane | | | | | | | |
| | N/S | E/W | Bus | | N/S | E/W | Bus |
| Delay | 9.47 | 19.92 | 2.29 | Speed | 15.99 | 8.96 | 16.17 |
| SD Delay | 1.76 | 0.94 | 0.17 | SD Speed | 1.55 | 0.27 | 0.79 |
| 1 VS 2 Impact | | | | | | | |
| | 4.01% | 0.19% | -0.20% | | -1.32% | 0.08% | 0.21% |
| Sig Dif? | NO | NO | NO | Sig Dif? | NO | NO | NO |
| 1 VS 3 Impact | | | | | | | |
| | 3.29% | 0.07% | -1.72% | | -0.69% | 0.34% | 1.25% |
| Sig Dif? | NO | NO | NO | Sig Dif? | NO | NO | NO |
| 2 VS 3 Impact | | | | | | | |
| | -0.69% | -0.11% | -1.52% | | 0.64% | 0.26% | 1.03% |
| Sig Dif? | NO | NO | NO | Sig Dif? | NO | NO | NO |
| Delay= Seconds/Vehicle, Speed= Miles/Hour, Sig Dif= Significant Difference | | | | | | | |

Table 3.30 summarizes the results for scenario 2 and scenario 3.

Table 3.30: Scenario 2 & Scenario 3 Left-turn Pockets Bus Lane Effect

| 1- NOTSP & No Bus Lane | | | | | | | |
|---|---|---|---|---|---|---|---|
| | N/S | E/W | Bus | | N/S | E/W | Bus |
| Delay | 9.17 | 19.90 | 2.33 | Speed | 16.10 | 8.93 | 15.97 |
| SD Delay | 1.32 | 1.16 | 0.14 | SD Speed | 1.12 | 0.33 | 0.66 |
| 2- Bus Lane Only | | | | | | | |
| | N/S | E/W | Bus | | N/S | E/W | Bus |
| Delay | 9.53 | 19.94 | 2.32 | Speed | 15.89 | 8.93 | 16.00 |
| SD Delay | 1.70 | 0.92 | 0.17 | SD Speed | 1.55 | 0.26 | 0.81 |
| Scenario#2: TSP & Bus Lane | | | | | | | |
| | N/S | E/W | Bus | | N/S | E/W | Bus |
| Delay | 9.25 | 19.55 | 1.28 | Speed | 16.11 | 9.05 | 23.20 |
| SD Delay | 1.37 | 1.09 | 0.15 | SD Speed | 1.23 | 0.34 | 0.71 |
| Scenario#2: 1 VS 3 Impact | | | | | | | |
| | 0.93% | -1.75% | -44.97% | | 0.07% | 1.37% | 45.30% |
| Sig Dif? | NO | NO | YES | Sig Dif? | NO | NO | YES |
| Scenario#2: 2 VS 3 Impact | | | | | | | |
| | -2.96% | -1.94% | -44.86% | | 1.41% | 1.29% | 44.99% |
| Sig Dif? | NO | NO | YES | Sig Dif? | NO | NO | YES |
| Scenario#3: TSP & Bus Lane | | | | | | | |
| | N/S | E/W | Bus | | N/S | E/W | Bus |
| Delay | 9.49 | 20.15 | 0.69 | Speed | 15.94 | 8.84 | 30.98 |
| SD Delay | 1.50 | 1.20 | 0.19 | SD Speed | 1.32 | 0.33 | 0.85 |
| Scenario#3: 1 VS 3 Impact | | | | | | | |
| | 3.49% | 1.26% | -70.34% | | -1.01% | -0.98% | 94.03% |
| Sig Dif? | NO | NO | YES | Sig Dif? | NO | NO | YES |
| Scenario#3: 2 VS 3 Impact | | | | | | | |
| | -0.50% | 1.07% | -70.28% | | 0.32% | -1.07% | 93.62% |
| Sig Dif? | NO | NO | YES | Sig Dif? | NO | NO | YES |
| Delay= Seconds/Vehicle, Speed= Miles/Hour, Sig Dif= Significant Difference | | | | | | | |

Results here are nearly identical to the previous model without left-turn pockets. Which implies that the effect of adding a bus lane is significant regardless if there was a left-turn pocket or not. This does not mean that left-turn pockets are not an important part of TSP. The improvement percentages in scenario 3 are around 70% for both cases, keeping into account that the base case delay values are not the same. Left-turn pockets do significantly affect delays, as proven earlier in model 2.

## 3.5 Model 5: Multi-directional bus traffic in Two-way Corridor Single Intersection

This model serves as an attempt to answer this question: What if two buses traveling in opposite directions or on different streets arrive at the same time? How would TSP respond?

There could be a large number of situations where buses both arrive at the same time and request to pass. By nature, most of these requests are not a source of conflict specially buses traveling in opposite directions, they will both pass during the shared green time or both request an extension or truncation. In some cases however, when buses are not traveling in the same green phase, this may present an issue of conflict of interest. To approach this a modification was made to the code to be able to pre-specify which bus will be given response priority from TSP. Multiple parameters can be used here, again the ultimate goal of all of these models is to be flexible and also effective at improving bus travel time and minimizing effect on general traffic. Some of the parameters that can act as decision variables for which bus is more important are: 1) pre-determined direction of travel, in some cases there is a corridor and cross-street that is less busy, in this case the user can modify the code to give priority to the corridor while also accepting requests from cross-streets. 2) Delays, in this case the code can read traffic average delays in both directions of travel and give priority to the bus with more delays to help minimize delays and also give that bus the priority to pass. The following describes the steps that were made to modify the code and create Scenario 4.

### 3.5.1 Scenario 4

The first step to let CORSIM handle different priority requests from different directions is to be able to specify the direction of the priority link, i.e. South-North, West-East, etc. CORSIM provides the following NETSIM array for the link directions:

XWIDT2_ANGLE(IL) Angle of link relative to North

Using this function would help to set the code and make it flexible with any inputs. Tests to see what type of data would be reported when using that array, results showed that the array contains all zeroes, which either means that there was an error in setting up the code or simply determining directions of travel with this approach is not ideal. This leads us to an issue of how to specify which links are important and which are not.

The best solution is to manually specify the priority links in the configuration file. Each link in CORSIM has its own unique numeric ID which is a set of two nodes linked in a specific direction of travel. The user would be able to identify a link as a pair of uplink – downlink_nodes. An example of a link heading from node 1 to node 2 is “1-2”. Now we can rank links by priority in the configuration file by writing the link ID and using a comma and report it in “priority_given_to” configuration option. For example, if there are nodes 1, 2, 3 and 4 and the desired priority is for link 1 to 2, then link 3 to 4, the following value of the “priority_given_to” configuration option should be used:

priority_given_to = 1-2,3-4

The CNetwork::ParseLinksLine() method was added to parse the “priority_given_to” option value. The method walks through each uplink-downlink node pair, storing each pair in the set of prioritized links, which is implemented as an STL set of pairs of two integers (std::set<pair<int, int>>). The variable for this set is defined using the CNetwork::priorityLinks member:

```
set<pair<int, int>> priorityLinks;
```

The ParseLinksLine() method gets executed from the CNetwork::LoadConfigFile(), which is invoked on the plugin load, so after plugin initialization, the CNetwork::priorityLinks member contains the list of all priority links.

As described in previous code breakdown descriptions, every time a bus requests a green signal extension, or a red light truncation, a pointer to the link where the bus is located is stored in the CNode::holdLink member of the downlink node, which gets accessed. In order to add the possibility to check the links priority, the CNetwork::TranceBUSLocation() method was modified to check if the bus's downlink node is currently held by a link with high priority. If it is, then the "lowPriority" flag is set to "true":

```
bool lowPriority = false;
CLink *holdLink = dNode ? dNode->GetHoldLink() : NULL;
if (holdLink) {
    int u = holdLink->GetUpNode()->GetID();
    int d = holdLink->GetDnNode()->GetID();
    if (priorityLinks.find(pair<int, int>(u, d)) != priorityLinks.end()) {
        lowPriority = true;
```

If the lowPriority flag is set to "true", this means that the bus is currently on a link that is not the highest priority in the list of links with buses on them. In that case, no action will be taken for the bus with lower priority until the request with a higher priority is over. In the case where a bus goes through these steps and also happens to be on a link with the highest priority, it will be granted access with no issues.

To test the multi-direction of buses effect on TSP, there will be a comparison between 2 cases tested in a two-way corridor single intersection with buses traveling North and East. The base case is the code with all modifications made in the previous steps which is in scenario 3 that has green extension, red truncation, give back green and non-moving vehicles conditions. The 2$^{nd}$ case, is with the modifications made here in Model 5, prioritizing North bus traffic over East traffic, which is made by prioritizing links where the North bus is traveling over links where East bus is traveling. The best way to present the results is to have a "Before" and "After" link prioritization, or as we called this modification "Conflict of Interest". Table 3.31 and Table 3.32 summarize the results of CORSIM simulations on bus traffic and general traffic.

**Table 3.31: Model 5 Bus Traffic Results**

| Bus Scenario#3 | | | | | | | |
|---|---|---|---|---|---|---|---|
| | N Bus | E Bus | All Bus | | N Bus | E Bus | All Bus |
| Delay | 2.25 | 6.63 | 4.44 | Speed | 16.69 | 6.64 | 11.67 |
| SD Delay | 0.51 | 1.40 | 2.45 | SD Speed | 2.61 | 1.20 | 5.46 |
| Bus Scenario#4 | | | | | | | |
| | N Bus | E Bus | All Bus | | N Bus | E Bus | All Bus |
| Delay | 2.22 | 6.51 | 4.36 | Speed | 17.15 | 6.79 | 11.97 |
| SD Delay | 0.67 | 1.49 | 2.45 | SD Speed | 3.63 | 1.22 | 5.88 |
| Impact | | | | | | | |
| | -1.21% | -1.79% | -1.65% | | 2.70% | 2.18% | 2.55% |
| Sig Dif? | NO | NO | NO | Sig Dif? | NO | NO | NO |
| Delay= Seconds/Vehicle, Speed= Miles/Hour, Sig Dif= Significant Difference | | | | | | | |

**Table 3.32: Model 5 General Traffic Results**

| Traffic Scenario#3 | | | | | |
|---|---|---|---|---|---|
| | N/S | E/W | | N/S | E/W |
| Delay | 9.62 | 22.45 | Speed | 14.71 | 8.20 |
| SD Delay | 0.62 | 1.79 | SD Speed | 0.56 | 0.46 |
| Traffic Scenario#4 | | | | | |
| | N/S | E/W | | N/S | E/W |
| Delay | 9.23 | 22.71 | Speed | 15.03 | 8.13 |
| SD Delay | 0.72 | 1.79 | SD Speed | 0.72 | 0.42 |
| Impact | | | | | |
| | -4.04% | 1.17% | | 2.14% | -0.84% |
| Sig Dif? | NO | NO | Sig Dif? | NO | NO |
| Delay= Seconds/Vehicle, Speed= Miles/Hour, Sig Dif= Significant Difference | | | | | |

Here it can be seen that the modification made in Model 5 did slightly improve bus traffic. Also, it improved traffic in N/S but gave E/W traffic some negative results. However, these improvements were not statistically significant. This is mainly due to the fact that the chances of both buses requesting TSP in the same time are very slim. To make these chances higher, another run was made with slight modification on the bus headways. Now both buses, North and East, have 3-minute headways. Table 3.33 and Table 3.34 summarize results of 3-minute headways.

**Table 3.33: Model 5 3-minute Headway Bus Traffic Results**

| Bus Scenario#3 | | | | | | | |
|---|---|---|---|---|---|---|---|
| | N Bus | E Bus | All Bus | | N Bus | E Bus | All Bus |
| Delay | 2.02 | 7.85 | 4.94 | | 26.35 | 8.90 | 17.62 |
| SD Delay | 1.35 | 2.94 | 3.71 | | 8.69 | 2.28 | 10.83 |
| Bus Scenario#4 | | | | | | | |
| | N Bus | E Bus | All Bus | | N Bus | E Bus | All Bus |
| Delay | 1.98 | 8.33 | 5.16 | | 25.77 | 8.57 | 17.17 |
| SD Delay | 1.81 | 3.16 | 3.94 | | 10.87 | 2.36 | 11.66 |
| Impact | | | | | | | |
| | -2.00% | 6.12% | 4.46% | | -2.22% | -3.63% | -2.58% |
| Sig Dif? | NO | NO | NO | Sig Dif? | NO | NO | NO |
| Delay= Seconds/Vehicle, Speed= Miles/Hour, Sig Dif= Significant Difference | | | | | | | |

**Table 3.34: Model 5 3-minute Headway General Traffic Results**

| Traffic Scenario#3 | | | | | |
|---|---|---|---|---|---|
| | N/S | E/W | | N/S | E/W |
| Delay | 9.50 | 22.52 | Speed | 14.80 | 8.17 |
| SD Delay | 0.69 | 1.81 | SD Speed | 0.69 | 0.47 |
| Traffic Scenario#4 | | | | | |
| | N/S | E/W | | N/S | E/W |
| Delay | 9.13 | 23.11 | Speed | 15.19 | 8.02 |
| SD Delay | 0.64 | 1.67 | SD Speed | 0.65 | 0.43 |
| Impact | | | | | |
| | -3.91% | 2.64% | | 2.63% | -1.90% |
| Sig Dif? | NO | NO | Sig Dif? | NO | NO |
| Delay= Seconds/Vehicle, Speed= Miles/Hour, Sig Dif= Significant Difference | | | | | |

Even though North bound bus delays are still less in Scenario 4 than Scenario 3, results show an overall increase in delays for buses. This is due to the larger increase in delays for buses traveling East. Traffic results show a decrease in delays for N/S and an increase in E/W, agreeing with bus delay results.

## 3.6 Model 6: Bus Stop Location in Two-way Corridor Single Intersection

Almost all studies agree on the fact that locating the bus stop far-side is better than having it near side. For the purposes of making this study inclusive of all possible parameters and proving what previous studies have confirmed, 2 cases have been tested and simulated in CORSIM. The first case is placing a bus stop 50 feet before the intersection, this case is called a near-side bus stop. The other case, is placing a bus station 50 feet after the intersection, this is called a far-side bus stop. The simulation model was built on Model 2, which had a two-way traffic corridor with a cross-street. Four different scenarios were applied to both cases to test the difference, no TSP and the three scenarios generated in this study. Table 3.35 summarize the results of both cases.

**Table 3.35: Bus Stop Station Results**

| NO TSP | | | | Results | |
|---|---|---|---|---|---|
| Near | | Far | | Impact | Sig Dif? |
| Delay | 5.07 | Delay | 2.75 | -45.84% | YES |
| SD Delay | 0.50 | SD Delay | 0.22 | | |
| Scenario#1 | | | | Results | |
| Near | | Far | | Impact | Sig Dif? |
| Delay | 4.71 | Delay | 2.76 | -41.41% | YES |
| SD Delay | 0.37 | SD Delay | 0.25 | | |
| Scenario#2 | | | | Results | |
| Near | | Far | | Impact | Sig Dif? |
| Delay | 3.84 | Delay | 1.61 | -58.07% | YES |
| SD Delay | 0.48 | SD Delay | 0.33 | | |
| Scenario#3 | | | | Results | |
| Near | | Far | | Impact | Sig Dif? |
| Delay | 3.55 | Delay | 1.14 | -67.97% | YES |
| SD Delay | 0.37 | SD Delay | 0.20 | | |

Delay= Seconds/Vehicle, Sig Dif= Significant Difference

As expected, in all cases, placing a bus stop far side is better as the fact that false requests can affect the performance of TSP. What is interesting in this table is the fact that the better the TSP is, from scenario 1 to 3, the greater the difference between near and far side bus stop locations. This shows how some calls actually make buses experience delays instead of taking advantage of the efficiency of TSP. Scenario 3 with near side bus stops reported delays of 3.55 seconds in comparison to 1.14 with far side. Both cases had the same scenario, but one was 67.97% better than the other one. Again, this agrees with most studies that conclude placing a bus stop far side is better than near side, and it also shows the magnitude of the difference.

## 3.7 Model 7: Transit Occupancies & Bus Headways in Two-way Corridor Single Intersection

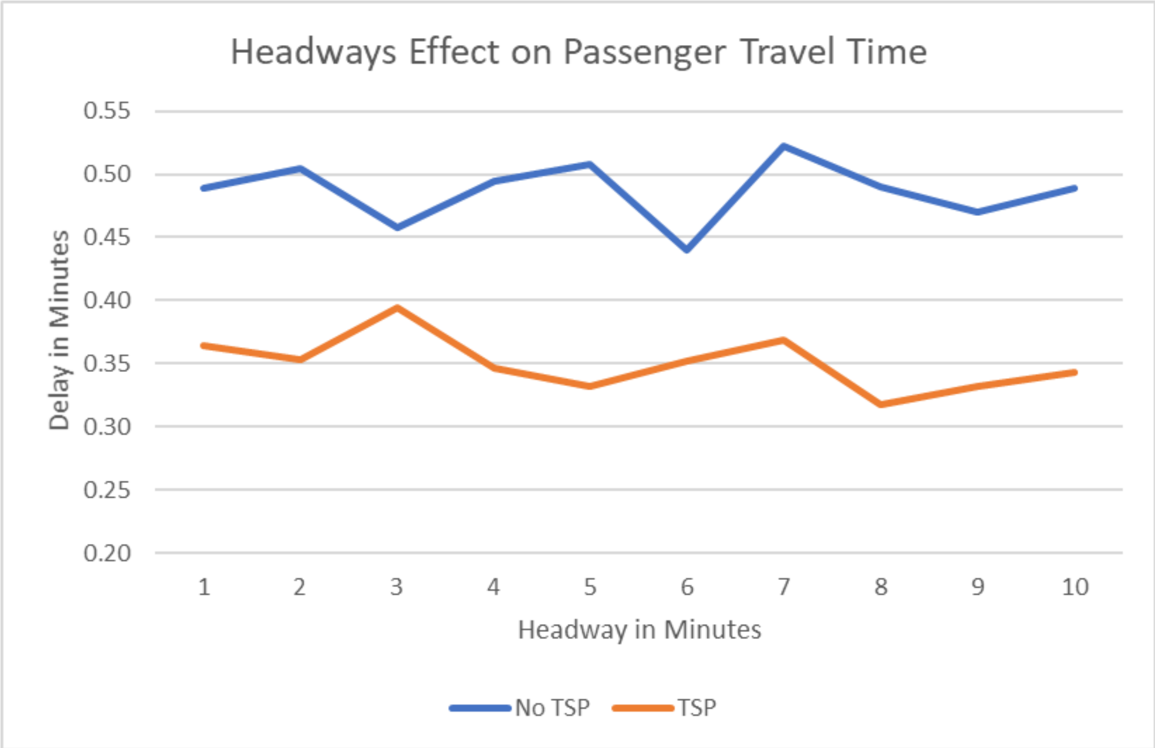
Generating random bus occupancies is not possible in CORSIM. The software by design handles characteristics of traffic as speed, delay location and also behavior of drivers. The only way to change bus occupancies is before running the simulation. Even when generating random occupancies through an extension and forcing a bus to stop at multiple bus stops, these occupancies do not change in number which means that these numbers are static and not necessarily dynamic. In order to see the effect of transit occupancies on TSP multiple runs of different bus headways would imply different bus occupancies. What is captured in these different bus headways is the disruptions to buses from a lot of factors like traffic delays, accidents and bus stops. This way of analyzing this parameter will not lead to a direct relationship between transit occupancies and delays but rather a relationship of the effect that transit occupancies have on bus headways that ultimately affects TSP. Table 3.36 summarizes 10 runs for buses with 1 to 10 minute headways and savings for delays per passenger in each run are reported. This model is built on Model 2 with 5-minute headways for the North bound bus. It uses the most up to date code, including all modifications made.

