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Evaluation of Transit Priority Treatments in Tennessee

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16. Abstract

Many big cities are progressively implementing transit friendly corridors especially in urban areas where traffic may be increasing at an alarming rate. Over the years, Transit Signal Priority (TSP) has proven to be very effective in creating transit friendly corridors with its ability to improve transit vehicle travel time, serviceability and reliability. TSP as part of Transit Oriented Development (TOD) is associated with great benefits to community liveability including less environmental impacts, reduced traffic congestions, fewer vehicular accidents and shorter travel times among others.This research have therefore analysed the impact of TSP on bus travel times, late bus recovery at bus stop level, delay (on mainline and side street) and Level of Service (LOS) at intersection level on selected corridors and intersections in Nashville Tennessee; to solve the problem of transit vehicle delay as a result of high traffic congestion in Nashville metropolitan areas. This study also developed a flow-delay model to predict delay per vehicle for a lane group under interrupted flow conditions and compared some measure of effectiveness (MOE) before and after TSP. Unconditional green extension and red truncation active priority strategies were developed via Vehicle Actuated Programing (VAP) language which was tied to VISSIM signal controller to execute priority for transit vehicles approaching the traffic signal at 75m away from the stop line. The findings from this study indicated that TSP will recover bus lateness at bus stops 25.21% to 43.1% on the average, improve bus travel time by 5.1% to 10%, increase side street delay by 15.9%, and favour other vehicles using the priority approach by 5.8% and 11.6% in travel time and delay reduction respectively. Findings also indicated that TSP may not affect LOS under low to medium traffic condition but LOS may increase under high traffic condition

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CHAPTER 1: INTRODUCTION

1.1 Background

The demand for transportation network is highly increasing with increasing population growth, especially in urban areas of many big cities. Creating additional transportation infrastructure may not be the best economic solution to the problem of high demand for transportation as it is time consuming, not cost effective and may lead to more population increase in certain areas. It is therefore imperative to efficiently maximise the operation of existing infrastructures [1]. One very cost effective way to efficiently maximize the operation of existing infrastructure and effectively tackle the problem of increasing demand for transportation network is the implementation of transit friendly corridors through Transit Signal Priority (TSP). TSP will improve transit operation and reduce auto dependency with less environmental impact and fewer vehicular accidents.

Over the years TSP has proven to be effective in improving transit operations with its ability to make transit service faster, more reliable and less expensive, however it may have some negative effect on conflicting traffic [2] [3] [4]. TSP is the process of returning an early green or extending a green time for a transit vehicle approaching a traffic signal in order to give priority to the transit vehicle. In other words it is the process of giving preferential treatment to Transit vehicles at signalised intersections. Signalized intersections are known to significantly contribute to transit vehicle delays and as such TSP has been used or recommended to mitigate the problem of transit vehicle delays at traffic signals. According to literature, TSP has the potential to greatly improve the attractiveness of transit vehicles by reducing passenger waiting times at bus stops especially in areas where the demand for transit vehicle is low [5]. Giving priority treatments to transit vehicles can greatly influence individual transportation mode choice as it expands mobility choices that reduce dependencies on automobiles, resulting to a reduction in vehicular accidents. Transit priority treatment such as Bus Signal Priority (BSP) has the potential to make buses competitive to other vehicles for its ability to reduce bus delays and favor other vehicles moving on the same approach by adjusting and modifying traffic signal timings to respond to buses [6] [7] [8].

The topic of this research seeks to proffer solution to the problem of high traffic congestion leading to poor bus serviceability and reliability in Nashville Tennessee. Poor bus serviceability and reliability are the main reasons people would prefer to use their private cars other than patronize buses vehicles. It is therefore imperative to prioritize buses at traffic signals to encourage public transportation mode choices. Research has shown that a bus service that is provided once within an hour is considered unattractive to all riders [9]. Other research have shown that bus services provided at a minimum half an hour or considerably every 15 minutes is considered attractive and would be more attractive even to automobile owners if provided at a minimum of 5mins. Although TSP will reduce transit delays, benefit other vehicle types on the priority approach there is no guarantee that TSP will yield a system wide benefit [10], this means that TSP may or may not improve the overall performance of the corridor under study. According to one research, TSP may not be required in all corridors but is very much required in corridors which experience heavy traffic that result in bus delays, it is particularly most efficient for intersections with LOS D or E [11].

This research seeks to answer questions on the level of effectiveness of TSP on the improvement of transit operation in the city of Nashville Tennessee. In other words this research tends to establish the impact of transit priority treatments such as BSP on the optimization of traffic operation and improvement of transit vehicle speed, while minimizing the negative impact on the general traffic. Our research objectives is in line with the main purpose of TSP which is to improve transit ridership, by reducing bus delays at traffic signals, with the sole aim of improving bus travel times and schedule adherence.

1.2 Problem Statement

Nashville is one of the fastest growing cities in the United States [12], and based on the U.S census data, Nashville Metropolitan area gained 30,875 people a year between July 2010 and 2015, and according to statistics an estimate of 85 people a day come in to Nashville [13]. This rapid growth rate is resulting to high traffic congestion especially in areas surrounded by business centers and Industries. The traffic congestion at signalized intersections is resulting to increased bus delays as a result buses are always late and are no longer attractive to road users even to automobile owners. Bus lateness is one of the major reasons why people will prefer to use their private vehicles other than patronize buses. If buses are prioritized at signalized intersections, their travel time will reduce; a reduction in bus travel time will increase the attractiveness of buses, and thus reduce auto dependency which will further lead to a reduction in traffic congestion. The corridor under study in this research is the Gallatin Pike corridor; which is a very busy bus route termed the Metropolitan Transportation Authority's (MTA) heaviest route with over 80 000 riders per month [9]. Gallatin corridor has a total of 48 signalized intersections, and buses using this corridor experience a lot of delays at these traffic signals as a result of the traffic congestion on the corridor at peak hours. The most cost effective method to address this issue of bus delays and traffic congestions without excessive impact on road users; is the implementation of TSP. This research has simulated the Gallatin pike corridor alongside Nolensville pike in order to investigate the effectiveness of TSP on bus delay reduction and schedule adherence. This study further developed delay models to predict control delay for under saturated and saturated flow conditions in an urban motorized environment with interrupted flow under mixed traffic conditions.

1.3 Research Objectives

Traffic signals are known to be one of the major contributors to bus delays at junctions with high traffic congestions, and thus improving bus saving at traffic signals is of great interest to transportation engineers. This research therefore aims to evaluate through microsimulation the magnitude and significance of TSP to improve mainline and crossing street transit and traffic operations in Nashville Tennessee, to establish knowledge on the role TSP play in creating an efficient transit transportation system and a more sustainable community and to develop delay models that predicts delay under certain flow conditions.

The study has the following specific objectives

- To evaluate the impact of TSP on mainline (bus route) and side street traffic operations.
- To evaluate the impact of TSP on bus schedule adherence in terms of late bus recovery.
- To evaluate the impact of TSP on control delay and LOS.
- To develop delay models for interrupted flow conditions to predict average delay per vehicle for a given flowrate.

CHAPTER 2: LITERATURE REVIREW

2.1 Overview

The literature review summarizes the methodologies, findings and conclusion from previous and ongoing researches related to TSP evaluation for urban motorized roads. Although there are several approaches of evaluating TSP, the literature review presented in this research focuses more on the microsimulation approach. The literature review further elaborates on the VISSIM microsimulation software and how it has effectively aided transportation engineers and researchers in analyzing and evaluating traffic flow characteristics. In addition the literature review presents TSP strategies as used by previous researchers and further differentiates between pre-emption and TSP.