**Table 3.36: Model 7 Results**

| Bus Passenger Travel Time (Minute) | | | | |
|---|---|---|---|---|
| Headway | Cumulative | | Per Person | |
| | NO TSP | TSP | NO TSP | TSP |
| 1 | 734.17 | 546.13 | 0.49 | 0.36 |
| 2 | 378.00 | 264.65 | 0.50 | 0.35 |
| 3 | 229.13 | 197.18 | 0.46 | 0.39 |
| 4 | 185.53 | 129.98 | 0.49 | 0.35 |
| 5 | 152.28 | 99.72 | 0.51 | 0.33 |
| 6 | 109.97 | 88.13 | 0.44 | 0.35 |
| 7 | 111.83 | 78.93 | 0.52 | 0.37 |
| 8 | 91.80 | 59.50 | 0.49 | 0.32 |
| 9 | 78.38 | 55.36 | 0.47 | 0.33 |
| 10 | 73.26 | 51.52 | 0.49 | 0.34 |

The cumulative travel time is for all the passengers in all buses, a huge difference can be seen here from 734.17 for 1 minute headways to only 73.26 in 10 minute headways, the reason is that in 1 minute headways there are around 60 buses each moving 25 passengers in comparison to only 6 buses for 10 minute headways. The column on the left simplifies the results by dividing the cumulative by passengers and frequency of buses, all values are around 0.44-0.51 without TSP and 0.32-0.39 with TSP. It can be seen here, regardless of how many passengers are being moved, TSP is still beneficial to the individual numbers. In comparing 6 buses traveling versus 60, yes TSP was not proved to be significantly better for bus delays. However, when looking at the individual (per person) values, TSP is actually beneficial to the point it kept the delays consistent even while having more buses coming in the system in compared to no TSP. Figure 3.8 is a graph showing the difference between TSP and NO TSP regarding headways and per person delays.

Figure 3.8: Model 7 headways versus per person delays




## 3.8 Summary

3.8.1 Network capacity: One-way versus two-way traffic

- Model 1 covered a one-way corridor traveling north with three scenarios:
  - Scenario 1 responded to a "late" bus coming into an intersection within the last few seconds of the green time. A typical response was built on reading the bus location and determining how many seconds of green time should be added to the current signal phase to grant the bus access to the intersection. Results showed that there was no significant difference in either bus delays/speed or traffic delays/speed.
  - Scenario 2 in addition to Scenario 1, truncates the red signal phase if a bus approached an intersection with a red light phase. In this scenario, both phases of green and red lights are covered leading to granting a response whenever a bus approaches. Results were significant for headways of 7 and 5 minutes only.
  - Scenario 3 in addition to Scenario 2, checks if it is worth giving priority to the bus by checking non-moving vehicles on the cross-street then deciding to grant access or not. It also gives back green time that was taken from the cross-street after a priority request is granted and the green phase is over. Just like Scenario 2, results were only significant for 5 and 7 minutes bus headways.
- Model 2 covered a two-way corridor with three scenarios:

- Scenario 1 resulted in no significant difference in 5 and 7 minute headways and negative significant differences in 3-minute headways which is probably due to the fact that left-turns now face two lanes of traffic which disrupt the traffic flow.
  - Scenario 2 resulted in positive significant differences in 5 and 7 minutes but still negative significant differences in 3 minutes headways. Here the more realistic headway of 5 minutes and more is proved to be a better situation for TSP.
  - Scenario 3 has the same results as Scenario 2
- Bus lane
  - Model 4 tested the effect of adding a bus lane to 1) one-way traffic, 2) two-way traffic and 3) left-turn pockets in two-way traffic. The three TSP scenarios were tested in each of these three cases. Results compared to adding a bus lane only did not show significant differences in bus delays in all cases. Scenario 1 results showed no improvement in any of the cases. Scenario 2 and 3 results showed that adding a bus lane with TSP is significantly better than a bus lane without TSP and also better than no bus lane and no TSP.
- Buses in One versus two directions
  - Model 5 tested a modification that was added to account for situations when multiple buses request TSP. The model gave priority to buses traveling on a preset direction, in this case North bound bus requests where always prioritized over East bound buses. Running the simulation and seeing the effect of that change for 5-minute and 3-minute headways did not show any significant improvement to either bus traffic or general traffic.

2.2.2.18. Green Time

  - Analysis of Model 2 with maximum "Given Back Green" shows that giving back only 1 second of green time to the cross-street traffic significantly decreases bus delays and has less cross-street delays than all other cases.

2.2.2.19. Traffic Volume

- Cross-street flow
  - Analysis made on Model 2 cross-street traffic shows that with V/C more than 0.55 TSP starts to decrease in performance, this decrease is shown as increased cross-street delays. However, V/C ratio starting at 0.63 would cause significantly more delays for TSP in comparison to No TSP.
- Left-turns
  - Model 3 tested the effect of TSP with left-turn pockets. A 200' left-turn pocket was added to all directions of travel.

- Scenario 1 resulted in no significant difference in all bus headways. This shows an improvement in comparison to Model 2 which had negative effects on 3 minute headways.
- Scenario 2 resulted in positive significant differences in 5 and 7-minute headways only, while having no effect with 3-minute headways.
- Scenario 3 was the same as Scenario 2 with more improvements to bus delays.

2.2.2.20. Transit Arrivals

- Bus Stop location
  - Model 6 tested the difference of placing a bus stop near side versus the far side of the intersection. Analysis was made on the Model 2 case, with two-way traffic. The base case without using TSP proved that there is a significant difference between the two situations, near side versus far side bus stop locations. The three scenarios were simulated, and their results showed even larger significant differences than the base case. The results not only proved the difference it also showed the magnitude of the difference between the two.
- Bus Headway
  - Multiple bus headways were tested in Model 7 to show the effect of having different transit occupancies and also high/low bus traffic volumes. Results showed that TSP was effective in reducing bus passengers delays in headways ranging from 1 to 10 minutes.

2.2.2.21. Transit Occupancies

- Modeling transit occupancies was not possible in CORSIM, so another approach was tested which is covered in Model 7. The summary is explained in Bus headway section.

2.2.2.22. System Quality

- Detectors
  - All simulations were built using a real-time detector device that can be considered as a GPS or WiFi detection device performing without any mistakes, locating the bus location and speed every single second. Any change in the detector capabilities will dramatically change the results of all of the models built and tested. As these models were built knowing the bus speed, it is nearly impossible to get this data in reality using loop detectors or infrared detection. It was not necessary to prove that GPS detectors work better since the models were directly affected and built on the data gathered from the best detectors. This implies that any change in the detector quality will directly affect TSP quality.
- Signal Coordination (Progression)

- Testing progression on an isolated intersection level is not feasible due to the fact that one needs multiple intersections to use any time based coordination. This variable will be tested further in corridor and network levels.

# Chapter 4. One-way Corridor Model

In recap, the ultimate goal is to test all variables and factors listed in the TSP quality network. These factors and variables are:

1. Network capacity:
   a. One-way versus two-way of traffic.
   b. Bus lane.
   c. Buses in One versus two directions.
2. Green Time
3. Traffic Volume:
   a. Cross-street flow
   b. Left-turns
4. Transit Arrivals
   a. Bus Stop location
   b. Bus Headway
5. Transit Occupancies
6. System Quality
   a. Detectors
   b. Signal Coordination (Progression)

In addition to that, expanding the scope by testing these variables not only in an isolated intersection, but in corridors and mini-networks to see the cascading effect of changing multiple factors/variables on the overall quality of network service. In this chapter, all the previous scenarios and models are going to be used and tested on a one-way corridor. This would provide a better understanding of how changing these parameters affects TSP and also looking at more versatile TSP application situations. In the previous chapter, all tests where made on an isolated intersection depicting a sub-urban area where transit flows are least likely to be an issue. This chapter will serve as an introduction to the analysis of TSP scenarios and models in urban areas, where TSP is most likely needed and going be beneficial. As the goal of this study is to minimize delays for buses, to increase ridership and decrease congestion. Applying these scenarios will help determine if the scenarios created might be of benefit to achieve these goals. Once all variables/factors are tested in one-way corridors, the next step is to test the same scenarios and models on a two-way corridor which then will be followed by a chapter covering an Austin-based case study that shows real data and real traffic effects of the TSP scenarios.

## 4.1 Model 1: Corridor Progression

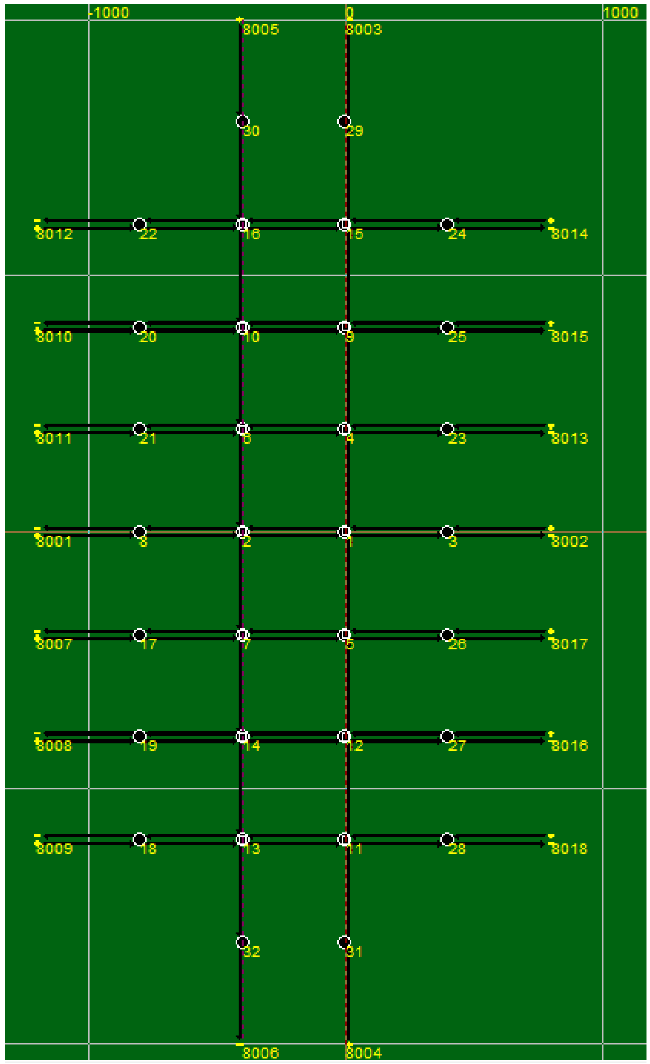
One of the desirable aspects of urban traffic control is signal progression. The ability to coordinate signals at multiple intersections in the same corridor to let traffic travel smoothly is a great technique for minimizing congestion. As discussed earlier, signal progression was one of the earliest ways to minimize bus travel time by coordinating signals that bus routes are going through. Once buses start traveling through these coordinated signals, in the best case they would not stop for red signals as they will travel through a window of green light. Testing TSP on a single intersection proved to be beneficial, but this led us to the next question regarding whether TSP can work on a bigger scale or not. Also, in previous research, the biggest downfall of TSP using progression only is that, on multiple occasions, buses miss the progression green window by being exposed to unexpected delays which makes them miss the preset accommodations in the traffic signal system. In this Model, the effect of progression would be tested first to see the impact and to decide on what base model to use to test all other models/scenarios. The first step is to create a base model in CORSIM. This model includes a one-way corridor traveling North and a one-way corridor traveling South, both intersecting with 7 two-way streets. The reason of including two corridors in this step is to expand the scope of most previous research that only covered one corridor, either two-way or one-way. With two corridors, not only the effect on the corridor traffic will be tested better but also the cross-street traffic now will deal with two different intersections. This will lead to results closer to reality than a single corridor and therefore was adapted in this study. For buses traveling in these corridors, one bus was assigned a North route with a headway of 5 minutes, another South route is assigned with 5-minute headways as well. Table 4.1 shows the assumptions that were made.

**Table 4.1: Model 1 Assumptions**

| Direction | Lanes | Turning | | | Green time | Cycle length | G/C ratio | Capacity per hour | Volume | V/C |
|---|---|---|---|---|---|---|---|---|---|---|
| | | Left | Thru | Right | | | | | | |
| **NB** | **3** | 15 | 70 | 15 | 55 | 90 | 0.61 | 3483 | 1500 | 0.431 |
| **SB** | **3** | 15 | 70 | 15 | | | | 3483 | 1500 | 0.431 |
| **EB** | **2** | 70 | 30 | 0 | 25 | | 0.28 | 1056 | 500 | 0.474 |
| **WB** | **2** | 0 | 30 | 70 | | | | | 500 | 0.474 |

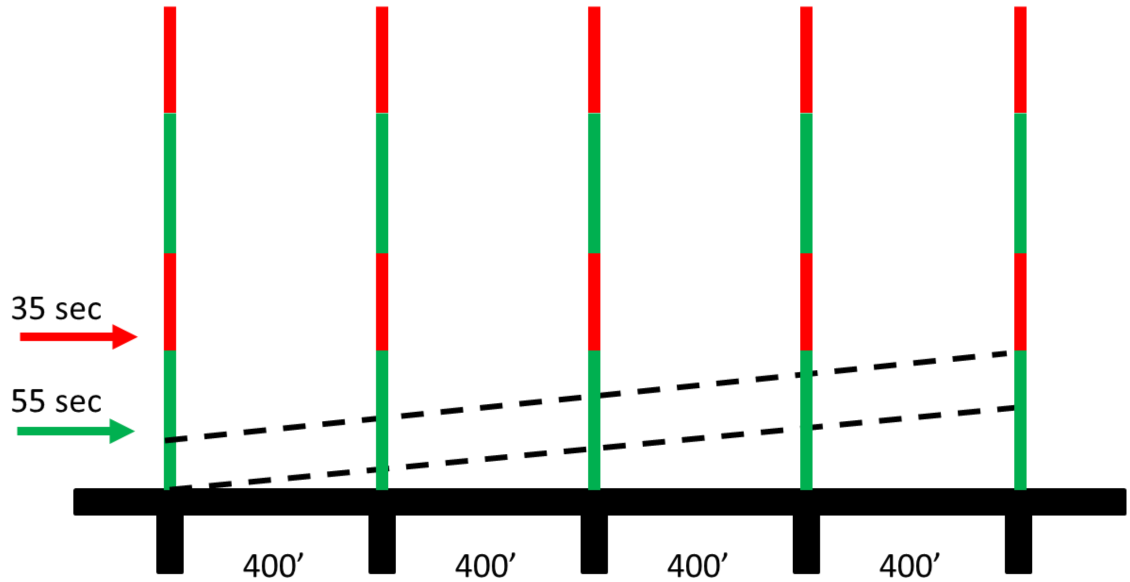
Figure 4.1 shows the CORSIM model with the two arterial streets and seven crossing streets.

**Figure 4.1: Model 1 CORSIM configuration**




The first step is to test the difference between setting all signals to start green together and implementing coordination between signals to create progression for traffic traveling in the main corridors. To achieve progression between intersections, certain variables need to be included in the Kell method calculations. These variables are speed of vehicles, distance between intersections and the offset time. A basic time-space diagram illustrates how the Kell method helps vehicles to travel in green "windows" without delays. Based on our model, a basic time-space diagram would look like Figure 4.2:

**Figure 4.2: Base case time-space diagram**




On the vertical axis, effective green and red lights for the corridors path are shown in their respective colors. The horizontal axis shows the intersections represented by the black blocks that are on the corridors path, with the distance between each. The dotted line represents the window that vehicles can travel encountering all green lights without delays. This dotted line's slop represents the speed, which is very high in this case, the lower the slope the higher the speed. It can be seen here that the green phase benefits are not maximized, the window is less than half the size of the green phase. Also, the speed is very high which might not be realistic and would defeat the purpose of applying progression to decrease congestion. The biggest aspect that is missing in this time-space diagram is offset time, you can notice that all intersection green signals time start at the same time. The next step is to calculate the offsets that are the successive travel times among intersections. This step is to know if the first intersection started green time at 12:00:00 exactly, when should the next intersection start? That offset time, in essence, is the time that traffic will take to get to the second intersection from the first one. And it is calculated in this formula:

$$Offset = \frac{\boldsymbol{d}}{\boldsymbol{V}} \qquad \text{(Mannering)}$$

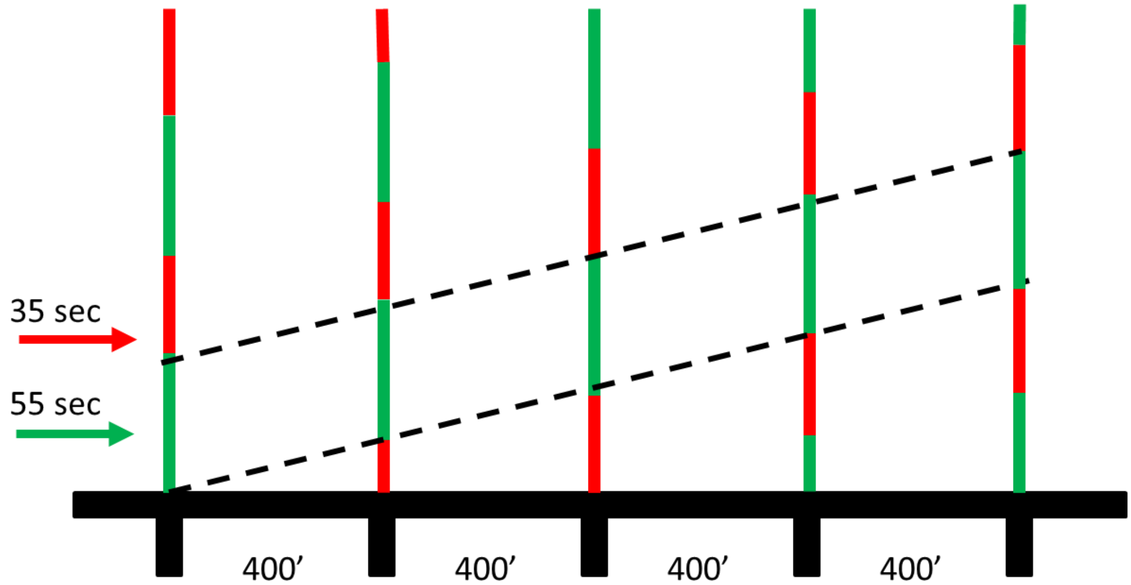
Where

d= Distance between intersections (feet)

V= Speed (ft/s)

In this model's case, the distance between intersection is 400 feet, with a speed of around 22 ft/s (after running 25 simulations and analyzing speed on main corridors). The offset is calculated to be 18 seconds. Once offset is calculated, the Kell method is used to create a time-space diagram that shows the "windows" of green lights between intersections. Figure 4.3 shows the created time-space diagram for this model:

**Figure 4.3: Model 1 18 Seconds time-space diagram**




Eighteen seconds after beginning of the green at the first intersection, the second intersection starts its green phase. It can be notice on the second intersection that when the first one started, there was 18 seconds of red time still in effect. The 55 seconds of green time is the window that a platoon of vehicles can travel through without stopping at red lights, which is maximized in comparison to the previous basic time-space diagram. The slop of the dotted line is now larger, which shows a lower progression. Certain constraints should be explained here, this speed is limited to the free flow speed of the corridor, adjusting progression can speed up traffic but to a point that is less than or equal to the free flow speed. In concept you can have a very small slope, which implies a very high speed as well. But in practice, free flow speed, that includes safety considerations is going to govern the speed of the corridor.

Another approach to maximize the potential of using progression to decrease traffic delays in the main corridor is by using the free flow speed instead of the current speed. If the free flow speed is set to 44 ft/s. applying the previous formula, the offset would be 9 seconds instead of 18 seconds. Two cases will be tested to see which speed would yield better results for progression versus a base case. Now that we have three models, one without progression (all intersection green signals start at the same time), one with 18 seconds offset and one with 9 seconds offset a simulation on CORSIM was made and Table 4.2 shows the impact of the change.

**Table 4.2: Model 1 Results**

| No progression | | | | | | | |
|---|---|---|---|---|---|---|---|
| | N/S | E/W | Bus | | N/S | E/W | Bus |
| Delay | 5.92 | 29.88 | 1.34 | Speed | 15.79 | 7.34 | 19.54 |
| SD Delay | 2.84 | 17.20 | 0.90 | SD Speed | 1.50 | 2.16 | 5.88 |
| Progression 18 Seconds | | | | | | | |
| | N/S | E/W | Bus | | N/S | E/W | Bus |
| Delay | 9.66 | 29.84 | 2.00 | Speed | 11.92 | 7.26 | 14.78 |
| SD Delay | 1.61 | 13.70 | 0.42 | SD Speed | 1.07 | 2.19 | 1.19 |
| Impact | | | | | | | |
| | 63.30% | -0.12% | 49.00% | | -24.54% | -1.08% | -24.36% |
| Sig Dif? | NO | NO | NO | Sig Dif? | YES | NO | NO |
| Progression 9 Seconds | | | | | | | |
| | N/S | E/W | Bus | | N/S | E/W | Bus |
| Delay | 5.87 | 27.94 | 0.69 | Speed | 14.73 | 7.58 | 23.80 |
| SD Delay | 0.99 | 12.56 | 0.58 | SD Speed | 0.69 | 2.30 | 4.56 |
| Impact | | | | | | | |
| | -0.80% | -6.48% | -48.72% | | -6.71% | 3.27% | 21.80% |
| Sig Dif? | NO | NO | NO | Sig Dif? | NO | NO | NO |

Looking at the results, using 18 seconds offset for progression dramatically increased delays on the main corridor, 63% for main traffic and 48-49% for buses. It also significantly decreased speed for traffic traveling in the main corridors. This dramatic increase is caused by shifting the traffic signals to operate assuming traffic would have speeds of 22 ft/s, which is slow moving traffic. After running multiple simulations to inspect why that offset, that was calculated according to the Mannering equation, was not ideal. Multiple reasons might have led to these negative unexpected negative effects: first reason, even though the speed of vehicles is close to 22 ft/s, there are a lot of vehicles added to main corridor links from cross-streets that generate queues blocking the traveling platoon of vehicles. In other words, when vehicles start traveling down the corridor, the progression assumes that there are little to no queues at the upcoming intersection. This is why it waits exactly 18 seconds until vehicles arrive at the intersection and then it turns green. Now in a perfect world this would be ideal is it minimizes wasted green time, however, as noticed in multiple simulation runs most of the times when vehicles approach the next intersection there a queue already waiting for green light. The second reason would be the classic dilemma between static and dynamic systems. When running the base case it was noticed that the speed of vehicles is 22 ft/s which is a good representation of a static base case, offset was calculated to be 18 seconds and then appropriate adjustments were made to the CORSIM model to better coordinate intersections. When vehicles are given coordinated green time, speed will increase, and it will no longer be 22 ft/s. however, the coordination still assumes that the vehicles are traveling at 22 ft/s which will ultimately lead to negative impacts instead of improving speed. A better approach is to design the coordination system based on free flow speed. That way, it will enable increases in speeds to a limit that is governed by the speed of the system. Even though speeds are not guaranteed to reach the free flow speed, they are likely to be increased beyond the static speed of 22 ft/s. Here it should be noted that multiple simulations were tested to make sure that the best way to allocate seconds of offset is using the free flow speed values.

Even though the 9 seconds offset value (400 ft/9 seconds=44 ft/second) did not significantly improve any aspects of the model, it improved the speed of the buses up to 54%. Some simulation runs reported 0 delays for buses which was not found in any of the previous simulations, 18 seconds or base case. In conclusion, the best case to build all of this chapter's simulation would be using progression with 9 seconds offset (44 ft/sec = 30 mph). From now on, all simulation while have the 9 seconds progression case as the model case to compare and test the effects of any changes/modifications.

### 4.1.1 All Scenarios

The next step is to test the three scenarios that were created in the previous chapter with signal coordination. A quick recap of the three scenarios is listed in Table 4.3.

**Table 4.3: All Scenarios Summary**

| | Scenario#1 | Scenario#2 | Scenario#3 |
|---|---|---|---|
| Inputs | 1- Bus location<br>2- Queue length | 1- Bus location<br>2- Queue length | 1- Bus location<br>2- Queue length<br>3-Cross-street delays |
| System is online | Only during green light | Always | Same as Scenario#2 |
| System Response | Green extension | Green extension & Red truncation | Same as Scenario#2 |
| Special Strategies | None | None | Gives Back Green time |

All scenarios use the live location of the bus and adapt accordingly, testing these scenarios on a corridor level is essential in the pursuit of proving TSP can have an important role in improving bus speeds without affecting general traffic. The previous runs, for isolated intersections, all agreed that if TSP did not improve the overall state of the system it will not have a significant negative impact. Scenario 3 will use the same assumptions used in the previous models, a maximum green given back of 1 second and a minimum of 2 non-moving cars on the cross-streets. Using the base case to compare each scenario impact on the delays and speeds of traffic and buses, Table 4.4 summarizes the CORSIM outputs.

**Table 4.4: Model 1 Nine Seconds Offsets, 30 mph Progression Speeds All Scenarios Results**

| No TSP | | | | | | | |
|---|---|---|---|---|---|---|---|
| Delay | N/S | E/W | Bus | Speed | N/S | E/W | Bus |
| Mean | 5.87 | 27.94 | 0.69 | Mean | 14.73 | 7.58 | 23.80 |
| SD | 0.99 | 12.56 | 0.58 | SD | 0.69 | 2.30 | 4.56 |
| Scenario#1 TSP | | | | | | | |
| Delay | N/S | E/W | Bus | Speed | N/S | E/W | Bus |
| Mean | 6.46 | 30.88 | 0.70 | Mean | 14.32 | 7.28 | 23.73 |
| SD | 1.38 | 16.03 | 0.56 | SD | 1.03 | 2.49 | 4.91 |
| Impact | | | | | | | |
| | 10.01% | 10.52% | 2.41% | | -2.80% | -3.94% | -0.27% |
| Sig Dif? | NO | NO | NO | Sig Dif? | NO | NO | NO |

| Scenario#2 TSP | | | | | | | |
|---|---|---|---|---|---|---|---|
| Delay | N/S | E/W | Bus | Speed | N/S | E/W | Bus |
| Mean | 7.16 | 31.94 | 0.71 | Mean | 13.86 | 7.20 | 23.16 |
| SD | 1.93 | 17.04 | 0.46 | SD | 1.52 | 2.57 | 3.65 |
| Impact | | | | | | | |
| | 21.91% | 14.33% | 2.77% | | -5.95% | -5.07% | -2.69% |
| Sig Dif? | NO | NO | NO | Sig Dif? | NO | NO | NO |

| Scenario#3 TSP | | | | | | | |
|---|---|---|---|---|---|---|---|
| Delay | N/S | E/W | Bus | Speed | N/S | E/W | Bus |
| Mean | 6.63 | 32.29 | 0.70 | Mean | 14.47 | 7.17 | 24.39 |
| SD | 2.23 | 16.95 | 0.79 | SD | 1.45 | 2.65 | 5.44 |
| Impact | | | | | | | |
| | 12.87% | 15.56% | 1.54% | | -1.79% | -5.36% | 2.49% |
| Sig Dif? | NO | NO | NO | Sig Dif? | NO | NO | NO |

Looking at the results, none of the three scenarios were successful in decreasing delays or increasing speeds in any of the traffic categories tested. Bus delays also slightly increased across the three scenarios but none of the results was proven to be significant. What is interesting in these results, is that traffic on both cross-streets and the main corridor has larger standard deviations now. Also, Scenario 3 bus delays had a very high standard deviation value as well. This is expected due to the fact that all scenarios change the traffic signal timing which ultimately affects progression. Having higher standard deviations also reflect the fact that the scenarios are sometimes beneficial for the system, and sometimes are extremely damaging. Looking at the East and West Traffic, some standard deviations were higher than the main corridor which raised a red flag that the distributions no longer be normal, which means the mean may not be the best measure of central tendency. This can be solved in two ways, either by using the median as a measure of central tendency or possibly increase the sample size if the population from which sampling is performed is actually normal. Another attempt was made using 100 runs instead of 25, but the results were not different. Therefore using the median was chosen as the best way to describe the center of the data. From now on all results will have the median and all impact percentages will be made based on the medians, not the means. However, we will continue using t-tests to test if there is a significant difference between the samples we obtained and that will be reported as well. Also, to make sure all the previous results in this study were accurate, random checks were made on the simulations to make sure that the median is close to the mean, which implies a normal distribution. None of the medians was more than +-0.05 unit different from the means. Another reason why we do not have to go back and include the median in the results is that the t-test that were used gave significant results, which means that the differences among the samples are statistically significant. At this point, it is safe to move forward with confidence in the results that were presented so far. Table 4.5 shows the new results with the median comparisons for the 4 cases.

**Table 4.5: Model 1 All Scenarios Adjusted Results**

| No TSP | | | | | | | |
|---|---|---|---|---|---|---|---|
| Delay | N/S | E/W | Bus | Speed | N/S | E/W | Bus |
| Mean | 5.87 | 27.94 | 0.69 | Mean | 14.73 | 7.58 | 23.80 |
| SD | 0.99 | 12.56 | 0.58 | SD | 0.69 | 2.30 | 4.56 |
| Median | 5.79 | 21.97 | 0.54 | Median | 14.69 | 8.09 | 25.67 |
| Scenario#1 TSP | | | | | | | |
| Delay | N/S | E/W | Bus | Speed | N/S | E/W | Bus |
| Mean | 6.46 | 30.88 | 0.70 | Mean | 14.32 | 7.28 | 23.73 |
| SD | 1.38 | 16.03 | 0.56 | SD | 1.03 | 2.49 | 4.91 |
| Median | 6.32 | 25.62 | 0.64 | Median | 14.36 | 7.24 | 25.02 |
| Impact | | | | | | | |
| | 9.18% | 16.58% | 19.07% | | -2.21% | -10.60% | -2.53% |
| Sig Dif? | NO | NO | NO | Sig Dif? | NO | NO | NO |
| | | | | | | | |
| Scenario#2 TSP | | | | | | | |
| Delay | N/S | E/W | Bus | Speed | N/S | E/W | Bus |
| Mean | 7.16 | 31.94 | 0.71 | Mean | 13.86 | 7.20 | 23.16 |
| SD | 1.93 | 17.04 | 0.46 | SD | 1.52 | 2.57 | 3.65 |
| Median | 7.42 | 22.89 | 0.53 | Median | 13.48 | 7.86 | 24.35 |
| Impact | | | | | | | |
| | 28.31% | 4.18% | -1.48% | | -8.25% | -2.86% | -5.14% |
| Sig Dif? | NO | NO | NO | Sig Dif? | NO | NO | NO |
| | | | | | | | |
| Scenario#3 TSP | | | | | | | |
| Delay | N/S | E/W | Bus | Speed | N/S | E/W | Bus |
| Mean | 6.63 | 32.29 | 0.70 | Mean | 14.47 | 7.17 | 24.39 |
| SD | 2.23 | 16.95 | 0.79 | SD | 1.45 | 2.65 | 5.44 |
| Median | 5.78 | 24.68 | 0.46 | Median | 14.95 | 7.49 | 26.72 |
| Impact | | | | | | | |
| | -0.14% | 12.30% | -15.37% | | 1.77% | -7.48% | 4.10% |
| Sig Dif? | NO | NO | NO | Sig Dif? | NO | NO | NO |

Using the median in the percentage of impact calculations shows that, for Scenario 1 bus delays increased up to 19% which is really damaging for bus traffic, and traffic delays on both directions of travel increased. Scenario 2 shows the largest delay increases for North/South traffic while having minimum effects on cross-street traffic. The issue of Scenario 2 is that it only decreased bus delays by close to 2%. The best outcome came with Scenario 3 as it was successful in decreasing bus delays 15%. These results are the first step toward proving that TSP is actually beneficial to bus traffic in corridors. The traditional TSP systems, that only has green extension (Scenario 1) or green extension and red truncation (Scenario 2) worked well in the single intersection cases but failed in this case where a main corridor is considered. This can be due to two factors, in this case a one-way street might limit the performance of TSP. Also, this case was built on a corridor with progression, neither of these scenarios gave back any green time, which means every time the bus request green time, the progression is changed, and the green window is disturbed. Scenario 1 with the green give back was successful in responding to the bus requests, granting faster access while also having almost no effect on the North/South bound traffic. The only issue here is the cross-street traffic delays were increased 12%, however these results are not significant. All in all, none of these results are significantly different but the bus traffic delay decreased 15% and the cross-street delay increased 12%.

While the previous runs were made using 9 seconds offsets (30 mph), the results might be different for the case with no progression. The progression case as discussed earlier could limit the performance of TSP and vice versa. The next step is to use TSP without progression on the same corridor as an attempt to understand the relationship between progression and the scenarios created in this study. Another 4 runs (No TSP and 3 scenarios) were made and summarized in Table 4.6 to see the effect of progression on TSP effectiveness. The table summarizes results of running 4 cases on the CORSIM model with no progression.

**Table 4.6: Model 1 All Scenarios No Progression Results**

| | | | | | | | |
|---|---|---|---|---|---|---|---|
| No TSP | | | | | | | |
| Delay | N/S | E/W | Bus | Speed | N/S | E/W | Bus |
| Mean | 6.02 | 26.97 | 1.45 | Mean | 15.75 | 7.58 | 19.39 |
| SD | 2.80 | 10.26 | 1.08 | SD | 1.99 | 2.02 | 6.59 |
| Median | 5.21 | 24.04 | 1.53 | Median | 16.01 | 7.73 | 16.33 |
| Scenario#1 TSP | | | | | | | |
| Delay | N/S | E/W | Bus | Speed | N/S | E/W | Bus |
| Mean | 6.44 | 29.35 | 1.37 | Mean | 15.29 | 7.31 | 19.63 |
| SD | 2.61 | 13.12 | 1.00 | SD | 1.70 | 2.22 | 6.19 |
| Median | 5.35 | 24.82 | 1.39 | Median | 15.66 | 7.59 | 18.36 |
| Impact | | | | | | | |
| | 2.79% | 3.25% | -9.24% | | -2.22% | -1.83% | 12.39% |
| Sig Dif? | NO | NO | NO | Sig Dif? | NO | NO | NO |
| | | | | | | | |
| Scenario#2 TSP | | | | | | | |
| Delay | N/S | E/W | Bus | Speed | N/S | E/W | Bus |
| Mean | 8.74 | 34.01 | 1.09 | Mean | 13.10 | 6.76 | 20.81 |
| SD | 3.00 | 17.43 | 0.63 | SD | 1.81 | 2.27 | 5.36 |
| Median | 6.09 | 27.86 | 1.37 | Median | 13.35 | 7.29 | 18.60 |
| Impact | | | | | | | |
| | 16.93% | 15.89% | -10.87% | | -16.60% | -5.66% | 13.88% |
| Sig Dif? | NO | NO | NO | Sig Dif? | NO | NO | NO |
| | | | | | | | |
| Scenario#3 TSP | | | | | | | |
| Delay | N/S | E/W | Bus | Speed | N/S | E/W | Bus |
| Mean | 8.10 | 31.09 | 1.75 | Mean | 13.88 | 7.10 | 17.18 |
| SD | 2.80 | 13.99 | 1.24 | SD | 2.12 | 2.31 | 4.52 |
| Median | 5.64 | 25.53 | 1.23 | Median | 13.80 | 7.15 | 18.78 |
| Impact | | | | | | | |
| | 8.26% | 6.17% | -19.56% | | -13.78% | -7.41% | 15.02% |
| Sig Dif? | NO | NO | NO | Sig Dif? | NO | NO | NO |

For the cases with no progression, Scenario 1 had the least effects on general traffic with percentages ranging from 2-4%. Even though Scenario 2 was successful in decreasing bus delays up to 10%, it is not the best case as it affected the North/South traffic severely with increases up 26%. Scenario 3 decreased bus delays by 19% but also had negative effects on general traffic. After running t-tests on all categories, no value was found to be significantly different than the base case values. The model that is going to be used for all of the next analysis in this chapter is the one with no progression as TSP proved to work with and without progression with minimal differences. What is interesting in these results is that TSP did not perform as good as it did when it was used in Chapter 3, the single isolated intersection model. All scenarios failed to provide significant impacts on traffic delays, not only that, all scenarios did affect the general traffic heavily. These results show that using TSP in the one-way corridor might not be ideal to be used but it is worth exploring the relationship of the different parameters of interest.

### 4.1.2 Max Green

Scenario 3 is the best scenario created in this study, due to its flexibility in dealing with cross-street traffic. GBG, or give back green time as earlier discussed, works as a factor in Scenario 3 that minimizes effects on cross-street traffic by returning extra seconds of green time that was taken away by the bus request for green light. The amount of green time taken away from cross-streets varies a lot, so the code was designed to give back green time with a ceiling for the highest amount of time to be given back. This ceiling is called "Max green", which is the maximum green time given back after a bus requests additional green time or the cross-street red light was truncated. For the case of a single intersection, this factor is significant in improving bus delays with minimal delays for cross-streets. The previous analysis reported that giving back 1 second of green time is ideal and generated the best results in comparison to many other green return amounts. Table 4.7 summarizes results for runs with max green ranging from 0 to 20 seconds, also a base case was included for comparison.

**Table 4.7: Model 1 Max Green Analysis**

| Max Green | N/S Delay | E/W Delay | Bus Delay | | N/S Speed | E/W Speed | Bus Speed |
|---|---|---|---|---|---|---|---|
| NO TSP | 5.21 | 24.04 | 1.53 | | 16.01 | 7.73 | 16.33 |
| 20 | 5.99 | 26.14 | 1.34 | | 13.47 | 6.44 | 18.29 |
| 15 | 6.03 | 26.54 | 1.33 | | 13.32 | 6.41 | 18.20 |
| 10 | 6.54 | 27.64 | 1.32 | | 13.20 | 6.35 | 18.52 |
| 9 | 5.50 | 23.08 | 1.35 | | 13.54 | 6.54 | 17.75 |
| 8 | 5.20 | 21.88 | 1.30 | | 12.99 | 6.29 | 17.07 |
| 7 | 5.18 | 23.04 | 1.29 | | 11.64 | 5.59 | 15.81 |
| 6 | 5.71 | 21.05 | 1.28 | | 13.80 | 7.09 | 19.04 |
| 5 | 5.70 | 23.07 | 1.20 | | 13.82 | 6.74 | 19.09 |
| 4 | 5.65 | 23.69 | 1.30 | | 13.82 | 6.66 | 18.10 |
| 3 | 6.17 | 27.14 | 1.34 | | 13.26 | 6.30 | 17.88 |
| 2 | 6.10 | 26.80 | 1.33 | | 13.17 | 6.27 | 18.29 |
| 1 | 5.64 | 22.53 | 1.23 | | 13.80 | 7.15 | 18.78 |
| 0 | 5.80 | 25.52 | 1.28 | | 13.69 | 6.61 | 18.99 |

All values shown above represent the median of these runs, the median was used again to best show the measure of central tendency. From looking at the bus delay results, none of these variables seems significantly different than the others, as all values fall in the range of 1.30 +- 0.10. The only value that seems to be an outlier is the case with no TSP that shows a bus delay of 1.53 seconds and the slowest bus speed. To further analyze the data, A one-factor ANOVA test was performed to see if any means, not medians, significantly differed. The null hypothesis states that all means are equal with the alternative stating at least one mean is different than the others. Table 4.8 shows the ANOVA results.