2.2 Transit Signal Priority (TSP) and Road Space Priority (RSP) Measures

Transit signal priority is the process of modifying the traffic signals to respond to transit vehicles as they approach a signalized intersection [14]. It is the process of giving priority to transit vehicles at signalized intersections, to reduce the amount of delay transit vehicles experience at traffic signals which will in turn reduce transit vehicle travel time along the corridor. Many cities are increasingly utilizing TSP to implement transit friendly corridors especially in urban areas with increasing population. Transit friendly corridors also called Transit Oriented Development (TOD) corridors are known to be associated with great benefits and play a very vital role in community development and livability; including little environmental impact fewer traffic congestion, less vehicular accidents and shorter travel time amongst other benefits when compared to Traditional Single Occupant Vehicle (SOV) corridors [15]. Although TSP has the ability to improve the performance of a transit corridor, its effectiveness can be improved by combining it with RSP; such as Dedicated Bus Lanes (DBLs) and Queue Jump Lanes (QJLs) [16]. DBLs are lanes dedicated only to buses specifically used in Bus Rapid Transit (BRT) where as QJLs are typically right turn lanes that stretch out over traffic queue at a signalized intersections, and in most cases are combined with priority transit phases. They could also be combined with merge areas downstream the signalized intersection to allow a bus back into the traffic stream [17]. They are provided so that transit vehicles that may be stopped at signalized intersection as a result of the general traffic can move ahead of the general traffic so as to provide transit vehicles with advanced green time in relation to the general traffic [5]. According to research the maximum amount of bus savings that can be gained from QJLs is approximately 9 seconds per intersection. Although QJLs can increase the effectiveness of TSP by allowing transit vehicles to cross the intersection before other vehicles, it may cause delays to right-turning vehicles when a bus is at the start of the right turn lane [18]. One research concluded that the performance of TSP with QJLs in terms of bus serviceability is better improved when integrated with near side bus stop designs; however there may be some negative impact on other traffic. The research also concluded that compared to far-side bus stop near side bus stop combined with TSP and QJLs reduced bus delay up to 25 percent. In other words in terms of bus delay reduction and overall intersection delay, QJLs with a near side bus stop is more effective when compared to far-side bus stop [19].

2.3 Studies of Similar Work

Many researches have presented findings based on the impact of TSP on the improvement of Transit vehicle operations, but very few have analyzed and evaluated the effectiveness of TSP on bus schedule adherence. This research further evaluates the magnitude and significance of TSP on bus schedule adherence in terms of late bus recovery.

Cambridge Systematics, Inc. [20], evaluated the impact of TSP on transit operational strategies on Oakland Park Boulevard with the aim of improving transit vehicle running times in the corridor. According to them the main purpose of the study was to test alternative transit operation strategies/designs on Oakland Park Boulevard and identify the best strategies for improving bus travel times and reliability. They concluded that signals optimization and coordination would benefit operations conditions for the general traffic without significant impact on transit vehicles. In their evaluation they discovered that TSP alone improved bus saving by 3-4%, QJL at 2%, and a combination of both yielded 5-6% savings.

Bashir Ahmed [21] analyzed and evaluated the effect of the usual extension and recall on bus travel time savings and its impact on the general traffic, considering a 70 meters bus detection distance. His study concluded that; extension provides less bus travel time savings when buses are detected 70m away from the stop line, i.e., bus travel time savings will improve by extension if buses were detected well up steam the stop line, to reduce the negative impact on general traffic. He further concluded that recall better improves bus priority when compared to extension; with the usual detection, however integrating recall and extension yields greater benefits.

Guler and Menendez [22], encouraged the use of pre-signals to better utilize the capacity of the main signal while still providing priority to buses. Their objective was to analytically quantify and empirically evaluate the delays encountered by cars and buses with the use of pre-signals. They concluded that utilizing pre-signals can minimize the negative impact bus priority have on the general traffic, as compared to dedicating a lane for bus-use only or operating buses and cars completely mixed.

Truong et al [16] explored the combined effect of TSP and RSP including TSP and DBL, TSP and QJLs. He utilized Time space diagrams to analyze the combined and separate effect of TSP and RSP (i.e. TSP w/QJLs or TSP w/DBLs) on bus delay at an intersection level, with the objective of finding out whether combing TSP and RSP will create an additive effect, where the combined effect of TSP and RSP measures is equal to the sum of their separate effects. (TSP w/QJLs = TSP+ QJLs or TSP w/DBLs= TSP + DBLs). He concluded that there is a considerable benefit from combining TSP and RSP measures, in particular from combining TSP with QJLs as there is an over-additive effect on bus delay savings.

2.4 Benefits and Need for TSP

The main purpose of TSP is to improve transit ridership, by reducing bus delays at traffic signals, as a result bus travel times and schedule adherence is improved and an improvement in bus schedule adherence will reduce bus bunching which is as a result of the inability of buses to adhere to their schedule. TSP will also improve community livability for its ability to boost transit vehicle movement without excessive impact on other road users. Improvement of transit vehicle reliability will further reduce high auto dependency and expand mobility choices; if auto dependency is reduced, there will also be a reduction in energy consumption, greenhouse gases and other pollutants [23] [24].

TSP has been implemented in various cities across the United States and has yield plentiful benefits in the livability of those states. Early green and green extension TSP strategies were implemented for buses at 15 intersections along Cermak Road in Chicago Illinois. Benefits were 7 to 20% reduction in bus travel time (which is dependent on time of day and direction of travel) [23]. TSP yielded other great benefits in Chicago as it improved bus Schedule reliability, increased passenger satisfaction level with a 1.5 seconds/vehicle average in vehicular delay; however there was an increase in side street delay by 8.2 seconds/vehicle [23]. The city of Minneapolis prioritized buses on 3 intersections in Louisiana Ave. They utilized early green and green extension priority strategy with actuated transit phase and realized a bus travel time reduction from 0 to 38% with a 23% increase in traffic delay [26]. There was a 6 to 25% reduction in transit signal delay in San Francisco, California when TSP was implemented on 16 intersections for Light Rail Transit (LRT) and Trolleys [27].

2.5 Principles of TSP operation

TSP system has three major components: the transit vehicle detection system, communication system, and the traffic signal control system .The transit vehicle detection system generates a priority request via a vehicle to infrastructure communication between the transit vehicle with an on board transmitter and a receiver at the traffic signal, the request is then sent to the traffic signal control system (via communication system) which then executes the priority request. In this research the traffic signal controller gives priority to transit vehicles only when conflicting phases have at least used up their minimum green time [28]. Figure 1 below illustrates an example of the components of TSP.