Table 4.8: Model 1 Max Green ANOVA Results

| ALL Bus Delay ANOVA Results | | | | |
|---|---|---|---|---|
| *Groups* | *Count* | *Sum* | *Average* | *Variance* |
| NOTSP | 25 | 35.85 | 1.43 | 0.03 |
| 0 | 25 | 37.59 | 1.50 | 0.07 |
| 1 | 25 | 38.06 | 1.52 | 0.07 |
| 2 | 25 | 38.50 | 1.54 | 0.24 |
| 3 | 25 | 39.16 | 1.57 | 0.06 |
| 4 | 25 | 39.29 | 1.57 | 0.08 |
| 5 | 25 | 36.21 | 1.45 | 0.07 |
| 6 | 25 | 37.10 | 1.48 | 0.08 |
| 7 | 25 | 34.46 | 1.38 | 0.04 |
| 8 | 25 | 36.97 | 1.48 | 0.07 |
| 9 | 25 | 38.51 | 1.54 | 0.08 |
| 10 | 25 | 38.83 | 1.55 | 0.16 |
| 15 | 25 | 38.75 | 1.55 | 0.10 |
| 20 | 25 | 39.57 | 1.58 | 0.05 |
| ANOVA | | | | |
| *Source of Variation* | *SS* | *df* | *MS* | *F* |
| Between Groups | 1.16 | 13 | 0.09 | 1.04 |
| Within Groups | 28.63 | 336 | 0.09 | |
| | | | *P-value* | *F crit* |
| Total | 29.78 | 349 | 0.41 | 1.75 |

With a P-value of 0.41, we fail to reject the null hypothesis and conclude that there is no significant difference among these means. This means that there is no significant effect of using any value as the maximum green given back. These results were expected, since Scenario 3 for the two arterial network is not significant in decreasing delays, compared to the isolated intersection case when it was significant.

### 4.1.3 Non-Moving Vehicles

The other factor in Scenario 3 to be tested is the number of non-moving cars that will have priority on top of a bus requesting green time. The steps of Scenario 3 check if there is a pre-determined number of vehicles on the crossing street before responding to a bus request. In the previous step, the isolated intersection model concluded that any number of vehicles will have a significant impact on reducing bus delays while also having no effect on cross-street delays. This step was integrated into the code to make sure that buses will not have access if there are any non-moving vehicles on the cross-street , which implies congestion, buses in that case will wait until there is less than 1, on average, non-moving cross street vehicle before green time is allocated. Table 4.9 summarizes results for Model 1 with the non-moving vehicle threshold ranging from 0 to 10.

Table 4.9: Model 1 Non-Moving Vehicles Analysis

| Non-moving cars | Delays | | | | Speed | | |
|---|---|---|---|---|---|---|---|
| | N/S | E/W | Bus | | N/S | E/W | Bus |
| NO TSP | 5.21 | 24.04 | 1.53 | | 16.01 | 7.73 | 16.33 |
| 10 | 6.66 | 25.37 | 1.45 | | 11.12 | 6.09 | 16.91 |
| 5 | 6.10 | 21.94 | 1.41 | | 11.52 | 7.18 | 17.64 |
| 4 | 5.84 | 22.75 | 1.36 | | 14.05 | 6.99 | 18.08 |
| 3 | 6.17 | 24.43 | 1.39 | | 12.29 | 6.37 | 17.47 |
| 2 | 5.64 | 22.53 | 1.23 | | 13.80 | 7.15 | 18.78 |
| 1 | 5.62 | 22.44 | 1.26 | | 13.95 | 7.06 | 18.68 |
| 0 | 5.80 | 20.79 | 1.20 | | 13.65 | 7.34 | 18.23 |

Results show very minimal differences between the simulation runs, all bus delays now are less than the no TSP case, but none seems to be significantly different. The case of 0 non-moving vehicles has the lowest value for bus delays and also East/West traffic delays but it adds delays to the North/South traffic. Running a one-factor ANOVA test results in a P-value of 0.26 which means, again, none of these values are significantly different than the others. Leading us to another confirmation that regardless of what values or assumptions are used in Scenario 3 it will not yield significant results in this specific model.

#### 4.1.4 Cross-Street Volume Analysis

In the case of the single intersection, it was easy to visualize the effect that Scenario 3 has on delays. In two arterial street model, Scenario 3 did not yield significant effects. Due to these limitations, a cross-street volume analysis will not add any value to this chapter, therefor it will not be included.

## 4.2 Model 2: Left-Turn Pockets

For this model, left-turn pockets will not be tested as it is a one-way street with no opposing traffic that might create left-turn queues. The issue of opposing traffic is found in two-way streets. Using left-turn pockets in that scenario was proved to be significant in single intersections. This solution significantly affects the performance of TSP as it keeps left turn queues from blocking traffic going through the intersection. However, this is not an issue in one-way traffic models.

## 4.3 Model 3: Bus Lane Effect

Testing this variable would show us what relationship exists, if any, between traffic and buses in situations when they do not share a lane. The single intersection case proved that there is a significant difference when a bus lane is added and TSP as well. In this step, a simulation run before and after adding a bus lane will be made. The results should cover the effect of adding a bus lane on TSP performance, to achieve that we will compare the base case with and without a bus lane, then all three scenarios with and without a bus lane. Table 4.10 compares the cases of no TSP and no bus lane, with a bus lane only and Scenario 1.

**Table 4.10: Model 3 Scenario 1 Results**

| 1- NOTSP & No Bus Lane | | | | | | | |
|---|---|---|---|---|---|---|---|
| Delay | N/S | E/W | Bus | | N/S | E/W | Bus |
| Mean | 6.02 | 26.97 | 1.45 | Mean | 15.75 | 7.58 | 19.39 |
| SD | 2.80 | 10.26 | 1.08 | SD | 1.99 | 2.02 | 6.59 |
| Median | 5.21 | 24.04 | 1.53 | Median | 16.01 | 7.73 | 16.33 |
| 2- Bus Lane Only | | | | | | | |
| Delay | N/S | E/W | Bus | | N/S | E/W | Bus |
| Mean | 4.70 | 27.06 | 1.56 | Mean | 16.84 | 7.85 | 17.51 |
| SD | 1.00 | 12.81 | 0.75 | SD | 1.17 | 2.53 | 3.89 |
| Median | 4.47 | 22.91 | 1.58 | Median | 16.68 | 7.95 | 16.70 |
| 3- TSP & Bus Lane | | | | | | | |
| Delay | N/S | E/W | Bus | | N/S | E/W | Bus |
| Mean | 5.39 | 27.13 | 1.65 | Mean | 16.36 | 7.91 | 17.14 |
| SD | 2.44 | 14.05 | 0.80 | SD | 2.01 | 2.57 | 4.01 |
| Median | 4.48 | 24.99 | 1.65 | Median | 16.60 | 7.27 | 16.32 |
| 1 VS 2 Impact | | | | | | | |
| | -14.20% | -4.69% | 3.30% | | 4.20% | 2.91% | 2.24% |
| Sig Dif? | NO | NO | NO | Sig Dif? | NO | NO | NO |
| 1 VS 3 Impact | | | | | | | |
| | -13.85% | 3.95% | 7.80% | | 3.70% | -5.88% | -0.05% |
| Sig Dif? | NO | NO | NO | Sig Dif? | NO | NO | NO |
| 2 VS 3 Impact | | | | | | | |
| | 0.40% | 9.06% | 4.36% | | -0.48% | -8.55% | -2.24% |
| Sig Dif? | NO | NO | NO | Sig Dif? | NO | NO | NO |

Delay= Seconds/Vehicle, Speed= Miles/Hour, Sig Dif= Significant Difference

Adding a bus lane for Scenario 1 generated higher bus delay values, this shows the adding a bus lane will not simply make buses in one-way corridor travel faster. It also shows that using TSP and adding a bus lane will not produce a reduction in bus delays. Even though general traffic traveling North and South delays had been reduced more than 10%. Bus delays increasing defeat the purpose of TSP. This means that TSP or adding bus lane will not beneficial for the system. In cases like that it is better to leave the system as is or otherwise further damages would occur on bus delays and general traffic. The next step is to test the impacts of Scenario 2 and Scenario 3 on the same two base cases. Table 4.11 summarizes these results.

**Table 4.11: Model 3 Scenario 2 & Scenario 3 Results**

| | | | | | | | |
|---|---|---|---|---|---|---|---|
| 1- NOTSP & No Bus Lane | | | | | | | |
| Delay | N/S | E/W | Bus | Speed | N/S | E/W | Bus |
| Mean | 6.02 | 26.97 | 1.45 | Mean | 15.75 | 7.58 | 19.39 |
| SD | 2.80 | 10.26 | 1.08 | SD | 1.99 | 2.02 | 6.59 |
| Median | 5.21 | 24.04 | 1.53 | Median | 16.01 | 7.73 | 16.33 |
| 2- Bus Lane Only | | | | | | | |
| Delay | N/S | E/W | Bus | Speed | N/S | E/W | Bus |
| Mean | 4.70 | 27.06 | 1.56 | Mean | 16.84 | 7.85 | 17.51 |
| SD | 1.00 | 12.81 | 0.75 | SD | 1.17 | 2.53 | 3.89 |
| Median | 4.47 | 22.91 | 1.58 | Median | 16.68 | 7.95 | 16.70 |
| Scenario#2: TSP & Bus Lane | | | | | | | |
| Delay | N/S | E/W | Bus | Speed | N/S | E/W | Bus |
| Mean | 7.46 | 31.32 | 0.94 | Mean | 13.87 | 7.39 | 20.98 |
| SD | 1.91 | 16.82 | 0.46 | SD | 1.54 | 2.81 | 2.94 |
| Median | 7.31 | 28.89 | 0.85 | Median | 13.64 | 6.65 | 20.85 |
| Scenario#2: 1 VS 3 Impact | | | | | | | |
| | 40.52% | 20.16% | -44.63% | | -14.81% | -13.95% | 27.64% |
| Sig Dif? | NO | NO | NO | Sig Dif? | NO | NO | NO |
| Scenario#2: 2 VS 3 Impact | | | | | | | |
| | 63.77% | 26.07% | -46.40% | | -18.24% | -16.38% | 24.84% |
| Sig Dif? | NO | NO | NO | Sig Dif? | NO | NO | NO |
| Scenario#3: TSP & Bus Lane | | | | | | | |
| Delay | N/S | E/W | Bus | Speed | N/S | E/W | Bus |
| Mean | 7.03 | 29.58 | 1.40 | Mean | 14.64 | 7.92 | 18.39 |
| SD | 2.64 | 16.74 | 0.80 | SD | 2.03 | 2.83 | 4.03 |
| Median | 6.70 | 27.03 | 1.23 | Median | 14.89 | 7.12 | 18.39 |
| Scenario#3: 1 VS 3 Impact | | | | | | | |
| | 28.70% | 12.43% | -19.56% | | -7.02% | -7.79% | 12.59% |
| Sig Dif? | NO | NO | NO | Sig Dif? | NO | NO | NO |
| Scenario#3: 2 VS 3 Impact | | | | | | | |
| | 50.00% | 17.96% | -22.12% | | -10.77% | -10.40% | 10.11% |
| Sig Dif? | NO | NO | NO | Sig Dif? | NO | NO | NO |

Delay= Seconds/Vehicle, Speed= Miles/Hour, Sig Dif= Significant Difference

In the case of Scenario 2 and adding a bus lane, TSP was successful in decreasing median bus delays around 46%, however this huge decrease came with an expensive price tag that cost general traffic delay increases of 20% to 63% percent. The case of Scenario 3 had the same type of results but only in a smaller magnitude, it decreased bus delays by 19% to 22% and had negative impacts on general traffic of 12% to 50%. To move forward, the best case is once again Scenario 3 that minimizes bus delays by a considerable amount while also minimizing impacts on general traffic.

## 4.4 Model 4: Multi-directional bus traffic

In the single intersection case, Scenario 4 was created to give priority to certain buses in the case of multiple requests from buses not traveling in the same direction. The condition for this model, Scenario 4 will give priority to buses traveling in the North/South direction over buses traveling East/West. The same base case will be used while adding buses traveling East on one of the cross streets with a headway of 5 minutes, and buses traveling West on another street with the same headways. In this model, a run with Scenario 3 will be compared with a run with Scenario 4. Table 4.12 summarize the results for both runs.

**Table 4.12: Model 4 Results**

| Bus Scenario#3 | | | | | |
|---|---|---|---|---|---|
| Delay | N/S Bus | E/W Bus | Speed | N/S Bus | E/W Bus |
| Mean | 1.80 | 5.38 | Mean | 17.35 | 8.47 |
| SD | 1.18 | 2.26 | SD | 4.54 | 3.92 |
| Median | 1.59 | 5.15 | Median | 16.21 | 7.90 |
| Bus Scenario#4 | | | | | |
| Delay | N/S Bus | E/W Bus | Speed | N/S Bus | E/W Bus |
| Mean | 1.75 | 5.28 | Mean | 17.05 | 8.66 |
| SD | 1.13 | 2.29 | SD | 4.75 | 3.59 |
| Median | 1.57 | 5.17 | Median | 16.61 | 7.80 |
| Impact | | | | | |
| | -1.25% | 0.29% | | 2.47% | -1.27% |
| Sig Dif? | NO | NO | Sig Dif? | NO | |
| Delay= Seconds/Vehicle, Speed= Miles/Hour, Sig Dif= Significant Difference | | | | | |

Results show very minimal differences between Scenario 4 and Scenario 3. Following the single intersection results pattern, North/South bound bus traffic delays are now minimized using Scenario 4 and the effect on East/West is increased delays. According to these results, the case where both buses require TSP in the same time period is very slim and highly unlikely to happen.

## 4.5 Summary

This chapter includes a CORSIM model built with two main corridors intersecting 7 cross-streets. These two corridors are each 3 lane one-way streets, one traveling North only and one is traveling South only. The reason behind choosing this setting is to make sure that the area of interest is larger than a single intersection and also larger than the traditional single one-way corridor that is historically tested in previous studies. There were 4 models tested in this chapter:

1. Model 1 includes a base case with 3 unrestricted lanes of travel for each corridor, no left turn pockets and one 5 min headway bus traveling North, another traveling South.

2. Model 2 includes left-turn pockets, after setting up this model, results showed no difference as the one-way corridors by design have no left-turn queues, results were not reported in this study.

3. Model 3 includes a comparison of adding a bus lane to the base case model.

4. Model 4 serves as an example of how TSP would treat multi-direction bus traffic, while keeping the North/South buses in the model, two 5 min headways buses were added to the network, one traveling East and one traveling West (both on different cross-streets)

The following bullet points summarize the results found in this chapter.

2.2.2.23. The effect of progression:

Using Kell method, a space-time diagram was created to show the impacts of progression on the network based on the spacing of the intersections and also the offset time between the signal cycles. Two progression offset values were calculated based on the existing speed of the main corridor and also the free flow speed. Both values were used to adjust two different cases and compared to the base case, results showed that 9 seconds offset proved to make buses travel faster, however not significantly faster, while 18 second progression significantly decreased traffic speeds on the North/South corridor.

2.2.2.24. Effectiveness of the three TSP scenarios

The 9 seconds progression offset (30 mph progression speed) and the base case are not significantly different, but with the 9 seconds offset case being slightly better, both cases were used to compare the three scenario effects. Using the mean to compare both results showed 1% to 3% changes, but standard deviations were also very high compared to the single intersection case. This was expected due to the fact that now there are more parameters and variables involved in each simulation run, which will generate values with larger variations. To overcome this issue the median was used as a supplement to the means as a measure of central tendency. All results in this chapter used the median to show the percentage of impact. The base case showed improvements better than the case of 9 seconds offset. Scenario 1 showed increased bus delays in the progression phase, while both Scenario 2 and Scenario 3 showed reductions in bus delays. Overall, the best case scenario is Scenario 3 as it results in up to a 19% reduction in bus delay, while only 6 to 8% increased delays to general traffic.

2.2.2.25. Quantify max green (for Scenario 3)

The Max green constraint works when Scenario 3 takes green time away from the cross-street and adds a specific amount of green time back to the cross-street green time. This value is called max green time. Multiple trials with different quantities of max green time given back were made with values ranging from 0 to 20 seconds. Results showed that even though the median for these results is smaller than the case of no TSP, ANOVA results showed no significant difference in the means of these values.

#### 2.2.2.26. Quantify non-moving vehicles (for Scenario 3)

This constraint works when Scenario 3 responds to a bus request by checking how many non-moving vehicles are on the cross-street before granting a green light to the bus direction of travel. Using values from 0 to 10 non-moving cars as a constraint for Scenario 3, results showed no significant difference among the tested values and also the case of no TSP.

#### 2.2.2.27. Analyze cross-street volumes

This case was not tested due to the fact that none of the previous constraints were significant.

#### 2.2.2.28. The effect of adding bus lanes

For this parameter, three sets of cases were compared. Case 1 the base case was compared to the base case with an added bus lane as case 2 and Case 3 in which the bus lane with additional features were employed. Comparing each scenario to the first two cases, Scenario 1 showed increased delays in bus travel time, while both Scenario 2 and Scenario 3 showed reductions. However, both scenarios had large values of negative impacts on the general traffic leading to a conclusion that TSP is not the best way to handle bus traffic in one-way corridors.

#### 2.2.2.29. Analyze multi-direction bus traffic

After adding buses to cross-streets, Scenario 4 was adjusted to give priority to buses traveling in North/South corridor. Impact percentages were very minimal ranging from 0 to 2%. Results showed no significant difference between Scenario 3 and Scenario 4 which means the chances of two buses requesting green time simultaneously is very small.

# Chapter 5. Two-way Corridor Model

This chapter serves as an extension of chapter 4 that covered a corridor with one-way traffic. On chapter 5, a corridor with two-way traffic is tested. Traffic behavior for one-way traffic is different than two-way, one of the biggest differences is the ability to take a left-turn with no opposing traffic. Also, the fact that all allocated green time will be for traffic going one direction only in comparison to two directions can change the quality of the intersection dramatically. These different behaviors affect the performance of TSP, therefore there is a need to test the effect of TSP on a two-way corridor as well. This chapter will cover all factors tested in the previous chapter, these models are listed as follows:

1. The effect of progression
2. Effectiveness of the three TSP scenarios
3. Quantify max green (for Scenario 3)
4. The effect of adding left-turn pockets
5. The effect of adding bus lanes
6. Analyze multi-direction bus traffic

## 5.1 Model 1: Corridor Progression

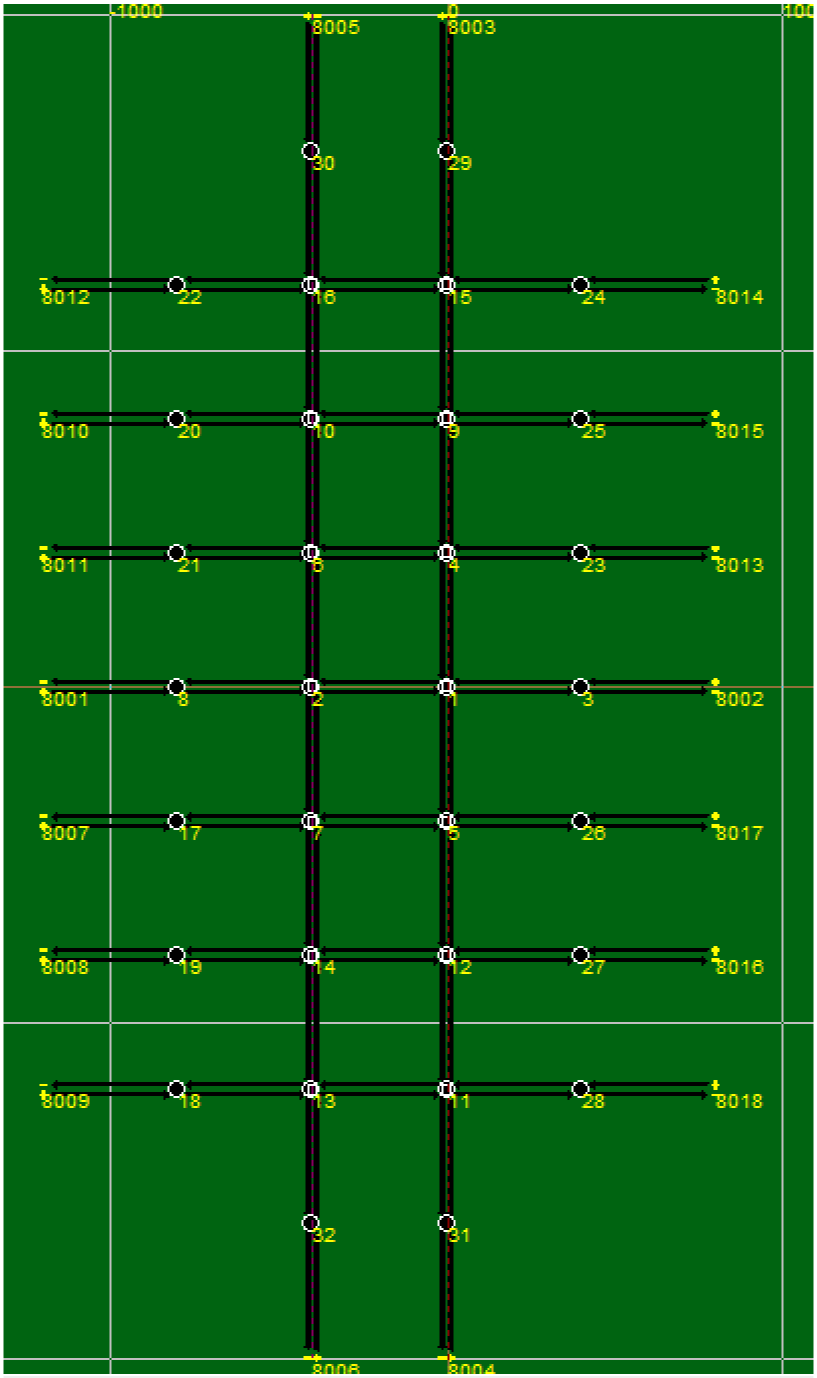
This model will use chapter 4's base model with a few adjustments to the assumptions and the CORSIM configurations. To be consistent with the previous assumptions, signal times and flows did not change, two-way links were added on top of the one-way links, the main corridor is now two lanes traveling in opposing directions, instead of a three-lane one-way corridor. Table 5.1 summarizes the assumptions in this model.

**Table 5.1: Model 1 Assumptions**

| Direction | Lanes | Turning | | | Green time | Cycle length | G/C ratio | Capacity per hour | Volume | V/C |
|---|---|---|---|---|---|---|---|---|---|---|
| | | Left | Thru | Right | | | | | | |
| NB | 2 | 15 | 70 | 15 | 55 | 90 | 0.61 | 2322 | 1000 | 0.431 |
| SB | 2 | 15 | 70 | 15 | | | | 2322 | 1000 | 0.431 |
| EB | 2 | 40 | 20 | 40 | 25 | | 0.28 | 1056 | 500 | 0.474 |
| WB | 2 | 40 | 20 | 40 | | | | | 500 | 0.474 |

Figure 5.1 shows the CORSIM configuration used in this chapter.

**Figure 5.1: Model 1 CORSIM configuration**




The first step in this chapter is to test the effect of progression on bus travel time and the general traffic. In the previous chapter, the Kell method was used to draw the time-space diagram to come up with the best offset time to create progression between the corridors intersections. In this chapter, the complexity level of progression is higher than the one-way streets. Using a simple 9 second progression offset is no longer feasible as there are two directions of travel requiring progression. Mannering (2013) approached this by determining the cycle length based on the speed of traffic and the distance between intersections, once the cycle length is calculated, 50% of that cycle length will be the new effective green light for the direction of travel. However, this approach will put the main corridor effective green time at 0.5 instead of the current 0.61 of the available green time. The cycle length based on speed and distance between intersections may be estimated using the following equation:

$$C_{progression} = \frac{d}{V} * 2 \qquad \text{(Mannering)}$$

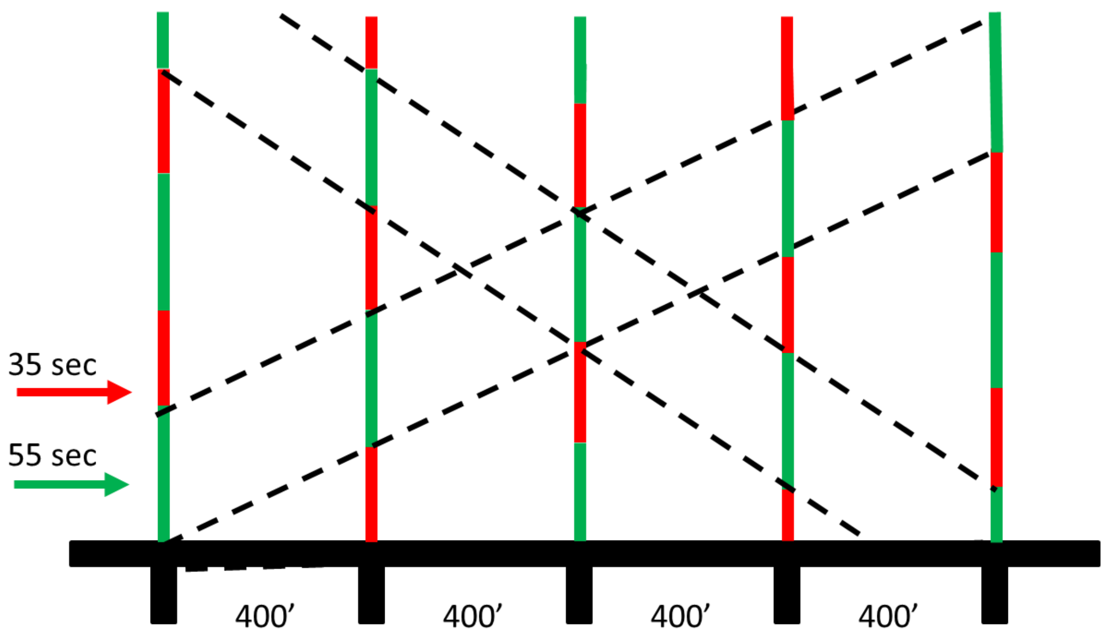
Where

d= Distance between intersections (feet)

V= Speed (ft/s)

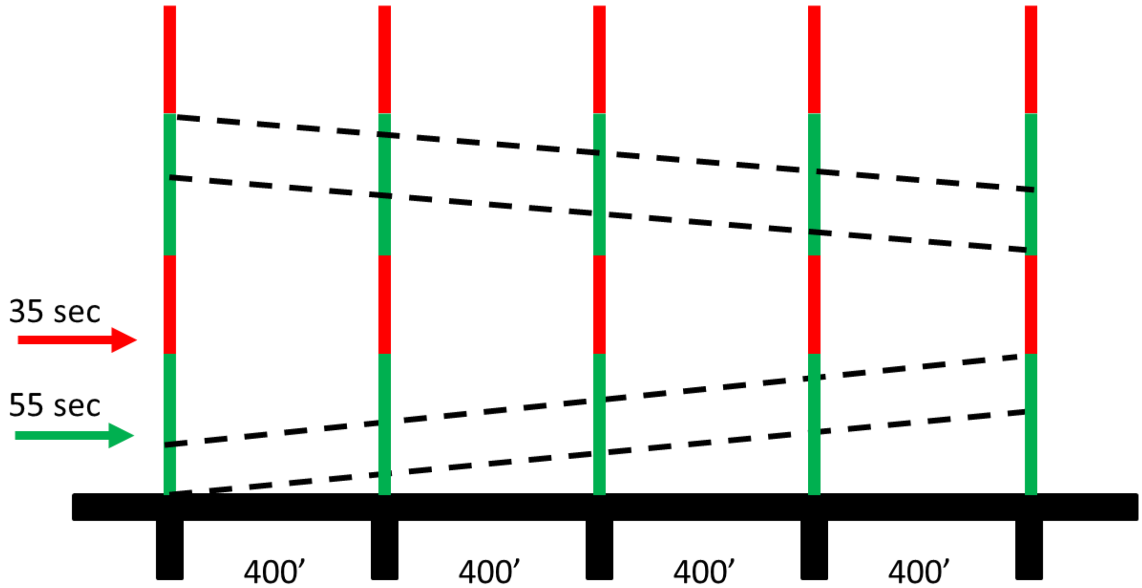
The results for the new cycle are offset is 18 seconds or 36, using 44 ft/s or 22 ft/s respectively. This is almost one-third of the existing signal cycle length. This makes changing the cycle length not ideal for testing TSP and keeping the consistency of all models. Using Kell method to draw a time-space diagram resulted in Figure 5.2, which shows if using an offset of 35 seconds there is a potential perfectly symmetric graph that implies a good progression on both directions of travel.

**Figure 5.2: Model 1 35 seconds time-space diagram**




The major issues with this graph are that speed is now lowered to around 10 ft/s which defeats the purpose of coordinating signals to let cars travel faster. While keeping the cycle length at 90 seconds, with the main corridor's green time as 55 seconds it will be challenging to create a progression that would work under the current free flow speed of 30 mph. Running few different Kell method graphs to get the best case of progression it was found that using no progression, or offset of zero for all intersection while be the most ideal case. Figure 5.3 shows all intersection start simultaneously. This will have speeds of around 44 ft/s while also letting around 27 vehicle platoons to travel in that bandwidth.

**Figure 5.3: Model 1 no offset time-space diagram**




At this point to see the effect of progression on traffic, three values 9, 18 and 35 need to be tested and compared to the base case with no progression (zero offset). Using offset values of 9, 18 and 35 seconds in CORSIM, Table 5.2 summarizes the results. The 35 sec offset provides a progression speed of 11 ft/s, 18 seconds is 22 ft/s and 9 seconds is 44 ft/sec with the case of zero progression providing slightly more than 44 ft/s.

**Table 5.2: Model 1 Progression Effect**

| No TSP | | | | | | | |
|---|---|---|---|---|---|---|---|
| Delay | N/S | E/W | Bus | Speed | N/S | E/W | Bus |
| Mean | 12.20 | 20.75 | 2.24 | Mean | 11.12 | 8.29 | 13.22 |
| SD | 2.84 | 2.64 | 0.96 | SD | 1.44 | 0.43 | 4.55 |
| Median | 11.56 | 21.00 | 2.21 | Median | 11.21 | 8.24 | 13.47 |
| Progression 35 Seconds | | | | | | | |
| Delay | N/S | E/W | Bus | Speed | N/S | E/W | Bus |
| Mean | 15.74 | 21.00 | 4.27 | Mean | 9.59 | 8.22 | 9.03 |
| SD | 3.44 | 2.63 | 1.16 | SD | 1.54 | 0.45 | 2.38 |
| Median | 15.41 | 21.18 | 4.47 | Median | 9.44 | 8.17 | 8.55 |
| Impact | | | | | | | |
| | 33.30% | 0.82% | 102.36% | | -15.82% | -0.88% | -36.55% |
| Sig Dif? | NO | NO | NO | Sig Dif? | NO | NO | NO |

| Progression 18 Seconds | | | | | | | |
|---|---|---|---|---|---|---|---|
| Delay | N/S | E/W | Bus | Speed | N/S | E/W | Bus |
| Mean | 13.35 | 20.95 | 2.78 | Mean | 10.39 | 8.24 | 11.83 |
| SD | 2.45 | 2.55 | 0.91 | SD | 1.33 | 0.44 | 3.68 |
| Median | 12.91 | 21.27 | 2.65 | Median | 10.25 | 8.20 | 12.24 |
| Impact | | | | | | | |
| | 11.69% | 1.27% | 20.03% | | -8.59% | -0.56% | -9.15% |
| Sig Dif? | NO | NO | NO | Sig Dif? | NO | NO | NO |

| Progression 9 Seconds | | | | | | | |
|---|---|---|---|---|---|---|---|
| Delay | N/S | E/W | Bus | Speed | N/S | E/W | Bus |
| Mean | 12.32 | 20.92 | 2.28 | Mean | 10.96 | 8.24 | 13.59 |
| SD | 3.00 | 2.40 | 1.02 | SD | 1.42 | 0.39 | 5.32 |
| Median | 11.59 | 21.02 | 2.20 | Median | 11.03 | 8.23 | 13.17 |
| Impact | | | | | | | |
| | 0.29% | 0.07% | -0.39% | | -1.65% | -0.13% | -2.21% |
| Sig Dif? | NO | NO | NO | Sig Dif? | NO | NO | NO |

According to these results, using a 35 second offset is extremely damaging to the bus traffic. It also has negative impacts on North/South traffic. The 18 second offset also produced negative results on all categories. The only offset that results in reduction of bus traffic delay is 9 seconds and that reduction is only -0.39%. The best case to be used as the base case is the case with no progression since it has the lowest delays, meaning that all the next simulations will be built based on the model with zero offset between all signals.

5.1.1 All Scenarios

Following Chapters 3 and 4, a base case with the three scenarios is built in CORSIM. Table 5.3 shows the impact of these three scenarios on the base case.

**Table 5.3: Model 1 All Scenarios Results**

| No TSP | | | | | | | |
|---|---|---|---|---|---|---|---|
| Delay | N/S | E/W | Bus | Speed | N/S | E/W | Bus |
| Mean | 12.20 | 20.75 | 2.24 | Mean | 11.12 | 8.29 | 13.22 |
| SD | 2.84 | 2.64 | 0.96 | SD | 1.44 | 0.43 | 4.55 |
| Median | 11.56 | 21.00 | 2.21 | Median | 11.21 | 8.24 | 13.47 |
| Scenario#1 TSP | | | | | | | |
| Delay | N/S | E/W | Bus | Speed | N/S | E/W | Bus |
| Mean | 12.85 | 20.79 | 2.28 | Mean | 10.79 | 8.27 | 13.06 |
| SD | 3.03 | 2.66 | 0.96 | SD | 1.45 | 0.44 | 4.60 |
| Median | 12.10 | 21.20 | 2.22 | Median | 10.87 | 8.26 | 13.30 |
| Impact | | | | | | | |
| | 4.64% | 0.94% | 0.39% | | -3.01% | 0.26% | -1.22% |
| Sig Dif? | NO | NO | NO | Sig Dif? | NO | NO | NO |
| | | | | | | | |
| Scenario#2 TSP | | | | | | | |
| Delay | N/S | E/W | Bus | Speed | N/S | E/W | Bus |
| Mean | 13.54 | 24.95 | 2.00 | Mean | 10.42 | 7.34 | 14.40 |
| SD | 3.18 | 2.81 | 0.89 | SD | 1.54 | 0.54 | 4.84 |
| Median | 12.92 | 24.75 | 1.88 | Median | 10.33 | 7.35 | 14.68 |
| Impact | | | | | | | |
| | 11.76% | 17.84% | -14.68% | | -7.88% | -10.87% | 8.97% |
| Sig Dif? | NO | NO | NO | Sig Dif? | NO | NO | NO |
| | | | | | | | |
| Scenario#3 TSP | | | | | | | |
| Delay | N/S | E/W | Bus | Speed | N/S | E/W | Bus |
| Mean | 13.14 | 24.65 | 1.97 | Mean | 10.60 | 7.41 | 14.57 |
| SD | 2.88 | 2.72 | 0.93 | SD | 1.46 | 0.55 | 4.98 |
| Median | 12.66 | 24.41 | 1.92 | Median | 10.48 | 7.44 | 14.55 |
| Impact | | | | | | | |
| | 9.49% | 16.19% | -13.21% | | -6.50% | -9.72% | 8.00% |
| Sig Dif? | NO | NO | NO | Sig Dif? | NO | NO | NO |

These results are similar to the results found in Chapter 4 Model 1. Scenario 2 results in the best reduction of bus delays while Scenario 3 had overall better impact by minimizing bus delays while also having minimum impacts on general traffic. These results were somehow expected given that none of the previous scenarios proved to be significant with Chapter 4, one-way corridor. this is due to the fact that these two models now have higher number of parameters and variables to be included in the model than the single isolated intersection. One single intersection compared to 14 intersection added a lot of noise in the model and it was seen that the means of the scenarios runs are more scatter leading to a smaller chance of finding significant difference while testing for it.

Here it should be noted that after running t tests, none of the 6 categories tested for the three scenarios yielded significant differences. This means that TSP used in a one-way corridor or a two-way corridor will not have significant impacts on minimizing bus delay. At this point, there is no need to analyze the following models as there will likely be no significant effects:

- Max green
- Non-moving cars
- Cross-street volume analysis
- Multi-direction bus travel

Even though there was no significant difference found, these results are considered positive as all medians for the simulation runs that were made moved toward a reduction in bus delays.

## 5.2 Model 2: Left-Turn Pockets

This model is essential in understanding the effect of TSP because after failing to find significant effects, one solution might be removing queues that are caused by left-turners. To test the effect of left-turn pockets, the CORSIM model was adjusted to have 200’ left-turn pockets for the main corridor travel paths. Table 5.4 shows the results for all scenarios versus the base case all having left-turn pockets.

**Table 5.4: Model 2 Left-Turn Pockets Results**

| No TSP | | | | | | | |
|---|---|---|---|---|---|---|---|
| Delay | N/S | E/W | Bus | Speed | N/S | E/W | Bus |
| Mean | 8.59 | 19.92 | 1.47 | Mean | 13.68 | 8.45 | 16.76 |
| SD | 2.18 | 2.17 | 0.81 | SD | 1.50 | 0.37 | 6.50 |
| Median | 7.98 | 20.04 | 1.35 | Median | 13.71 | 8.43 | 16.91 |
| Scenario#1 TSP | | | | | | | |
| Delay | N/S | E/W | Bus | Speed | N/S | E/W | Bus |
| Mean | 8.74 | 19.93 | 1.45 | Mean | 13.58 | 8.45 | 16.77 |
| SD | 2.29 | 2.17 | 0.77 | SD | 1.50 | 0.38 | 6.15 |
| Median | 8.08 | 20.05 | 1.33 | Median | 13.66 | 8.43 | 17.14 |
| Impact | | | | | | | |
| | 1.27% | 0.05% | -1.81% | | -0.38% | 0.05% | 1.31% |
| Sig Dif? | NO | NO | NO | Sig Dif? | NO | NO | NO |

| Scenario#2 TSP | | | | | | | |
|---|---|---|---|---|---|---|---|
| Delay | N/S | E/W | Bus | Speed | N/S | E/W | Bus |
| Mean | 9.60 | 23.07 | 1.23 | Mean | 12.67 | 7.70 | 17.88 |
| SD | 1.74 | 2.24 | 0.61 | SD | 1.16 | 0.60 | 6.03 |
| Median | 9.58 | 22.94 | 1.13 | Median | 12.58 | 7.70 | 18.08 |
| Impact | | | | | | | |
| | 20.10% | 14.46% | -16.17% | | -8.27% | -8.69% | 6.91% |
| Sig Dif? | NO | NO | NO | Sig Dif? | NO | NO | NO |

| Scenario#3 TSP | | | | | | | |
|---|---|---|---|---|---|---|---|
| Delay | N/S | E/W | Bus | Speed | N/S | E/W | Bus |
| Mean | 9.20 | 21.85 | 1.37 | Mean | 13.05 | 7.98 | 17.74 |
| SD | 2.00 | 2.07 | 0.89 | SD | 1.34 | 0.57 | 6.89 |
| Median | 9.12 | 21.73 | 1.27 | Median | 12.94 | 8.03 | 17.64 |
| Impact | | | | | | | |
| | 14.31% | 8.46% | -6.37% | | -5.65% | -4.66% | 4.31% |
| Sig Dif? | NO | NO | NO | Sig Dif? | NO | NO | NO |

Surprisingly, the effects were not significant. The percent reduction values are now less than those found in the case where there are no left-turn pockets. Even though bus delays values are now significantly less in comparison to the case of no left-turn pockets, none of the scenarios showed significant improvement in any of the 6 tested categories.

## 5.3 Model 3: Bus Lane Effect

In Model 3, a bus lane was added to both directions of travel in hopes to get significant impacts for TSP in this chapter. Table 5.5 shows the results of running a simulation with a base case that has no TSP and no bus lane, along with another base case of an additional bus lane, both cases compared to Scenario 1 results.