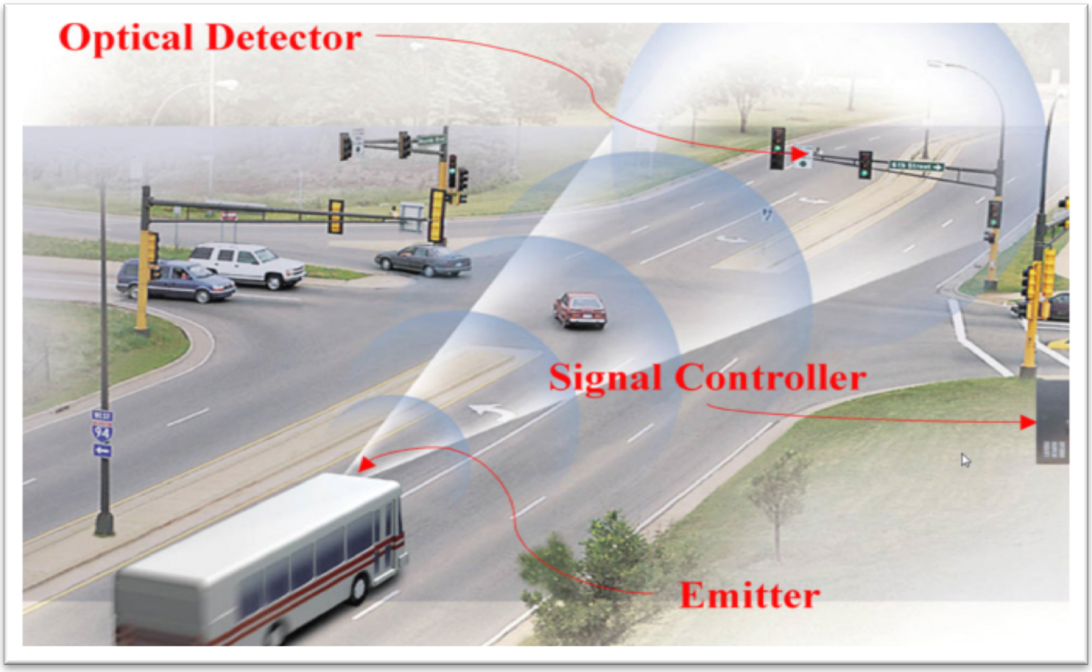

Figure 1: Example of TSP Components Source: [29]

2.6 TSP Strategies

Strategies for implementing TSP include: The passive priority, active priority and the use of pre-signals. The main essence of all these priority strategies is to improve transit vehicle travel times through a junction, improve bus regularity and punctuality, and to also provide economic benefit the communities [21].

2.6.1 Passive Priority

Passive Priority deals with re-optimizing signal timings to take care of streams of traffic containing significant bus flows; it allocates more green time to approaches having higher bus flow than it would for others [30]. Passive techniques does not require specialized hardware detection system, it simply improves traffic for all vehicles along the transit route; this implies that, passive priority strategy can be an efficient form of TSP if transit operations are predictable, with a sound knowledge of passenger loads, bus routes, bus schedules and dwell times [5]. Passive priority strategy is very efficient when transit vehicle operations are predictable with high transit frequency and low traffic volume on the bus route. The passive priority strategies includes: Adjustment of the cycle length which has to do with reduction of the cycle lengths at isolated intersections to give priority to buses, area-wide timing plan which involves giving preferential progression for buses through signal offsets, phase splitting which introduces special phases at intersection for bus movement, and metering vehicles which has to do with buses using special reserved lanes, signal phases, or rerouting buses to non-metered signals [31] [8].

2.6.2 Active Priority

Unlike passive priority, active priority requires a specialized hardware detection system, which involves a transmitter on the transit vehicle and detectors; active priority detects transit vehicles approaching a signalized intersection and adjusts the signal dynamically to respond to the approaching transit vehicle. This implies that active priority gives priority to buses by making the transit signal responsive to the arrival of a bus detected on the approach [30].

Active priority can be conditional or unconditional. Conditional priority compares transit vehicle to their schedule, in other words priority is given to only buses behind schedule whereas unconditional priority means all transit vehicles on the bus route are given priority. Although unconditional priority better improves schedule adherence by reducing intersection delay, conditional priority interferes less with traffic [32].

Active priority applies approaches such as: green extension, recall or early green approach, and an actuated transit phase. A green extension extends the green time to give priority to the approaching TSP equipped Vehicle. According to research green extension is one of the most effective approaches of TSP as it does not require an additional clearance interval, yet significantly gives priority to transit vehicles [23]. Recall or early green approach reduces the green time of the preceding phases in order to accelerate the return to green for movement where a TSP equipped vehicle has been detected [5]. This means that if a bus arrives at a signalized intersection in the beginning or middle of a red phase, the red phase is truncated and green phase is injected to allow the bus to go through [33]. This process is called red truncation and can only occur when the signal is red for the TSP vehicle approaching the intersection [5]. Extension provides less bus travel time savings, when buses are detected 70m away from the stop line, but bus travel time savings will improve by extension if buses were detected earlier i.e. farther away from the stop line as this will help reduce the negative impact on the general traffic. On the other hand recall better improves bus priority as compared to extension, by detecting buses 70m away from the stop line, but may have a negative impact on general traffic. But when recall and extension are integrated, bus priority benefit is much higher [21]. An actuated transit phase is displayed only when a transit vehicle is detected at the signalized intersection, rather than approaching the intersection [5] [14]. Figure 2 below shows an illustration of the green extension and red truncation active priority strategies.

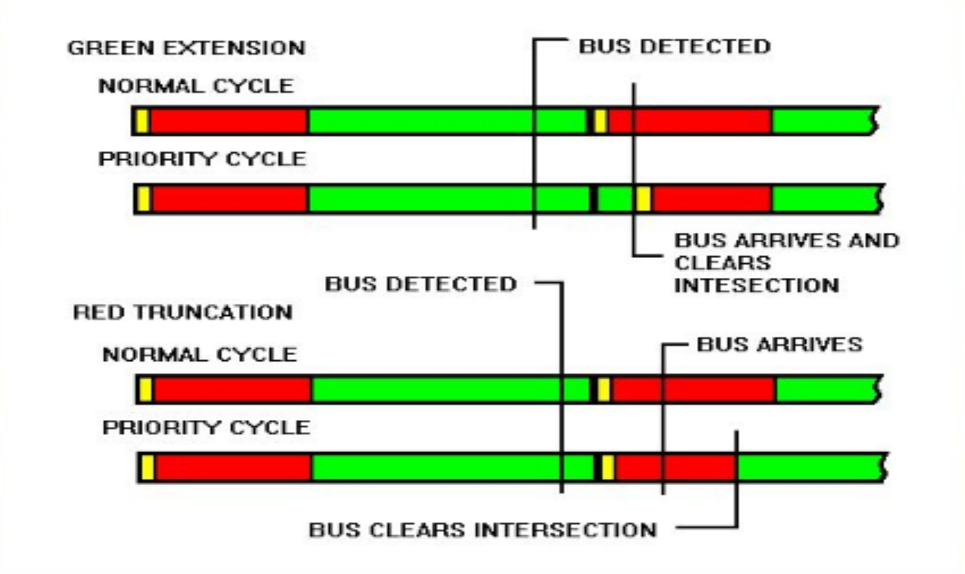

Figure 2: Green Extension and Red Truncation Active Priority Strategies, Source [34]

2.6.3 Pre-signals: A strategy for TSP

Another strategy which could reduce the negative interaction between buses and cars at signalized intersections has been to install an additional traffic signal (called pre-signals) upstream of the main signal to help minimize the conflicts between cars and buses [35].The use of pre-signals better utilizes the capacity of the main signal in giving priority to buses. Utilizing pre-signals can minimize the negative impact bus priority have on general traffic, as compared to dedicating a lane for bus-use only [36]. Pre-signals are installed ahead of the main signal to provide buses with priority access to the downstream junction [37]. If they are placed closer to the intersection buses could skip over longer queues, and have more priority, although, they would result in a longer red duration at the pre-signal and increased car delays [35].