**Table 5.5: Model 3 Scenario 1 Results**

| 1- NOTSP & No Bus Lane | | | | | | | |
|---|---|---|---|---|---|---|---|
| | N/S | E/W | Bus | | N/S | E/W | Bus |
| Mean | 12.20 | 20.75 | 2.24 | Mean | 11.12 | 8.29 | 13.22 |
| SD | 2.84 | 2.64 | 0.96 | SD | 1.44 | 0.43 | 4.55 |
| Median | 11.56 | 21.00 | 2.21 | Median | 11.21 | 8.24 | 13.47 |
| 2- Bus Lane Only | | | | | | | |
| | N/S | E/W | Bus | | N/S | E/W | Bus |
| Mean | 10.81 | 19.60 | 1.43 | Mean | 11.98 | 8.57 | 16.59 |
| SD | 2.92 | 1.53 | 0.71 | SD | 1.68 | 0.43 | 5.88 |
| Median | 10.22 | 19.52 | 1.53 | Median | 12.07 | 8.55 | 16.36 |
| 3- TSP & Bus Lane | | | | | | | |
| | N/S | E/W | Bus | | N/S | E/W | Bus |
| Mean | 11.11 | 19.79 | 1.45 | Mean | 11.82 | 8.51 | 16.62 |
| SD | 3.10 | 1.53 | 0.74 | SD | 1.73 | 0.43 | 6.10 |
| Median | 10.51 | 19.76 | 1.53 | Median | 11.83 | 8.53 | 16.20 |
| 1 VS 2 Impact | | | | | | | |
| | -11.56% | -7.07% | -30.82% | | 7.67% | 3.77% | 21.50% |
| Sig Dif? | NO | NO | NO | Sig Dif? | NO | NO | NO |
| 1 VS 3 Impact | | | | | | | |
| | -9.04% | -5.93% | -30.57% | | 5.55% | 3.48% | 20.30% |
| Sig Dif? | NO | NO | NO | Sig Dif? | NO | NO | NO |
| 2 VS 3 Impact | | | | | | | |
| | 2.85% | 1.23% | 0.36% | | -1.97% | -0.28% | -0.99% |
| Sig Dif? | NO | NO | NO | Sig Dif? | NO | NO | NO |

Delay= Seconds/Vehicle, Speed= Miles/Hour, Sig Dif= Significant Difference

Looking at the comparison of the First case versus the Second case, it can be seen that adding a bus lane will reduce bus delays and also general traffic delays, this behavior was not noticed in chapter 4 with one-way corridors as adding a bus lane resulted in delays for bus travel time. This could be because in the earlier case we had 3 lanes of traffic with an additional bus lane, but in this case we have only 2 lanes with an additional bus lane. This comparison means that buses in both cases had a designated lane, but one case had no opposing traffic and free flow for all lanes during green signals which maximizes the use of the green time. But in this case left turns face opposing traffic this effect can be seen in the results. Table 5.6 summarizes the same comparison made in the previous table, but with Scenario 2 and Scenario 3.

**Table 5.6: Model 3 Scenario 2 & Scenario 3 Results**

| | | | | | | | |
|---|---|---|---|---|---|---|---|
| 1- NOTSP & No Bus Lane | | | | | | | |
| | N/S | E/W | Bus | | N/S | E/W | Bus |
| Mean | 12.20 | 20.75 | 2.24 | Mean | 11.12 | 8.29 | 13.22 |
| SD | 2.84 | 2.64 | 0.96 | SD | 1.44 | 0.43 | 4.55 |
| Median | 11.56 | 21.00 | 2.21 | Median | 11.21 | 8.24 | 13.47 |
| 2- Bus Lane Only | | | | | | | |
| | N/S | E/W | Bus | | N/S | E/W | Bus |
| Mean | 10.81 | 19.60 | 1.43 | Mean | 11.98 | 8.57 | 16.59 |
| SD | 2.92 | 1.53 | 0.71 | SD | 1.68 | 0.43 | 5.88 |
| Median | 10.22 | 19.52 | 1.53 | Median | 12.07 | 8.55 | 16.36 |
| Scenario#2: TSP & Bus Lane | | | | | | | |
| | N/S | E/W | Bus | | N/S | E/W | Bus |
| Mean | 11.18 | 23.55 | 0.68 | Mean | 11.59 | 7.64 | 21.49 |
| SD | 2.42 | 2.58 | 0.38 | SD | 1.44 | 0.76 | 6.24 |
| Median | 10.86 | 23.25 | 0.60 | Median | 11.55 | 7.62 | 22.81 |
| Scenario#2: 1 VS 3 Impact | | | | | | | |
| | -6.06% | 10.67% | -72.90% | | 2.99% | -7.55% | 69.35% |
| Sig Dif? | NO | NO | NO | Sig Dif? | NO | NO | NO |
| Scenario#2: 2 VS 3 Impact | | | | | | | |
| | 6.22% | 19.09% | -60.83% | | -4.34% | -10.90% | 39.38% |
| Sig Dif? | NO | NO | NO | Sig Dif? | NO | NO | NO |
| Scenario#3: TSP & Bus Lane | | | | | | | |
| | N/S | E/W | Bus | | N/S | E/W | Bus |
| Mean | 11.24 | 21.96 | 1.12 | Mean | 11.65 | 7.99 | 18.64 |
| SD | 2.76 | 2.33 | 0.69 | SD | 1.55 | 0.70 | 6.28 |
| Median | 10.85 | 21.57 | 0.98 | Median | 11.66 | 8.08 | 19.42 |
| Scenario#3: 1 VS 3 Impact | | | | | | | |
| | -6.17% | 2.69% | -55.50% | | 3.96% | -2.00% | 44.22% |
| Sig Dif? | NO | NO | NO | Sig Dif? | NO | NO | NO |
| Scenario#3: 2 VS 3 Impact | | | | | | | |
| | 6.09% | 10.51% | -35.67% | | -3.44% | -5.56% | 18.70% |
| Sig Dif? | NO | NO | NO | Sig Dif? | NO | NO | NO |

Delay= Seconds/Vehicle, Speed= Miles/Hour, Sig Dif= Significant Difference

Scenario 2 results in the highest reduction in bus delays up to 72%. This also resulted in a higher impact on general traffic with median values of up to 19%. While Scenario 3 had negative impacts of up to 10% on general traffic it also resulted in a very high impact on the case where it is used with a bus lane vs no bus lane and no TSP case. This shows that TSP used with a bus lane it can improve bus delays. While previous results showed that Scenario 3 TSP only improved bus delays by 13% and the case of No TSP and no bus lane compared to adding a bus lane (1 versus

2 in the Scenario 1 results) showed 30%. Using both at the same time resulted in a massive 55% reduction.

## 5.4 Summary

This chapter includes a CORSIM model built with two main corridors intersecting with 7 cross-streets. These two arterial streets each have 2 lane two-way corridors. This serves as an expansion of the previous chapter were only one-way streets were considered as the main corridors. Choosing different types of corridors means different characteristics of traffic flow which was reflected in the results. There were 4 models tested in this chapter:

- Model 1 includes a base case with 2 unrestricted lanes of travel for each two-way street, no left turn pockets and buses with 5 minute headways traveling North and South.

- Model 2 includes left-turn pockets, this model was built based on the base case, same assumption and traffic flows with an addition of 200’ left turn pockets in the main corridor direction at all intersections.

- Model 3 includes a comparison of adding a bus lane to the base case model.

2.2.2.30. The effect of progression:

In this chapter, two progression offset values were calculated based on the existing speed of the main corridor and also the free flow speed, while also keeping the 9 seconds offset value from the previous chapter. The three values were used to adjust three different cases and are compared to the base case. Results showed that 9 seconds offset allowed buses to travel faster by only 0.39%, while the 18 second progression offset increased bus speeds of up to 20% and the worst case was the 35 seconds offset which increased delays by 102%. The only case with minimal to no impact on all 6 categories tested was the case of 9 second progression. However, the case of no offset progression was chosen to be the base case for all the next models.

2.2.2.31. Effectiveness of the three TSP scenarios

After running the three scenarios and comparing results to the base case, Scenario 1 had very minimal impacts across all 6 categories, while both Scenario 2 and Scenario 3 showed reductions in bus delays, 14% and 13% respectively. For general traffic, both scenarios, 2 and 3 had similar impacts on general traffic with Scenario 3 producing slightly less delay.

2.2.2.32. The effect of adding bus lanes

Following chapters 4 and 5, cases were created to test the effect of bus lanes: 1 main base case with no bus lane, 1 bus lane case and 3 scenarios. After comparing each scenario to the first two cases, Scenario 1 showed reductions in delays for buses and also general traffic in comparison to no bus lane and no TSP. However, Scenario 1 did not improve the case where there was a bus lane, leading to conclusion that either using TSP or adding a bus lane, both will result in approximately same delay reductions. While both Scenario 2 and Scenario 3 showed reductions for bus delays in comparison to no bus lane and only a bus lane, both resulted in increased delays for general traffic in the case of using a bus lane versus TSP. This leads to a conclusion that using TSP, either Scenario 2 or 3 without a bus lane decreases bus delays while also decreasing North/South general traffic delays. The only difference is that Scenario 2 decreases bus delays up to 72% while increasing cross-street delays by 10%, while Scenario 3 decreases bus delays up to 55% while only increasing cross-street delays by 2%. In conclusion, the best case is Scenario 3.

Since none of the values for Scenario 3 were significantly different, testing the following parameters will not result in any significant difference and analyzing their results will not add to the study:

1. Max green
2. Non-moving vehicles
3. Cross-street volumes
4. Multi-direction bus traffic.

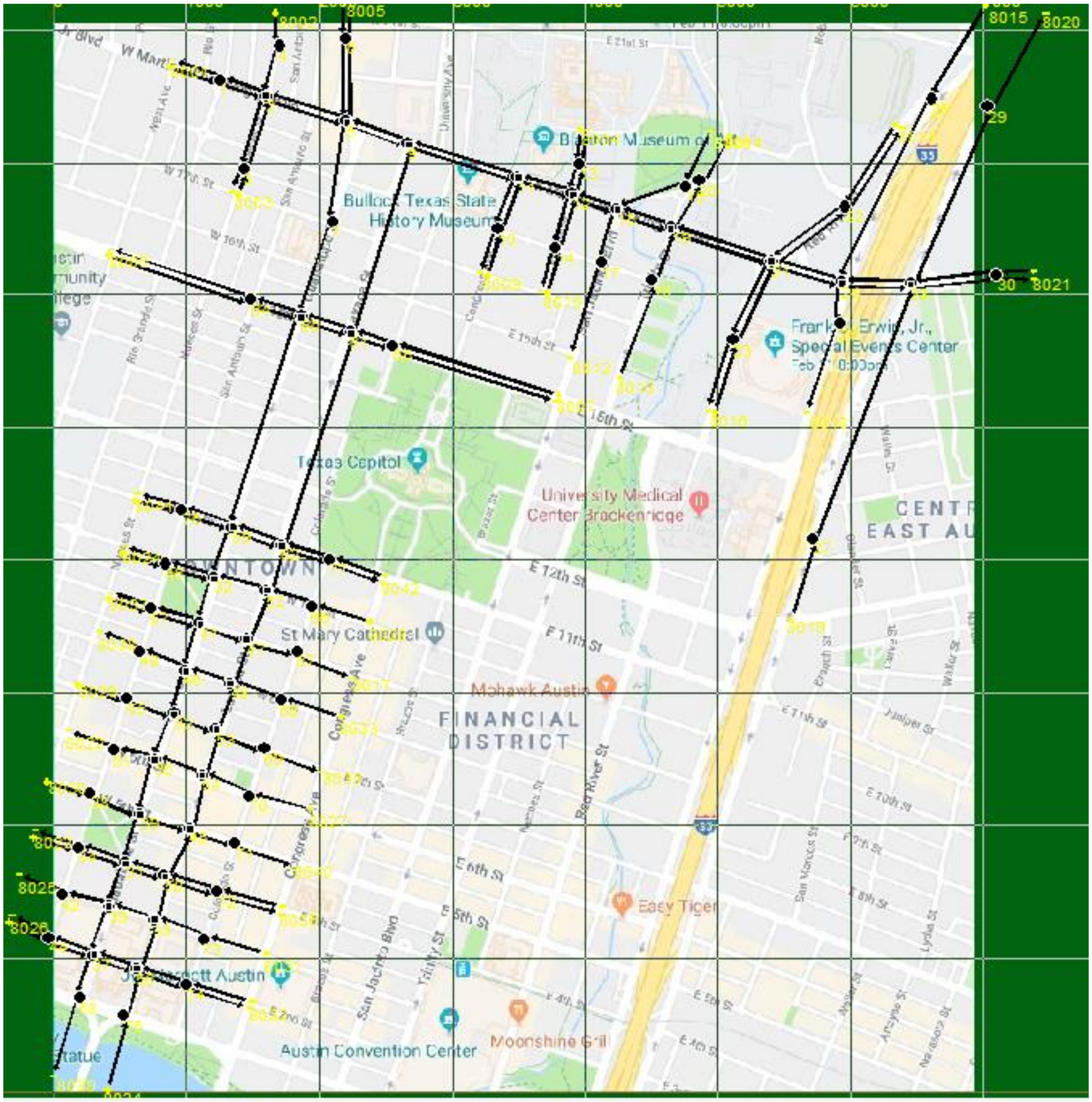
# Chapter 6. Case Study

After testing a single intersection and two different types of corridors a better understanding of TSP is now attained. A final step to make sure the tested TSP scenarios actually work in practice, is through a case study that depicts real life data. Austin city downtown was chosen as it includes both cases of one-way and two-way corridors with heavy bus traffic. Based on that, a CORSIM model was developed, considering the Martin Luther King Jr Boulevard (MLK Blvd) corridor running from Nueces Street to I-35 intersecting with Guadalupe and Lavaca Streets from MLK ($19^{th}$ St) to Caesar Chavez ($1^{st}$ St). The reason behind using this specific segment of Austin streets is that it has the perfect mix of the previously tested models. The first step in this study was to check for an isolated intersection, which can be found in Guadalupe/Lavaca intersecting with $15^{th}$ street, those two intersections have a distance of at least 1000 feet to the nearest intersection. This case is similar to an isolated intersection. The other two models, one-way corridor and two-way corridor can also be found in this segment, Guadalupe and Lavaca are both 3 to 4 lanes one-way streets traveling North/South in downtown Austin. MLK represents a heavy traffic East/West corridor with two-way traffic. This segment represents these three scenarios combined providing a realistic aspect so that TSP testing includes a real world component. Here it should be noted that, if the designed TSP works or fails in this model, it does not necessary mean that it would work or fail in other scenarios. The larger the network, the more variables and parameters are added to the objective function which makes it more complex and therefore harder to identify statistically significant effects. This model serves as an approach to test the designed TSP in this study on a real case that is relatable to the readers.

## 6.1 Model 1: Austin Base Case

The base case includes modeling of the whole system with the current signal timings in place. There are only 4 bus routes, one going North on Lavaca, one going South on Guadalupe, and two traveling East/West on MLK. The reason behind having only 4 routes is to start with a model that has the real-life data for traffic but simple controlled bus traffic, to see how TSP would react to the flow of buses and also be able to compare it to previous models where TSP was tested on 5 minute headways. Traffic volume inputs were provided via City of Austin that represent 5-6 PM traffic for these intersections. Mason Gemar from the Center for Transportation Research aided in obtaining signal timings for application in CORSIM from the City of Austin (2010) Traffic Data. Each intersection was calibrated with the geometric design, number of lanes, traffic flow, and current signal timings. The high level of detail in creating the CORSIM model is essential in best depicting reality while using simulation. The CORSIM configuration for this model is show in Figure 6.1.

**Figure 6.1: Downtown Austin CORSIM configuration**



For a higher level of precision, the nodes and links were built on top of a google maps snapshot to make sure the distance and shape of links match reality. Also, google maps was used to measure the distances in feet between each node and then manually entered in CORSIM to ensure the ratio between simulation and reality is consistent all throughout the network. A simulation in CORSIM was built and a base run was made along with the 3 scenarios and Table 6.1 summarizes the delay results.

**Table 6.1: Austin Base Model All Scenarios Delay Results**

| NO TSP | | | | | | |
|---|---|---|---|---|---|---|
| | Traffic | | | | Bus | |
| Delay | MLK Main | MLK Cross | G/L Main | G/L Cross | MLK Bus | G/L Bus |
| Mean | 65.10 | 87.29 | 16.51 | 26.30 | 9.84 | 2.68 |
| SD | 65.28 | 60.90 | 33.41 | 32.87 | 8.38 | 2.91 |
| Median | 41.19 | 65.81 | 6.50 | 13.59 | 7.77 | 1.89 |
| Scenario#1 TSP | | | | | | |
| | Traffic | | | | Bus | |
| Delay | MLK Main | MLK Cross | G/L Main | G/L Cross | MLK Bus | G/L Bus |
| Mean | 58.43 | 78.67 | 10.39 | 20.65 | 9.20 | 2.62 |
| SD | 63.98 | 57.92 | 9.35 | 22.07 | 7.92 | 2.58 |
| Median | 31.37 | 51.52 | 6.39 | 12.83 | 6.87 | 1.92 |
| Impact | | | | | | |
| Mean | -10.24% | -9.88% | -37.07% | -21.50% | -6.50% | -2.32% |
| Median | -23.85% | -21.70% | -1.77% | -5.56% | -11.50% | 1.75% |
| Scenario#2 TSP | | | | | | |
| | Traffic | | | | Bus | |
| Delay | MLK Main | MLK Cross | G/L Main | G/L Cross | MLK Bus | G/L Bus |
| Mean | 77.03 | 128.16 | 11.88 | 25.71 | 5.89 | 1.79 |
| SD | 124.47 | 169.18 | 18.63 | 26.60 | 6.93 | 2.00 |
| Median | 29.73 | 53.48 | 7.58 | 15.76 | 3.34 | 0.98 |
| Impact | | | | | | |
| Mean | 18.33% | 46.82% | -28.03% | -2.23% | -40.16% | -33.23% |
| Median | -27.82% | -18.73% | 16.55% | 15.96% | -57.01% | -48.25% |
| Scenario#3 TSP | | | | | | |
| | Traffic | | | | Bus | |
| Delay | MLK Main | MLK Cross | G/L Main | G/L Cross | MLK Bus | G/L Bus |
| Mean | 46.56 | 77.36 | 11.89 | 24.46 | 7.53 | 2.26 |
| SD | 60.25 | 73.28 | 15.09 | 23.89 | 7.62 | 2.19 |
| Median | 16.17 | 43.61 | 6.81 | 14.36 | 5.01 | 1.60 |
| Impact | | | | | | |
| Mean | -28.48% | -11.37% | -27.95% | -6.99% | -23.55% | -15.91% |
| Median | -60.75% | -33.74% | 4.74% | 5.69% | -35.56% | -15.25% |

The results show very large values of standard deviations, again this shows how the process of running random seeds of traffic values and driver behaviors will produce random results. Having a very random sample in this case is a double-edge weapon, it is negative in terms of showing very uncertain results but also positive in providing TSP opportunities to handle these very random cases. Before CORSIM starts the simulation, the traffic flows are created using random draws from user specified distributions. To create replicate simulation runs, the seeds for the random number generators must be changed. Essentially all driver and vehicle characteristics from driver type, to vehicle type, to desired speed and destination are specified for every driver-vehicle unit using this random draw process. Decision processes that occur during simulation are generally deterministic rather than stochastic processes. This process effect was minimal in the single intersection case, it was noticeable in the corridors case and it is very obvious in the network case. Running t tests in all of these categories of comparison resulted in none being significantly different, this was expected especially after the previous two models produced non-significant effects as well. Looking at the delay results, all categories have the impact percentage of both the mean and median. The reason of including both is that it easier for the reader to compare the effect of TSP by looking at both measures of central tendency. However, the true effect of scenarios in this case must be measured using the median as it is the more appropriate measure of central tendency when the sampled population is skewed, and this can be seen when the mean is not the same as the median. Looking at Scenario 1, MLK bus traffic delay was reduced, while having a very minimal effect on Guadalupe/Lavaca bus traffic. This might be expected if a bus traveling in a one-way corridor might not be blocked by left-turners (no queues). Scenario 2 was successful in reducing bus delay the most with reductions ranging from 33% to 57% for the mean and medians on both MLK and Guadalupe/Lavaca bus traffic. This can be explained in the fact that this scenario will always grant buses access, both green extension and red truncation will be granted regardless of what traffic conditions are, maximizing the potential of TSP minimizing bus travel. For Scenario 3, bus delay reductions were limited to 15%, for both mean and median, in the Guadalupe/Lavaca corridor while reductions of 23% to 35% were seen in the MLK bus traffic. This reflects that the Guadalupe/Lavaca corridor has more cross-traffic which is accounted for when responding to a bus request. Instead of having reductions of up to 48% in Scenario 2, Scenario 3 reported lower values. MLK corridor bus savings for Scenario 3 were closer to Scenario 2 results as MLK has less cross-street traffic. Now for the general traffic delay reductions, Scenario 1 reduced general traffic delay on MLK but had minimal positive impact on the Guadalupe/Lavaca traffic corridor. Scenario 2 had the worst effect on all general traffic aspects, it increased the average delays in MLK traffic and the median delays in Guadalupe/Lavaca traffic. This shows that even though TSP in Scenario 2 made buses travel faster, it severely impacted general traffic. This shows the classic dilemma between trying to minimize bus delays without increasing delays to general traffic. In this study, the goal was to build a scenario that is capable of reducing bus delays while also maintaining a reasonable impact on general traffic. Scenario 3 has the potential of being that scenario, that minimized bus traffic delay with 15% to 35% reductions, while also having minimal impacts on general traffic, up to 5% on the Guadalupe/Lavaca medians while also having great reductions up to 60% in the MLK corridor. Table 6.2 shows the speed results.

**Table 6.2: Austin Base Model All Scenarios Speed Results**

| NO TSP | | | | | | |
|---|---|---|---|---|---|---|
| | Traffic | | | | Bus | |
| Speed | MLK Main | MLK Cross | G/L Main | G/L Cross | MLK Bus | G/L Bus |
| Mean | 9.23 | 6.70 | 14.90 | 9.75 | 9.66 | 17.42 |
| SD | 6.95 | 6.71 | 5.04 | 4.04 | 7.14 | 7.66 |
| Median | 7.89 | 5.51 | 15.80 | 10.63 | 7.11 | 17.80 |
| Scenario#1 TSP | | | | | | |
| | Traffic | | | | Bus | |
| Speed | MLK Main | MLK Cross | G/L Main | G/L Cross | MLK Bus | G/L Bus |
| Mean | 9.77 | 7.07 | 15.35 | 10.37 | 10.27 | 17.31 |
| SD | 7.03 | 6.70 | 4.82 | 3.82 | 7.17 | 7.40 |
| Median | 9.50 | 6.24 | 16.01 | 10.95 | 8.14 | 17.63 |
| Impact | | | | | | |
| Mean | 5.81% | 5.57% | 2.98% | 6.31% | 6.23% | -0.62% |
| Median | 20.48% | 13.22% | 1.36% | 3.01% | 14.44% | -0.94% |
| Scenario#2 TSP | | | | | | |
| | Traffic | | | | Bus | |
| Speed | MLK Main | MLK Cross | G/L Main | G/L Cross | MLK Bus | G/L Bus |
| Mean | 8.72 | 6.76 | 14.93 | 9.19 | 13.78 | 18.34 |
| SD | 6.92 | 6.53 | 5.23 | 3.94 | 8.50 | 7.28 |
| Median | 11.21 | 6.49 | 14.98 | 9.85 | 11.87 | 18.82 |
| Impact | | | | | | |
| Mean | -5.53% | 0.97% | 0.21% | -5.81% | 42.61% | 5.28% |
| Median | 42.18% | 17.86% | -5.20% | -7.32% | 66.98% | 5.74% |
| Scenario#3 TSP | | | | | | |
| | Traffic | | | | Bus | |
| Speed | MLK Main | MLK Cross | G/L Main | G/L Cross | MLK Bus | G/L Bus |
| Mean | 11.10 | 7.38 | 14.62 | 9.37 | 12.07 | 17.83 |
| SD | 6.89 | 6.52 | 5.25 | 3.95 | 7.38 | 6.97 |
| Median | 11.38 | 6.36 | 16.47 | 11.64 | 11.38 | 18.18 |
| Impact | | | | | | |
| Mean | 20.30% | 10.21% | -1.92% | -3.96% | 24.93% | 2.32% |
| Median | 44.31% | 15.43% | 4.26% | 9.51% | 59.98% | 2.14% |

The speed results show that the best scenario in maximizing bus speeds is Scenario 2 but it is the only scenario that had speed decreases of more than 5% in the Guadalupe/Lavaca corridor. Scenario 1 had positive impacts in almost all tested categories except for a less than 1% reduction in Guadalupe/Lavaca bus speeds. Scenario 3 is the best case as it increased bus speeds in both corridors and also increased the median speed across general traffic in both corridors as well.

## 6.2 Model 2: Austin Modified Case

Now the base case is modeled, the final step in this study is to convert all the hypotheses about TSP into reality. The way to do this is to build a simulation that fully depicts reality, in all aspects. The Austin modified case includes all buses traveling in the network. The information for bus routes and headways were obtained from the Austin transit authority: CapMetro (Capital Metropolitan Transportation Authority 2018). Bus routes that intersect or travel along MLK Blvd or Lavaca/Guadalupe corridor were included in the model. In total, there are 48 buses that at least pass one intersection in the area of interest. Some of these buses have a higher frequency than others and some are local buses, other are rapid buses. To best test TSP buses that might confound the analysis process need to be excluded from the model. In order for buses to be included in the model, they must have at least 5 minute headways and it also must pass through at least two intersections as some buses only pass through one intersection. Table 6.3 displays the remaining bus routes with their headway values.

**Table 6.3: Model 2 Bus Routes**

| Intersection | # | Bus Route | Direction | Headway (sec) |
|---|---|---|---|---|
| Guadalupe | 1 | 801 | S | 780 |
| | 2 | 803 | S | 780 |
| | 3 | 1 | S | 1500 |
| | 4 | 3 | S | 2100 |
| | 5 | 5 | S | 1800 |
| | 6 | 19 | S | 2400 |
| | 7 | 18 | W | 1800 |
| Lavaca | 8 | 801 | N | 780 |
| | 9 | 803 | N | 780 |
| | 10 | 1 | N | 1500 |
| | 11 | 3 | N | 2100 |
| | 12 | 5 | N | 1800 |
| | 13 | 19 | N | 2400 |
| | 14 | 18 | E | 1800 |
| Congress | 15 | 103 | S | 1800 |
| | 16 | 142 | N | 1800 |
| San Jacinto | 17 | 935 | N | 1020 |
| | 18 | 18 | E | 1800 |
| | 19 | 18 | W | 2400 |
| | 20 | 672 | I | 1200 |
| Red River | 21 | 671 | O | 840 |
| | 22 | 672 | O | 1200 |
| | 23 | 641 | W | 900 |

After choosing the bus that are going to be included in the model, now a model that depicts reality is complete to be tested. A base run was made and compared to the 3 scenarios. Table 6.4 summarizes the delay results.

**Table 6.4: Austin Modified Model All Scenarios Delay Results**

| NO TSP | | | | | | |
|---|---|---|---|---|---|---|
| | Traffic | | | | Bus | |
| Delay | MLK Main | MLK Cross | G/L Main | G/L Cross | MLK Bus | G/L Bus |
| Mean | 62.30 | 83.41 | 10.03 | 20.39 | 13.52 | 3.27 |
| SD | 64.58 | 59.76 | 8.44 | 21.18 | 12.50 | 3.07 |
| Median | 36.16 | 59.25 | 6.45 | 12.78 | 9.00 | 2.35 |
| Scenario#1 TSP | | | | | | |
| | Traffic | | | | Bus | |
| Delay | MLK Main | MLK Cross | G/L Main | G/L Cross | MLK Bus | G/L Bus |
| Mean | 68.19 | 98.06 | 10.26 | 20.52 | 14.81 | 3.13 |
| SD | 67.47 | 66.19 | 8.93 | 21.00 | 12.74 | 2.97 |
| Median | 53.39 | 78.81 | 6.23 | 13.28 | 9.68 | 2.10 |
| Impact | | | | | | |
| Mean | 9.44% | 17.56% | 2.34% | 0.62% | 9.57% | -4.18% |
| Median | 47.62% | 33.00% | -3.30% | 3.89% | 7.59% | -10.88% |
| Scenario#2 TSP | | | | | | |
| | Traffic | | | | Bus | |
| Delay | MLK Main | MLK Cross | G/L Main | G/L Cross | MLK Bus | G/L Bus |
| Mean | 50.04 | 85.31 | 9.28 | 24.78 | 12.71 | 2.52 |
| SD | 60.22 | 66.75 | 8.12 | 22.22 | 12.92 | 2.60 |
| Median | 21.79 | 61.93 | 7.31 | 15.92 | 8.62 | 1.48 |
| Impact | | | | | | |
| Mean | -19.68% | 2.29% | -7.48% | 21.53% | -5.98% | -22.82% |
| Median | -39.76% | 4.51% | 13.42% | 24.58% | -4.16% | -37.13% |
| Scenario#3 TSP | | | | | | |
| | Traffic | | | | Bus | |
| Delay | MLK Main | MLK Cross | G/L Main | G/L Cross | MLK Bus | G/L Bus |
| Mean | 45.69 | 77.33 | 10.94 | 23.72 | 10.12 | 2.73 |
| SD | 59.16 | 72.34 | 15.01 | 23.69 | 10.93 | 2.76 |
| Median | 17.01 | 47.88 | 7.03 | 14.41 | 6.58 | 1.74 |
| Impact | | | | | | |
| Mean | -26.66% | -7.29% | 9.17% | 16.31% | -25.14% | -16.38% |
| Median | -52.97% | -19.20% | 9.06% | 12.75% | -26.84% | -26.04% |

The same pattern can be noticed in comparison to the base case model. Having multiple buses with different directions of travel increased the variation of delay values for the bus traffic, however, buses are still traveling faster due to TSP effect. Scenario 1 increased delays on the MLK corridor, while decreasing delays on the Guadalupe/Lavaca corridor. Scenario 2 had the highest percentage of decreased delays, up to 37% for the Guadalupe/Lavaca corridor bus traffic but only a 4% decrease on the MLK corridor. MLK corridor now behaves differently than the base case due to the fact that there are multiple buses now traveling in several segments of MLK, in comparison to the buses traveling in all intersection on MLK in the base case model. With buses traveling in fewer intersections, having different headways it can be seen that the way Scenario 2 handled requests did not maximize the potential of TSP and most likely had conflicting buses which resulted in minimal overall MLK bus traffic delay decreases. Scenario 3, is the best case in this model as it decreases both bus traffic, on Guadalupe/Lavaca and MLK, by around 26% while only having 9 to 12% increased delays on Guadalupe/Lavaca corridor general traffic. It also decreased delays on MLK by 19% and 52%, for MLK cross-street and main corridor traffic, respectively. The speed values shown in Table 6.5 matches the results found in the delays section. The last two rows of the previous table summarize the findings of this study: using TSP is ideal in real life situations beneficial in reducing bus delays and two-way corridor delays while having minimal negative impacts on one-way corridors. If TSP is going to be applied to a network, it would be used in two-way corridors or isolated intersection. Only to be used in one-way corridors when general traffic delays are to be neglected. Otherwise, all previous studies that proved TSP is beneficial in one-way corridor needed to include the effect of TSP on general traffic. If these studies did include effects on general traffic, these effects will be negative, most likely.

**Table 6.5: Austin Modified Model All Scenarios Speed Results**

| NO TSP | | | | | | |
|---|---|---|---|---|---|---|
| Traffic | | | | | Bus | |
| Speed | MLK Main | MLK Cross | G/L Main | G/L Cross | MLK Bus | G/L Bus |
| Mean | 9.31 | 6.80 | 15.45 | 10.35 | 9.69 | 17.29 |
| SD | 6.98 | 6.73 | 4.84 | 3.78 | 6.97 | 7.49 |
| Median | 8.15 | 5.78 | 16.19 | 10.86 | 6.70 | 17.57 |
| Scenario#1 TSP | | | | | | |
| Traffic | | | | | Bus | |
| Speed | MLK Main | MLK Cross | G/L Main | G/L Cross | MLK Bus | G/L Bus |
| Mean | 8.75 | 6.12 | 15.40 | 10.26 | 8.93 | 17.51 |
| SD | 6.85 | 6.81 | 4.83 | 3.77 | 6.63 | 8.47 |
| Median | 6.34 | 4.79 | 16.08 | 10.61 | 6.07 | 17.84 |
| Impact | | | | | | |
| Mean | -6.00% | -10.02% | -0.31% | -0.86% | -7.80% | 1.28% |
| Median | -22.13% | -17.09% | -0.67% | -2.28% | -9.35% | 1.55% |
| Scenario#2 TSP | | | | | | |
| Traffic | | | | | Bus | |
| Speed | MLK Main | MLK Cross | G/L Main | G/L Cross | MLK Bus | G/L Bus |
| Mean | 10.59 | 6.79 | 15.34 | 9.04 | 11.60 | 17.47 |
| SD | 7.16 | 6.75 | 5.04 | 3.80 | 8.55 | 6.15 |
| Median | 9.08 | 5.39 | 15.30 | 9.60 | 8.65 | 17.32 |
| Impact | | | | | | |
| Mean | 13.79% | -0.21% | -0.72% | -12.66% | 19.80% | 1.04% |
| Median | 11.49% | -6.63% | -5.45% | -11.59% | 29.18% | -1.42% |
| Scenario#3 TSP | | | | | | |
| Traffic | | | | | Bus | |
| Speed | MLK Main | MLK Cross | G/L Main | G/L Cross | MLK Bus | G/L Bus |
| Mean | 11.09 | 7.28 | 14.78 | 9.24 | 12.14 | 17.63 |
| SD | 6.89 | 6.62 | 5.18 | 3.95 | 7.56 | 6.75 |
| Median | 11.40 | 6.21 | 15.98 | 10.98 | 10.90 | 17.71 |
| Impact | | | | | | |
| Mean | 19.15% | 7.05% | -4.32% | -10.71% | 25.34% | 1.98% |
| Median | 40.00% | 7.46% | -1.28% | 1.14% | 62.74% | 0.76% |

Both Scenario 1 and Scenario 2 decreased speeds by at least 11% in one of the categories but had negative impacts on speeds on other categories as well. Scenario 1 decreased speeds in all categories except one while Scenario 2 increased speeds in only 2 categories. Speed results show that the only Scenario with increased speeds across 5 categories is Scenario 3, it only had decreased delays with less than 2% in Guadalupe/Lavaca main corridor. Which, again, proves that Scenario 3 is the best scenario to handle TSP in the Austin network models.

## 6.3 Summary

In summary, looking at TSP impact on a network level required building a simulation that depicts reality. Choosing a city that best represents a network that aligns with the models that were built here is essential to keep the consistency and flow of models built in this study. Available data is also an important aspect of choosing a model basis. City of Austin traffic data is accessible and there is a large network in which one can easily find a segment that aligns with the models built here. The MLK corridor intersecting with Guadalupe/Lavaca was chosen to be the area of interest. Along with traffic counts, turning movements and signal timings a model that represents a real-life case was built in CORSIM. Two models were used in this chapter to best understand the impacts of TSP.

The first model has all the real-life data except for bus traffic values, these values were assumed to be exactly the same as the previous chapters to better transition between the assumptions in this study to a model with all variables depicting reality. This base case model used the assumption of 5 min headway bus routes traveling North/South on the Guadalupe/Lavaca corridor and East/West in the MLK corridor. The results of running this model showed that all scenarios somehow decreased delays and increased speeds of buses. All scenarios also decreased traffic delays on MLK while only Scenario 1 decreased delays on Guadalupe/Lavaca corridor, those reductions were minimal, however. The best scenario in the first model is Scenario 3 as it decreased MLK delays the most and had the lowest impacts on Guadalupe/Lavaca corridor traffic, in comparison to Scenario 2. The reason behind this is that Scenario 3 takes into account cross-street traffic, which TSP uses in determining if a green phase is worth starting or not. Another reason is the green time given back to the cross-street which helps maintain progression while also minimizing delays on the cross-street.

Scenario 3 was also the best scenario in the modified model which had the actual bus values that existed in the network. Some restraints were applied to minimize confounding variables, any bus traveling in the network needs to at least cross two intersection in the selected segments in this model, it also must have at least 5-minute headways. Twenty-three bus routes were added to the CORSIM simulation and the results matched the results from the first model. However, Scenario 1 increased traffic delays on MLK which is due to the fact that there are more buses in the network now that a basic TSP is not capable of handling heavy bus traffic and now more prone to failure. Scenario 3 had lower impacts on MLK traffic as well, however still reducing delays. Scenario 2 and Scenario 3 increased delays on Guadalupe/Lavaca corridor traffic by at least 9%. These results show that with more parameters added to the simulation, results will vary more and TSP might not be the best option to control traffic. However, Scenario 3 is still successful in decreasing bus delay median values, by 26% for both corridors while also decreasing general traffic delay on MLK.

# Chapter 7. Summary and Conclusions

Transit signal priority systems main goal was to ensure faster travel times for buses, this goal minimized the delays of buses which increases the reliability of transit services. However, TSP was found in many studies to have severe impacts on general traffic, this generated a push-back from the cities to adapt any form of TSP. As the goal of city planners is to minimize traffic delays, adding a basic TSP will defeat that purpose and will only minimize transit delays, which is in most cases not the most important aspect of traffic. This led to further studies exploring the potential of TSP in minimizing bus delays while also maintaining automobile traffic delay reductions or at least not causing significant increases. Multiple TSP systems were generated throughout the years, some proved that TSP minimizes delays while others showed that TSP does not work in some specific cases. Most TSP systems were evaluated and tested at the intersection level or sometimes corridor level. Not testing networks, left a big aspect of traffic impacts outside of the picture. Also, most of the studies reported values of increase/decrease delays without testing for the significance of these values, some value as low as 5% might be statistically significant while some values up to 100% might not be statistically significant.

The issues of current research include: 1) the fact that these systems are developed and tested on a singular corridor, or isolated intersection sometimes makes their outputs very limited; and 2) testing any alteration in traffic on a small scale does not reflect the impacts seen on a bigger scale; 3) not providing statistical results which is essential to testing any TSP system.

This study serves as a combination of all possible parameters effecting TSP, and testing all these parameters in all possible cases, while also providing statistical tests to show the significance of TSP impacts. By doing that, this study evaluated the overall state of TSP practice as well as identified and investigated new approaches to improving TSP. Some of the approaches that were evaluated included the effect of adding/removing a bus lane, adding extra green signal time to the bus travel direction and compensating cross street traffic for green time loss. Exploring different vehicle over capacity ratios for both bus travel direction and cross-street to determine when TSP would be beneficial and deciding what the threshold might be.

This report includes 7 chapters. The first chapter introduced issues regarding modern day commuting and transit as an alternative to car use. The second chapter introduced transit signal priority systems, their history and potential impacts as a solution to prevent additional stress on the transportation network. The third chapter described the proposed solutions to reach the goals of this study and test these solutions based on simulations for an Isolated traffic signal intersection. Chapters four and five covered a one-way corridor case and two-way corridor case, respectively. A downtown Austin based case study was covered in chapter 6. This last chapter, covers the summary of this study.

Four scenarios were created to describe buses approaching an intersection and TSP responses:

- Scenario 1 responded to a "late" bus coming into an intersection within the last few seconds of the green time. A typical response was built on reading the bus location and determining how many seconds of green time was needed to be added to the current signal phase to grant the bus access to the intersection.