2.7 Approaches to TSP Evaluation

Over the years the effectiveness of TSP to improve transit operation has been evaluated using different approaches. These approaches include: the empirical, analytical and microsimulation approach.

Empirical approach entails observing traffic operations at certain intersection and or corridors to evaluate the effectiveness of TSP on Transit operations. Very few researches have used the empirical approach to evaluate the effectiveness of TSP on transit operation. Feng et al [2] used empirical approach to examine the performance of an existing TSP system and concluded that considering minor streets, TSP did not increase delays for vehicles as extension phases were given late green which reduced their effectiveness compared to phases which had early green. Guler and Menendez [22] empirically evaluated and analytically quantified the delays encountered by cars and buses with the use of pre-signals. The findings showed that empirical data through theoretical formulas can predict delay encountered in real life with a small error of 2% for total delay and 10% for individual delay.

The analytical approach involves using logical reasoning and mathematical models to evaluate the impact of TSP on transit operation. Liu et al. [38] used the analytical approach to analyze the impact of early green and extended green TSP strategies on both prioritized and non-prioritized approaches and concluded that the analytical approach can better enhance the microsimulation approach in complex situations.

The microsimulation approach entails using traffic microsimulation software for TSP evaluation. Although the microsimulation approach is highly rigorous and time consuming involving coding, calibration and validation, it is the most widely used approach for TSP evaluations [7]. Kamdar [8] utilized a 10 seconds green priority strategy through microsimulation, findings show that green extension strategy reduced control delay for transit vehicles by 5-13%. Alomari et al [39] utilized the microsimulation approach to evaluate bus rapid transit scenarios with and without TPS and concluded that TSP and BRT scenarios are effective in reducing travel times up to 26% [24]. Micro simulation software packages have gained significant popularity over the years, and are widely used both in industry and research specifically because of their ability to reflect the progressive nature of the transportation system in a stochastic fashion [21]. Different microsimulation software has been used including VISSIM, AIMSUN, PARAMICS, and CORSIM amongst many others. VISSIM is the most widely used microsimulation tool and has been rated the best for its ability to efficiently evaluate network performance including detailed operation of transit vehicles, bus priority methods and strategies at both corridor and signalized intersection level [6] [21]; it can model almost any traffic control logic using programming interface such as Vehicle Actuated Programming (VAP) language; it can also read MatLab, java, C# and C++ scripts through COM interface [40] [21] [41] [42]. VISSIM micro simulation software package was used to develop and evaluate transit operational strategies on Oakland Park Boulevard in Florida, to improve the flow of traffic and improve transit vehicle running times in the corridor [43]. Furth and Muller [32] conducted a study at a signalized intersection to evaluate the impact of conditional priority on traffic delay and found that conditional priority had almost no impact on traffic delay compared to absolute priority which had increased delay significantly.

CHAPTER 3: METHODOLOGY

3.1 Study Corridor Selection

To achieve the study objectives, a 1.83 mile long section along Gallatin Pike corridor located in Nashville Tennessee was selected. The section has 9 signalized intersections at an average spacing of 0.26miles, 7 stops in each direction at an average of 625ft apart, two lanes in each direction, a continuous shared left turn lane (TWLTL), posted speed limit of 35-45mph, and an average scheduled bus speed (including stops) of about 15mph. Gallatin Pike corridor is an arterial roadway and a busy bus route carrying passengers to/and from Nashville. According to MTA Gallatin road is the agency’s heaviest route with over 80 000 rides per month [9]. This study also selected three major intersections along Gallatin pike corridor for TSP evaluation, with the aim of comparing the result of corridor wide analysis to isolated intersection analysis and evaluation.

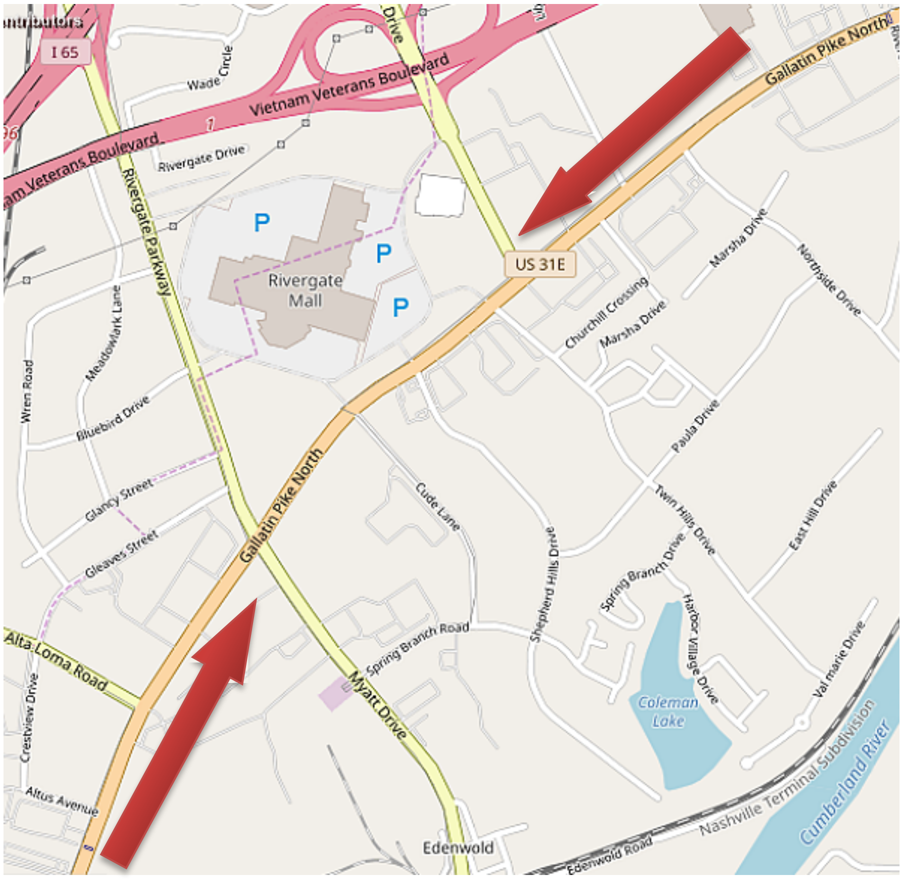

Figure 3: Map of Study Corridor

3.2 Micro Simulation Software Selection

VISSIM microsimulation software was used to model TSP due to its ability of accurately represent traffic operations theory such as detailed operations of buses, bus priority methods and strategies at signalized intersections [21]. VISSIM supported the purpose of this study as it was used to model traffic control logic via VAP language. This research therefore developed an unconditional green extension and red truncation TSP control logic using VAP language. The developed VAP code ties the TSP control logic to the VISSIM signal controller.

3.2 Data Collection

All the data needed for this study were collected along the study corridor or obtained from appropriate officials. A Miovision Scout unit [44] was used to take turning movement counts (TMC). The Miovision Scout unit is a traffic-counting device with video recording attributes that count and classify traffic per lane. This camera system was mounted on a stand with its top camera directed toward the intersection looking down on traffic. The camera was planted from 7AM to 12PM at different intersection within the study section on different days to collect Turning Movement Count (TMC). The TMC data was analyzed and the AM peak hour volume was used for simulation. Bus stop location, intersection layout, and lane configuration where extracted from google earth. Bus departure times and departure time offset were extracted from MTA bus schedule. Bus dwell times, boarding and alighting counts where collected on site upon boarding several buses. Several trips were made on the study corridor to collect general traffic travel times, bus travel times and speed data using Global Positioning System (GPS). Signal phasing and timing plan data were gotten from the Metro Nashville Department of Public Works.

3.3 Origin Destination (OD) Matrix Estimation

TMC collected in the field was used to estimate OD matrix based on the principle of conservation of vehicles (which states that vehicles in a network is neither created nor destroyed). This means that the number of vehicles coming into a network or a segment must be equal to the number of vehicles leaving the network or segment. The matrix was estimated using balanced proportioning to make sure that the number of vehicles entering the network is equal to the number of vehicles leaving the network. The estimated OD matrix was compared to the field TMC and the result showed a high consistency with a coefficient of determination of 86%. This means that the estimated OD matrix replicated the observed TMC as illustrated in Figure 4 below.

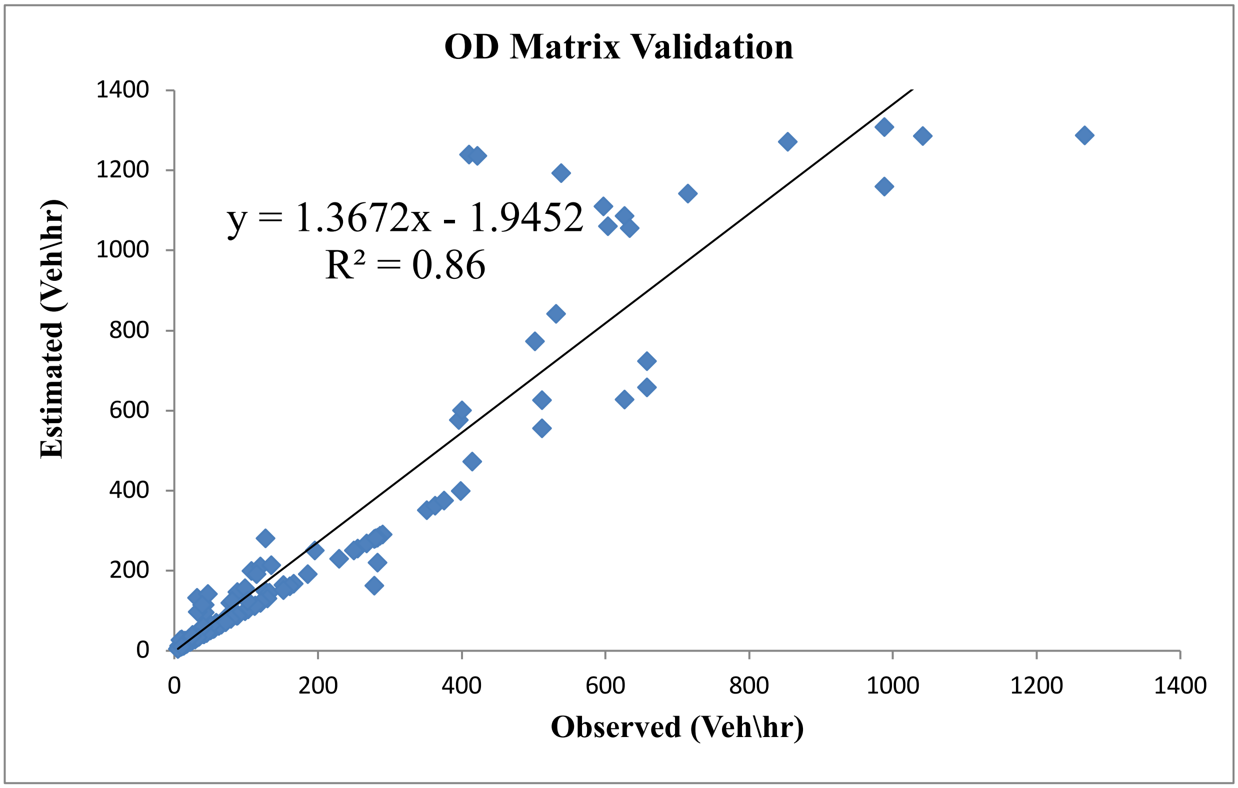

Figure 4: Validation of Estimated Origin Destination Matrix

3.4 Base Model Development

Links were used to code the geometry of the corridor alongside the geometry of the intersection while connectors were used to connect links and model turning movements. Urban (motorized) driving behavior type was defined in VISSIM using the Wiedemann 74 car following model to replicate the aggressive driving behavior of drivers in the urban motorized environment.

TMC data was analyzed according to the vehicle composition of the different types of vehicle such as cars, buses, Heavy Goods Vehicles (HGV) and Light Goods Vehicles (LGV) observed on the corridor. Vehicle types were entered in VISSIM along with their respective assigned distribution and relative flow. The desired speed parameter was used to create a desired speed ranging from 35mph to 45mph to replicate the speed distribution along the corridor. Vehicle routes were defined based on the relative flow of each movement. Minimum recall and gap out detectors where placed on all turning movement for full actuation of the corridor. This means that the network is fully actuated. Signal timing and phasing plans with no TSP strategy were developed in VAP language and tied to the VISSIM signal Controller, for normal operation of the traffic signals. Bus dwell times, boarding and alighting count, passenger flow characteristics, bus departure times, departure time offset and bus occupancy were coded as part of bus stop and public transportation line properties. In addition to the modelled corridor, three isolated intersection models were also developed and calibrated for peak hours: the intersection of Douglas Ave & Gallatin Pike was simulated with AM peak hour from 11:02am to 12:02pm, Due West & Gallatin Pike was simulated with AM peak hour from 7: 22am to 8:22am and West Old Hickory Blvd & Gallatin Pike was simulated for AM peak hour from 10:01am to 11:01am. Figures 5 is a sample of an isolated intersection model in VISSIM and its corresponding intersection geometry from google map. Figure 6 is a Sample of a section of the modelled corridor in VISSIM with its corresponding corridor geometry from google map.