- Scenario 2 in addition to Scenario 1, truncates the red signal phase if a bus approached an intersection showing a red-light phase. In this scenario, both phases of green and red lights are covered leading to granting a response whenever a bus arrives.

- Scenario 3 in addition to Scenario 2, checks if it is worth giving priority to the bus by checking non-moving vehicles on the cross-street then deciding to grant access or not. A default value of at least 2 non-moving cars was used and then modified. Scenario 3 also gives back green time that was taken from the cross-street after a priority request is granted and the green phase is over. The default value of green given back is 10 seconds, these values are varied and tested as well.

- Scenario 4 in addition to Scenario 3, was modified to account for situations when multiple buses request TSP. The model gave priority to buses traveling in a preset direction, all cases in this study priority was given to buses traveling North/South. These bus requests where always prioritized over East/West bound buses. Running this scenario and comparing it to the third scenario in all chapters did not show any significant improvement to either bus traffic or general traffic.

## 7.1 Isolated Intersection

Testing an isolated intersection with buses traveling North only, headways of 3, 5 and 7 minutes are used. The following cases/models were created in CORSIM simulation and tested, their results are summarized.

7.1.1 One-way corridor traveling North:

- Scenario 1 results showed that there was no significant difference in either bus delays/speed or traffic delays/speed.

- Scenario 2 results showed significant effects for headways of 7 and 5 minutes only.

- Scenario 3 Just like Scenario 2, results were only significant for 5 and 7 minutes bus headways.

7.1.2 Two-way corridor:

- Scenario 1 resulted in no significant difference in 5 and 7 minute headways and negative significant differences in 3-minute headways which is probably due to the fact that left-turns now face two lanes of traffic which disrupt the traffic flow.

- Scenario 2 resulted in positive significant differences in 5 and 7 minutes but still negative significant differences in 3 minute headways. Here the more realistic headway of 5 minutes or more is proved to be a better situation for TSP.

- Scenario 3 has the same results as Scenario 2

### 7.1.3 Bus lane:

The effect of adding a bus lane to 1) one-way traffic, 2) two-way traffic and 3) left-turn pockets in two-way traffic is examined. The three TSP scenarios were tested in each of these three cases. Results compared to adding a bus lane only did not show significant differences in bus delays in all cases. Scenario 1 results showed no improvement in any of the cases. Scenario 2 and 3 results showed that adding a bus lane with TSP is significantly better than bus lane without TSP and also better than no bus lane and no TSP.

### 7.1.4 Given Back Green Time:

Analysis on the two-way case for "Given Back Green" shows that giving back only 1 second of green time to the cross-street traffic significantly decreases bus delays and has less cross-street delays than all other cases.

### 7.1.5 Cross-street flow:

Analysis on the two-way case cross-street traffic shows that with V/C more than 0.55, TSP starts to decrease in performance, this decrease is shown as increased cross-street delays. However, V/C ratios greater than 0.63 would cause significantly more delays for TSP in comparison to No TSP.

### 7.1.6 Left-turns

To evaluate effects of having left-turn pockets a 200 feet left-turn pocket was added to all intersection approaches.

- Scenario 1 resulted in no significant difference across all bus headways. This shows an improvement in comparison to Model 2 which had negative effects on 3 minutes headways.
- Scenario 2 resulted in positive significant differences in 5 and 7-minute headways only, while having no effect with 3-minute headways.
- Scenario 3 was the same as Scenario 2 with more improvements to bus delays.

### 7.1.7 Bus Stop location

Analysis on a two-way case tested the difference of placing a bus stop near side versus the far side of the intersection. The base case without using TSP proved that there is a significant difference between near side versus far side bus stop locations. The three scenarios were simulated, and their results showed even larger significant differences than the base case. The results not only proved the difference it also showed the magnitude of the difference between the two.

### 7.1.8 Bus Headway

Analysis on a two-way case with multiple bus headways showed the effect of having different transit occupancies and also high/low bus traffic volumes. Results showed that TSP was effective in reducing bus passenger delays for headways ranging from 1 to 10 minutes.

## 7.2 One-way Corridor

This chapter includes a CORSIM model built with two main corridors intersecting with 7 cross-streets. These two corridors are each 3 lane one-way corridors, one traveling North only and one is traveling South only. Both of these main corridors have 5-minute bus headways bus.

The following summarizes the results found in this chapter:

7.2.1 The effect of progression:

Offset values for the progression were calculated to be 9 and 18 seconds. Both values were used to adjust two different cases and compared to the base case, results showed that a 9 seconds offset (30 mph) proved to make buses travel faster, however not significantly faster, while an 18 second offset (15 mph) significantly decreased traffic speeds on the North/South corridor.

7.2.2 Effectiveness of the three TSP scenarios

Scenario 1 increased bus delays in the progression phase, while both Scenario 2 and Scenario 3 showed reductions in bus delays. Overall, the best case is Scenario 3 in the base case as it results in up to a 19% reduction in bus delay, while only having 6 to 8% increased delays to general traffic. None of the results were significantly different.

7.2.3 Max green

Results showed that even though the median for these results is smaller than the case of no TSP, ANOVA did not identify significant differences among means of these values.

7.2.4 Non-moving vehicles

Using values from 0 to 10 non-moving cars as a constraint for Scenario 3, results showed no significant differences among treatment values and also the case of no TSP.

7.2.5 The effect of adding bus lanes

For the analysis of this effect, 5 cases were created: 1 main base case with no bus lane, 1 bus lane case and 3 scenarios. After comparing each scenario to the first two cases, Scenario 1 showed increased delays in bus travel time, while both Scenario 2 and Scenario 3 showed reductions. However, both scenarios had large values of negative impacts on the general traffic leading to a conclusion that TSP is not the best way to handle bus traffic in one-way corridors.

## 7.3 Two-way Corridor

This chapter includes a CORSIM model built with two main corridors intersecting with 7 cross-streets. These two corridors are each 2 lane two-way corridors. Both of these main corridors have 5-minute headway buses traveling through. Results for this chapter are summarized below:

7.3.1 The effect of progression:

Offset values were calculated to be 18 and 35, while also keeping the previous chapter 9 seconds offset into consideration. The three values were used to adjust three different cases and compared to the base case, results showed that 9 seconds offset proved to make buses travel faster by only 0.39%, while 18 second progression increased bus speeds of up to 20% and the worst case was the 35 seconds offset which increased delays by 102%. The only case with minimal to no impact on all 6 categories tested was the case of 9 second progression. However, the case of no progression was chosen to be the base case for all the next models.

7.3.2 Effectiveness of the three TSP scenarios

After running the three scenarios and comparing results to the base case, Scenario 1 had very minimal impacts across all 6 categories, while both Scenario 2 and Scenario 3 showed reductions in bus delays, 14% and 13% respectively. For general traffic, both scenarios, 2 and 3 had similar impacts on general traffic although Scenario 3 had slightly less delay.

7.3.3 The effect of adding bus lanes

Scenario 1 showed reductions in delays for buses and also general traffic in comparison to no bus lane and no TSP. However, Scenario 1 did not improve the case where there was a bus lane, leading to the conclusion that either using TSP or adding a bus lane will result in approximately the same delay reductions. While both Scenario 2 and Scenario 3 showed reductions for bus delays in comparison to no bus lane both resulted in increased delays for general traffic in the case of using a bus lane versus TSP. This leads to a conclusion that using TSP, either Scenario 2 or 3 without a bus lane decreases bus delays while also decreasing North/South general traffic delays. The only difference is that Scenario 2 decreases bus delays up to 72% while increasing cross-street delays by 10%, while Scenario 3 decrease bus delays up to 55% while only increasing cross-street delays by 2%. In conclusion, the best case is Scenario 3.

## 7.4 Case Study

Case study was built using City of Austin traffic data. MLK corridor intersecting with Guadalupe/Lavaca was chosen to be the area of interest. Along with traffic counts, turning movements and signal timings, a model that represents a real-life case is built on CORSIM. There were two models in this chapter to best understand the impacts of TSP.

The base model has all the real-life data with only 4, 5-minute headway, bus routes. These routes travel, North on Lavaca, South on Guadalupe, East/West on MLK. The results of running this model showed that all scenarios decreased delays and increased speeds of buses. All scenarios also decreased traffic delays on MLK while only Scenario 1 decreased delays on Guadalupe/Lavaca corridor, those reductions were minimal, however. The best scenario in the first model is Scenario 3 as it decreased MLK delays the most and had the lowest impacts on Guadalupe/Lavaca corridor traffic, in comparison to Scenario 2. The reason behind this is that Scenario 3 takes into account cross-street traffic, which TSP uses in determining if a green phase is worth starting or not. Another reason is the green time given back to the cross-street which helps maintain progression while also minimizing delays on cross-street.

The modified model had the actual bus values that existed in the network. Twenty-three bus routes were added to the CORSIM simulation and the results matched the results from the first model. However, Scenario 1 increased traffic delays on MLK which is due to the fact that there were more buses in the network for this test and a basic TSP is not capable of handling heavy bus requests without becoming more prone to failure. Scenario 3 had lower impacts on

MLK traffic as well, however still reducing delays. Scenario 2 and Scenario 3 increased delays on Guadalupe/Lavaca corridor traffic by at least 9%. These results show that with more parameters added to the simulation, results will vary more, and TSP might not be the best option to control traffic. However, Scenario 3 is still successful in decreasing bus delay medians, by 26% for both corridors while also decreasing general traffic delay on MLK.

## 7.5 Intellectual Contributions

The following aspects of this study are considered to be intellectual contributions to future research on TSP.

### 7.5.1 Give back green time

The concept of giving back green time is essential to maintain progression and flow of traffic, with multiple bus requests traffic signal phase lengths might change dramatically. The notion of giving back green time helps to keep the system stable, it also helps in reducing delays for cross-street traffic in multiple cases in this study.

### 7.5.2 Worth green

Some of the previous studies included a form of indicator of cross-street traffic flow. In this study, using the number of non-moving cars on the cross-street as that indicator proved to be significant in multiple cases. Detection devices such as existing loop detectors are needed to effectively show that cross-street traffic is experiencing delays and needs green time more than the direction of bus travel.

### 7.5.3 Statistical use

Almost all previous studies did not use statistics in analyzing their results, the use of statistics to show the significance of TSP is essential to ensure that TSP would be effective in real-life. The use of t tests and ANOVA proved that even if TSP showed major improvements in some cases, it might not be significant.

### 7.5.4 Multi-directional

The case of testing if multiple buses almost simultaneously requested green time is new to the industry, even though results showed that the response scenario created in this study did not provide any improvements, it served as an introduction to something worth exploring more.

## 7.6 Practical Contributions

After using CORSIM software to simulate different scenarios and different models. Three scenarios were tested. Scenario 1 only extends green time when a bus is arriving late, Scenario 2 extends green time and also truncated red if a bus arrived on red, Scenario 3 does both with additional conditions as detailed in part 1. The following is a summary of the practical contributions and recommendations to be used in practice.

### 7.6.1 Using TSP in isolated intersections

Most results in the isolated intersections proved that TSP is effective in minimizing bus delays with minimum general traffic delays, this suggests that TSP, if used in isolated intersections, will be beneficial to the network. The results show that placing bus stops on the far side of the intersection has always proven to be significantly better than placing near side. Isolated intersection Scenario 3, extends green time for late buses, truncates red for buses arriving on red time and also limits response if there was congestion on the crossing street. Scenario 3 also takes into account time that was taken away from cross streets and gives back that green time to the cross streets. The ideal number of seconds to be given time was found to be one second. The ideal number of non-moving cars to be included in the condition of cross street congestion indicator was found to be any number other than zero. In both cases, the most ideal scenario would be extending green, truncating red, while also making sure that there is less than 1 car that is not moving on the cross-street, after all of this is granted, the next cycle one second of green time will be added to the cross-street traffic. Table 7.1 shows all the possible situations that an engineer might face when designing a traffic control configuration or system to minimize congestion and bus traffic delays. The table summarizes the models and provides a handbook table to be used when designing TSP in an isolated intersection depending on bus headways, geometric design of the intersection and the possibility of having a bus lane.

**Table 7.1: Single Intersection Guide**

| One-way Traffic | 3 Minute Headway | | 5 Minute Headway | | 7 Minute Headway | |
|---|---|---|---|---|---|---|
| | General Delays | Bus Delays | General Delays | Bus Delays | General Delays | Bus Delays |
| Scenario#1 | Worse | Worse | Worse | Worse | Better | Worse |
| Scenario#2 | Worse | Same | Worse | Sig Better | Worse | Sig Better |
| Scenario#3 | Same | Worse | Worse | Sig Better | Same | Sig Better |
| Two-way Traffic | 3 Minute Headway | | 5 Minute Headway | | 7 Minute Headway | |
| | General Delays | Bus Delays | General Delays | Bus Delays | General Delays | Bus Delays |
| Scenario#1 | Same | Sig Worse | Better | Better | Better | Better |
| Scenario#2 | Worse | Sig Worse | Worse | Sig Better | Worse | Sig Better |
| Scenario#3 | Worse | Sig Worse | Worse | Sig Better | Worse | Sig Better |
| Left-Turns | 3 Minute Headway | | 5 Minute Headway | | 7 Minute Headway | |
| | General Delays | Bus Delays | General Delays | Bus Delays | General Delays | Bus Delays |
| Scenario#1 | Same | Worse | Same | Worse | Same | Worse |
| Scenario#2 | Worse | Worse | Worse | Sig Better | Same | Sig Better |
| Scenario#3 | Same | Worse | Same | Sig Better | Same | Sig Better |
| Bus-Lanes One-way | Bus Lane Only Compared to base model | | Bus Lane & TSP Compared to base model | | Bus Lane & TSP Compared To bus lane | |
| | General Delays | Bus Delays | General Delays | Bus Delays | General Delays | Bus Delays |
| Scenario#1 | Better | Better | Same | Worse | Same | Worse |
| Scenario#2 | Better | Better | Worse | Sig Better | Worse | Sig Better |
| Scenario#3 | Better | Better | Worse | Sig Better | Worse | Sig Better |
| Bus-Lanes Two-way | Bus Lane Only Compared to base model | | Adding TSP and Bus lane to base model | | Adding TSP to bus lane model | |
| | General Delays | Bus Delays | General Delays | Bus Delays | General Delays | Bus Delays |
| Scenario#1 | Worse | Better | Worse | Better | Same | Worse |
| Scenario#2 | Worse | Better | Worse | Sig Better | Same | Sig Better |
| Scenario#3 | Worse | Better | Worse | Sig Better | Same | Sig Better |
| Bus-Lanes Left-Truns | Bus Lane Only Compared to base model | | Adding TSP and Bus lane to base model | | Adding TSP to bus lane model | |
| | General Delays | Bus Delays | General Delays | Bus Delays | General Delays | Bus Delays |
| Scenario#1 | Same | Same | Same | Better | Better | Better |
| Scenario#2 | Same | Same | Better | Sig Better | Better | Sig Better |
| Scenario#3 | Same | Same | Worse | Sig Better | Better | Sig Better |

### 7.6.2 One-way: The effect of adding bus lanes

TSP is not ideal for one-way corridors. Results show that even though TSP reduced bus delays, it had very negative impacts on the general traffic. This was expected following the results with single intersection one-way results. For situations like this, TSP is not recommended as it will dramatically increase delays for general traffic and provide a very small improvement for buses. In other words, the little decrease in bus delays is not worth damaging general traffic delay values. Table 7.2 works as a guide to be used when designing TSP in one-way corridors.

**Table 7.2: One-way Corridor Guide**

| | 0 Second Progression | | 9 Seconds Progression | | | |
|---|---|---|---|---|---|---|
| | General Delays | Bus Delays | General Delays | Bus Delays | | |
| Scenario#1 | Worse | Better | Worse | Worse | | |
| Scenario#2 | Worse | Better | Worse | Better | | |
| Scenario#3 | Worse | Better | Worse | Better | | |
| Bus-Lanes | Bus Lane Only Compared to base model | | Bus Lane & TSP Compared to base model | | Bus Lane & TSP Compared To bus lane | |
| | General Delays | Bus Delays | General Delays | Bus Delays | General Delays | Bus Delays |
| Scenario#1 | Better | Worse | Worse | Worse | Worse | Worse |
| Scenario#2 | Better | Worse | Worse | Better | Worse | Better |
| Scenario#3 | Better | Worse | Worse | Better | Worse | Better |

### 7.6.3 Two-way: The effect of adding bus lanes

Results show that in the case of TSP with only green extension, either using TSP or adding a bus lane, will result in approximately the same delay reductions. Comparing the cost of these alternatives, adding TSP is less costly than taking away an existing traffic lane and allocating it for buses only. Using a more advanced TSP system will result in a reduction for bus delays while also decreasing general traffic delays. Table 7.3 serves as a guide to be used when designing TSP in two-way corridors.

**Table 7.3: Two-way Corridor Guide**

| One-way Traffic | 0 Second Progression | | Left-Turns | | | |
|---|---|---|---|---|---|---|
| | General Delays | Bus Delays | General Delays | Bus Delays | | |
| Scenario#1 | Worse | Same | Same | Better | | |
| Scenario#2 | Worse | Better | Worse | Better | | |
| Scenario#3 | Worse | Better | Worse | Better | | |
| Bus-Lanes | Bus Lane Only Compared to base model | | Bus Lane & TSP Compared to base model | | Bus Lane & TSP Compared To bus lane | |
| | General Delays | Bus Delays | General Delays | Bus Delays | General Delays | Bus Delays |
| Scenario#1 | Better | Better | Better | Better | Same | Same |
| Scenario#2 | Better | Better | Worse | Better | Same | Better |
| Scenario#3 | Better | Better | Worse | Better | Worse | Better |

### 7.6.4 Using TSP in networks

Based on the City of Austin case study, results showed that TSP is beneficial in reducing bus delays and two-way corridor delays while having minimal negative impacts on one-way corridors. All of the previous results show that it is ideal to use TSP in networks but under certain conditions. It will reduce bus delays and two-way corridor delays while having minimal negative impacts on one-way corridors. If TSP is applied to a network, it should be used in two-way corridors or isolated intersections. Only to be used in one-way corridors when general traffic delays are to be neglected.

## 7.7 Directions for Future Research

From a traditional approach on TSP, in this study the goal was to combine all previous research areas of interest and apply them in a single document that serves as a starting point for further extend research. Multiple variables were not proven to be significant. That could mean two things, it is indeed not related to TSP performance, or it means that further research and taking a deeper look into that variables is needed to understand how it is related to quality of TSP. Multi-directional bus traffic, in concept, is very interesting, however, testing for putting that into the TSP mechanism proved to be non-significant. This shows that further research might be needed to approach the phenomena, of two buses arriving at the same time, from a different directions.

Research on TSP extends back in time for more than 40 years now, with new emerging technologies all of the research results need to be customized and adapted to the new networks dynamics. In the past, TSP relied on progression signal timing hoping that buses will arrive at intersections in specific time windows. Those systems worked, but the reliability was very low. With further research, new technologies like loop detectors provided a way to know that the bus is actually here. Again, in practice this improved bus travel times but also the reliability was not maximized. This step of research used high-end simulation software that uses the exact location of buses to make sure that each response is built with maximum precision to ensure that no single second is wasted in the intersection. Even though results throughout this study were mostly positive and reduction of bus travel was made, using statistics proved that some of these results were proven not to be significant. The next step to ensure these uncertain results are more precise and the modification to the models are actually improving the overall quality of TSP, is to approach the dataset in a more statistically based way. The simple t-testing proved that with higher variables, the possibility of finding any significance decreases.

Another approach to further expand this research is through the use of autonomous vehicles. With emerging technologies and the current state of research of autonomous vehicles it provides a huge potential to be used with TSP. Platoons of connected cars can be designed to travel all with the same speed. Similar to a train on rails but instead cars on roads. This approach if proven to be doable in reality could be a game changer to TSP. Buses may be designed to be autonomous as well. The potential of using TSP would be an essential part of connecting vehicles in a bigger network of autonomous vehicles that can be modified and configured to behave a certain way with the ultimate goal of safety first, then reducing delays.

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