Figure 5: Sample of Study Intersection alongside its Corresponding VISSIM Model

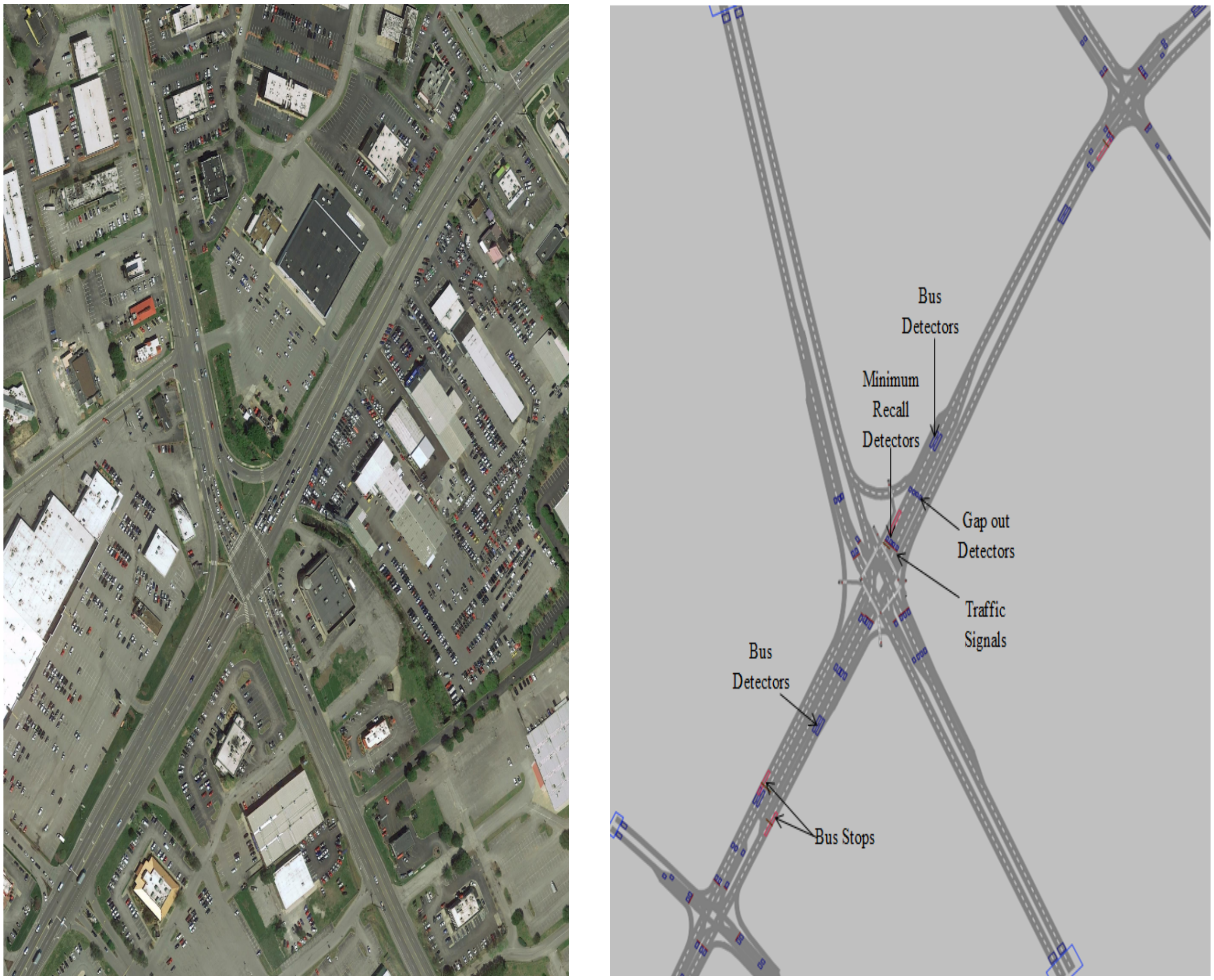

Figure 6: Section of Study Corridor alongside its Corresponding VISSIM Model

3.5 Dynamic Assignment

For a large network it is often very difficult and time consuming to manually define all the route choices from origin to destination because the route choice of drivers depends on signal control and traffic conditions. It is therefore imperative to model how drivers will choose from a set of possible routes based on a time dependent origin destination demand. Dynamic assignment in VISSIM is based on a repetitive simulation, and drivers are made to make their route decisions based on the travel cost they experienced in the previous simulation [45]. The iterative process is repeated until convergence is reached. Firstly, nodes were defined for all intersection and network boundaries making sure that the attribute "use for dynamic assignment" is checked. Zones as specified in the OD matrix were defined and parking lots were defined at network boundaries of every link in the network. Estimated Origin Destination Matrix was coded and the parameters defined based on vehicle compositions and class.

3.6 Model Calibration and Validation

3.6.1 Corridor Model Calibration

If a traffic simulation model is not well calibrated it cannot replicate the real situation. The model developed through VISSIM micro simulation was calibrated and validated to make sure it closely resembles the existing condition. As part of model calibration the traffic volumes from the OD matrix entered in VISSIM was compared to simulated traffic volumes, the comparison resulted in a strong coefficient of determination of 0.9984, see figure 7. This indicated that the simulated data closely matched the OD matrix which was coded in VISSIM. Speed data was also calibrated such that the difference between the simulated speed and observed speed is less than 5%. The model was validated using vehicle travel time which was not used in the model development process. The percentage error (PE) between the simulated travel time and the observed travel time was approximately 4%.

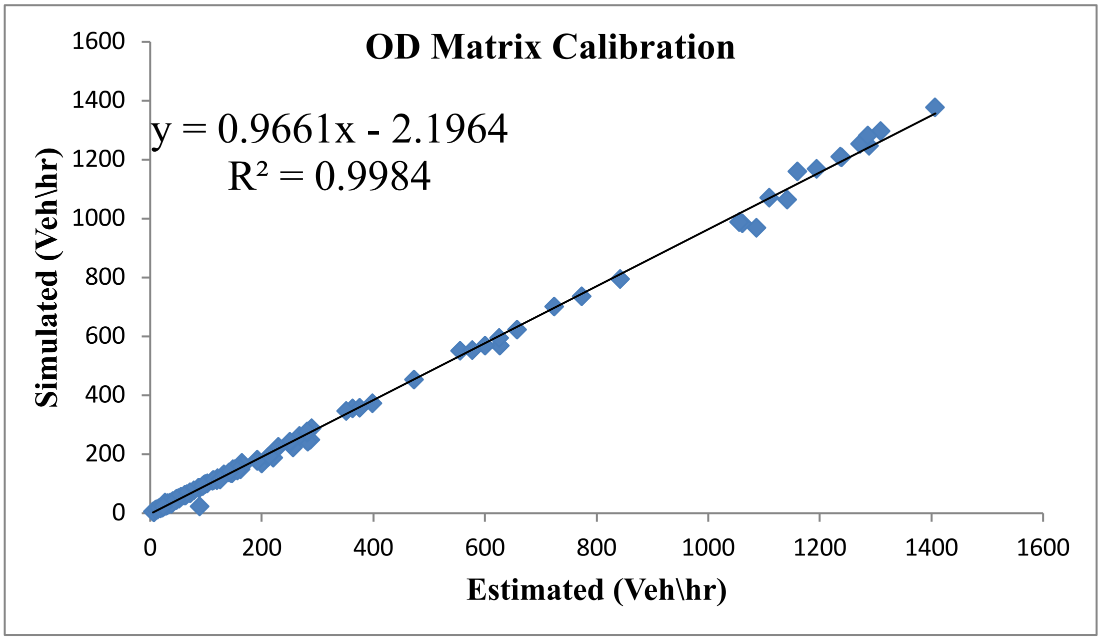

Figure 7: Calibration of OD Matrix from VISSIM Simulation

3.6.2 Isolated Intersection Model Calibration

As part of the calibration process the field TMC for each isolated intersection was compared against their corresponding simulated volumes using Geofferey E. Havers (GEH) model [46] as shown in equation 1.

$$\mathrm{GEH} = \sqrt{\frac{2(\alpha - \beta)^2}{\alpha + \beta}} \qquad (1)$$

Where α is observed volume and β is simulated volume

Node evaluation was used to extract simulated volumes based on the average of 10 simulation runs. A network is said to be calibrated if GEH value is less than 5 for 85 percent of the links and GEH less than 4 for sum of all link counts [46]. If GEH value is greater than 5, route choice assumptions, vehicle composition, driving behavior and parameters such as maximum and minimum look ahead distance, look back distance, average standstill distance, and lane changing rule adjusted are investigated.

3.7 TSP Implementation in VISSIM

After it was ascertained that the developed VISSIM model replicated the real situation, TSP was incorporated into the model. The traffic signal coded in the base model was adjusted to respond to the priority request of all buses utilizing the priority approach. To achieve this, this research developed an unconditional green extension and red truncation TSP signal logic via VAP language, the developed VAP code was tied to the VISSIM signal controller so that the signal controller adjust the signal to respond to a bus call. TSP detectors were placed 75m from the stop line to enable the signal respond to a bus upon a priority request at that distance. Green extension time is estimated for buses that require extension in order to completely cross the intersection before the signal changes to a red. If the signal is red as at the time the bus is detected by the TSP detector, the signal controller will only respond if conflicting phases have at least used up their minimum green. This means that the red phase will only be truncated when the green time for conflicting phases is greater than or equal to their minimum green time. This is to make sure conflicting phases have some amount of green time before priority is given to the priority phase; this is to reduce the amount of delay that may arise on the conflicting phases as a result of the priority given to the transit vehicle on the bus route [4]. Figure 8 illustrates the TSP signal logic developed in this study.

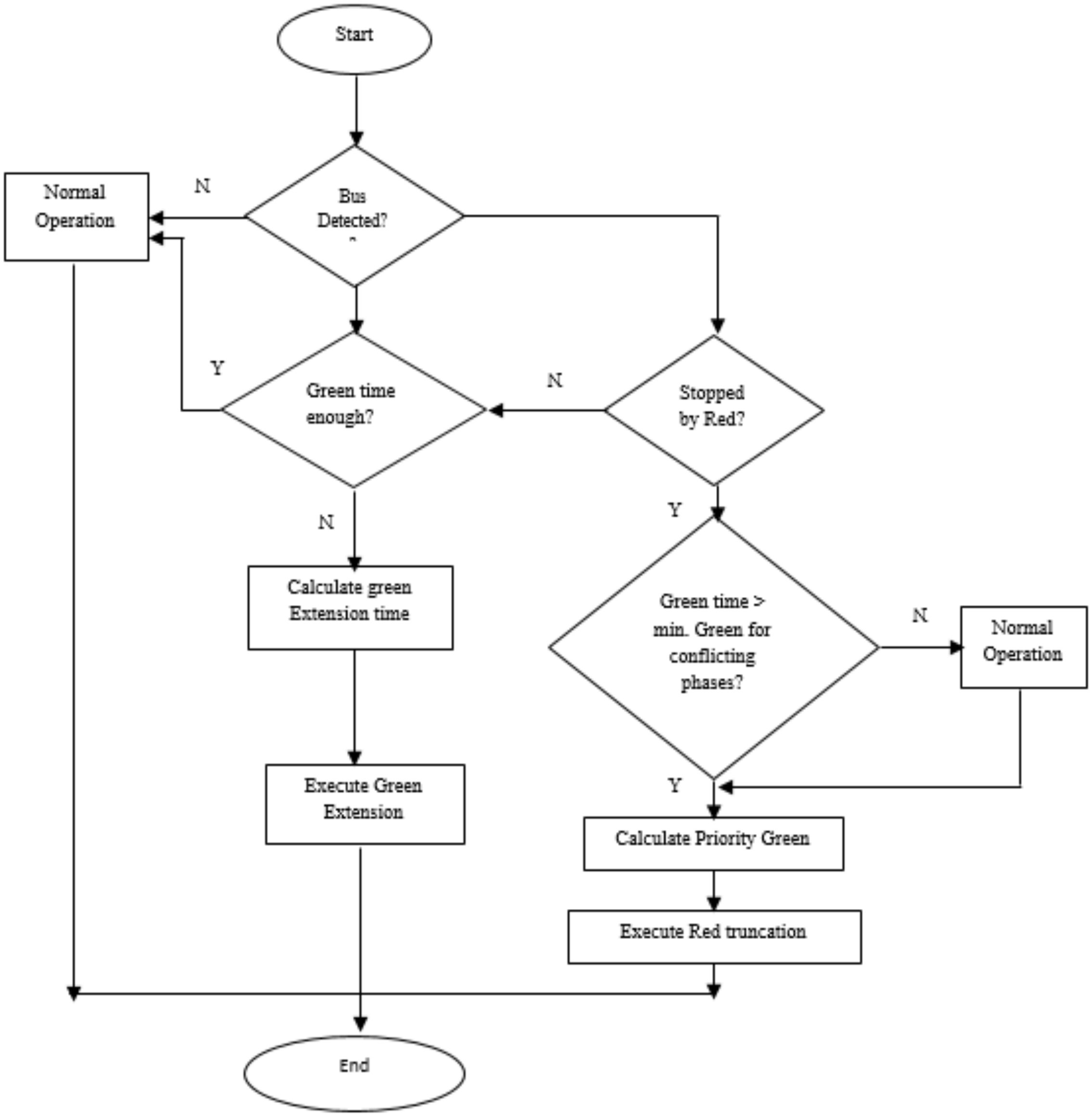

Figure 8: Transit Signal Priority Implementation in VAP

CHAPTER 4: DELAY MODELS

4.1 Delay Models

Some researchers have investigated and developed delay models based on certain conditions and scenarios, however very few studies have investigated the shape of a flow delay curve for interrupted flow conditions [47] [48] [49]. This study further investigates the shape and model of a flow-delay curve under TSP conditions considering the vehicle flowrate per lane group. Altun and Furth [3] developed a uniform delay model which predicts delays at traffic signals with TSP. They considered both green extension and red truncation as a function of arrival time in a cycle when predicting the delay experienced by buses at the traffic signals as shown in figure 9, where 'R' is the red truncation of the priority route, 's' is the saturation flow rate, 'v' is the volume, 'r' is a uniform random variable from 0 to 1 to represent bus arrival time within a given signal cycle, 'C' is the cycle length, 'e' is the red truncation time, and 'x' is the green extension amount.

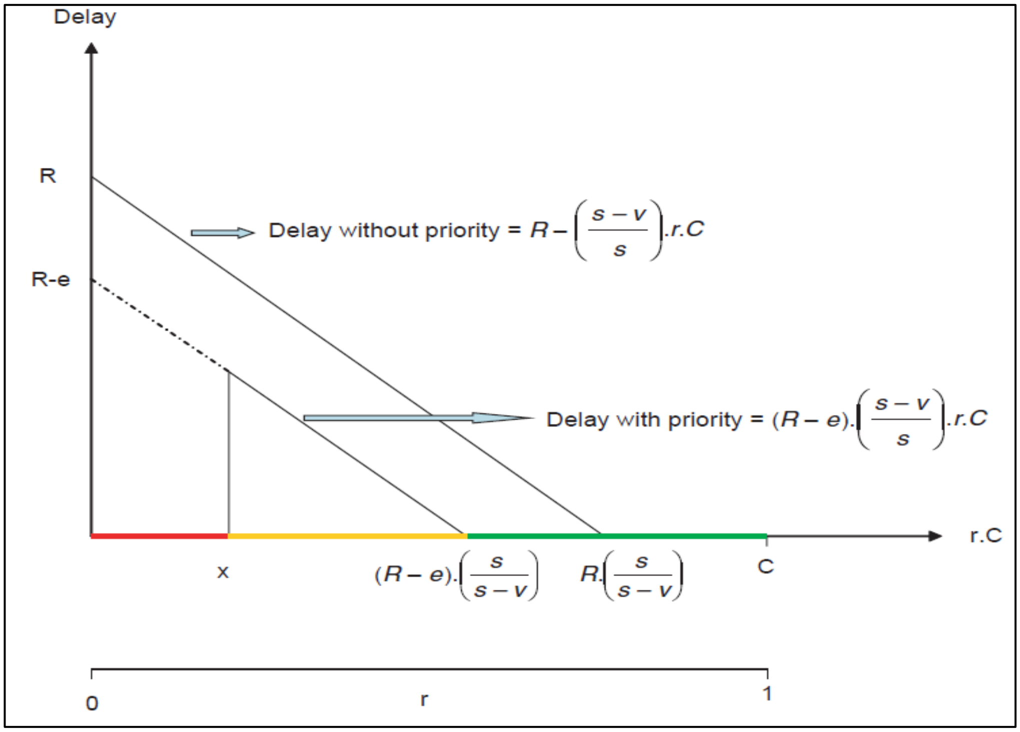

Figure 9: Uniform Delay Model to Predict Delay at Traffic Signals, Source [3].

This research has therefor developed a flow-delay model for urban motorized environment with interrupted flow under mixed traffic condition for the base and TSP scenarios. The model developed predicts delay for under-saturated and saturated conditions accounting for traffic controls, urban driving behavior, roadway geometry, vehicle types and composition. Figure 10 illustrates the shape and pattern of a flow-delay model under uninterrupted traffic flow conditions for under-saturated and oversaturated conditions [47] [49]. In figure 10, region A pictures under-saturated flow conditions were arrival or demand flow is lower than the capacity associated with uninterrupted travel speed ($q_a \leq Q$), region C represents oversaturated condition were arrival flow rate is above capacity ($q_a > Q$) associated with reduced travel speed. The shape of traffic flow curve on a particular road segment may vary depending on factors such as time of traffic volume collection, traffic composition and types, weather conditions, number of lanes, lane width, and driving behavior.

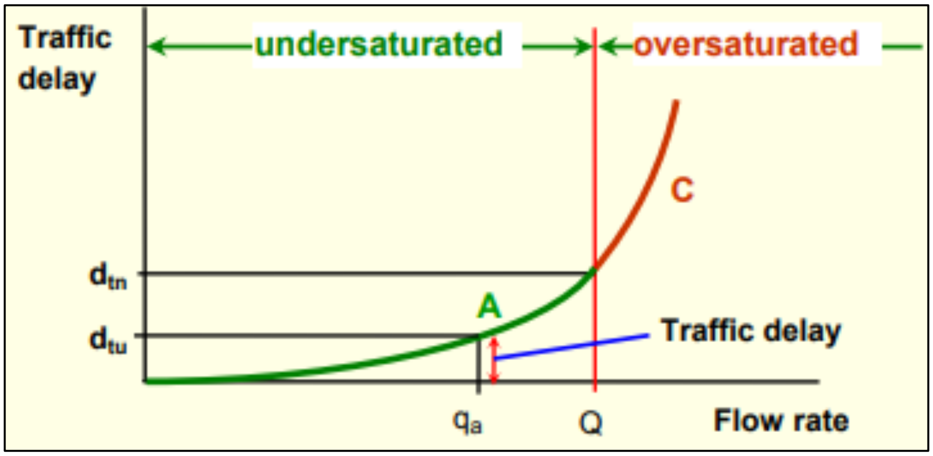

Figure 10: Delay as a function of flow rate for uninterrupted traffic streams

The flow delay developed in this research is related to the Webster's uniform delay model, published in 1958 [50] with the assumption of a stable flow and a simple uniform arrival function as represented by equation 2 to 7 [51]. F

igure 11 illustrates the Webster's uniform delay model, where the aggregate delay is estimated as the area between the arrival and departure curve.

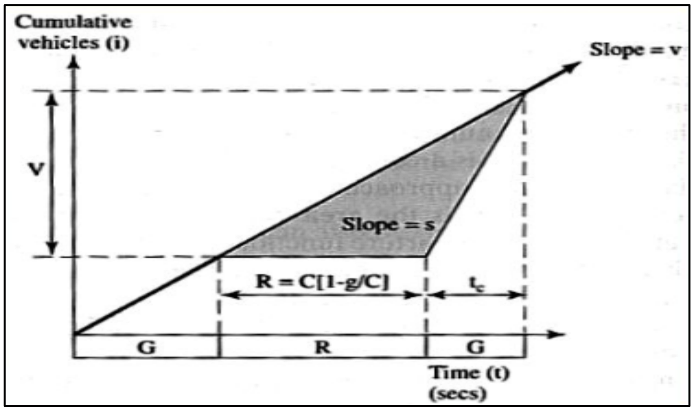

Figure 11: Webster's Uniform Delay model

From Webster's uniform delay model

$$\mathrm{UD_a} = \frac{1}{2}\mathrm{RV} \tag{2}$$

Where

UD_a = Aggregate Uniform Delay Veh-sec

R= Length of RED phase

V= Total Vehicles in queue, Veh

$$\mathrm{R} = \mathrm{C}[1 - ({}^{\mathrm{g}}/_{\mathrm{C}})] \tag{3}$$

$$\mathrm{V} = \mathrm{v}(\mathrm{R} + \mathrm{t_c}) \tag{4}$$

$$\mathrm{t_c} = \frac{\mathrm{R}}{[(\frac{\mathrm{s}}{\mathrm{v}}) - 1]} \tag{5}$$

$$\mathrm{UD_a} = \frac{1}{2}\mathrm{C}^2\left[1 - \left(\frac{\mathrm{g}}{\mathrm{C}}\right)\right]\left[\frac{\mathrm{vs}}{\mathrm{s - v}}\right] \tag{6}$$

The Average uniform delay is given by

$$\mathrm{UD} = \frac{1}{2}\mathrm{C}\frac{[1 - {}^{\mathrm{g}}/_{\mathrm{C}}]^2}{[1 - {}^{\mathrm{v}}/_{\mathrm{s}}]} \tag{7}$$

4.1.1 Flow Delay Model from Microscopic Simulation

Vehicle flow and delay data extracted from simulation was used to develop a relationship between flow and delay. Saturation flow was defined in the model by combining the additive part of safety distance and multiplicative part of safety distance parameters in the Wiedemann 74 car following model. These parameters where calibrated so that the model replicate the maximum saturation flow for a two way multilane highway.

Figure 12 and 13 shows a flow (vph) and delay (seconds) data from microscopic simulation for the base and TSP scenario respectively as developed by this research. The flow and delay data have been fitted by equation 8 with the coefficients for α and β alongside their coefficient of determination (R^2) presented in table 1.

$$D = \frac{\alpha \mathrm{q_a}}{1 - \beta \mathrm{q_a}} \tag{8}$$

Where

D = Traffic Delay(s)

$\mathrm{q_a}$= Arrival (demand) flow Rate (vehicle)

$\alpha = \frac{1}{2}\mathrm{C}[1 - {}^{\mathrm{g}}/_{\mathrm{C}}]^{2}$, and $\beta = {}^{1}/_{\mathrm{s}}$

Table 1: Flow Delay Model Coefficient

Model	α	β	R^2
No TSP	0.01	0.000228	0.979
TSP	0.00499	0.0003	0.928

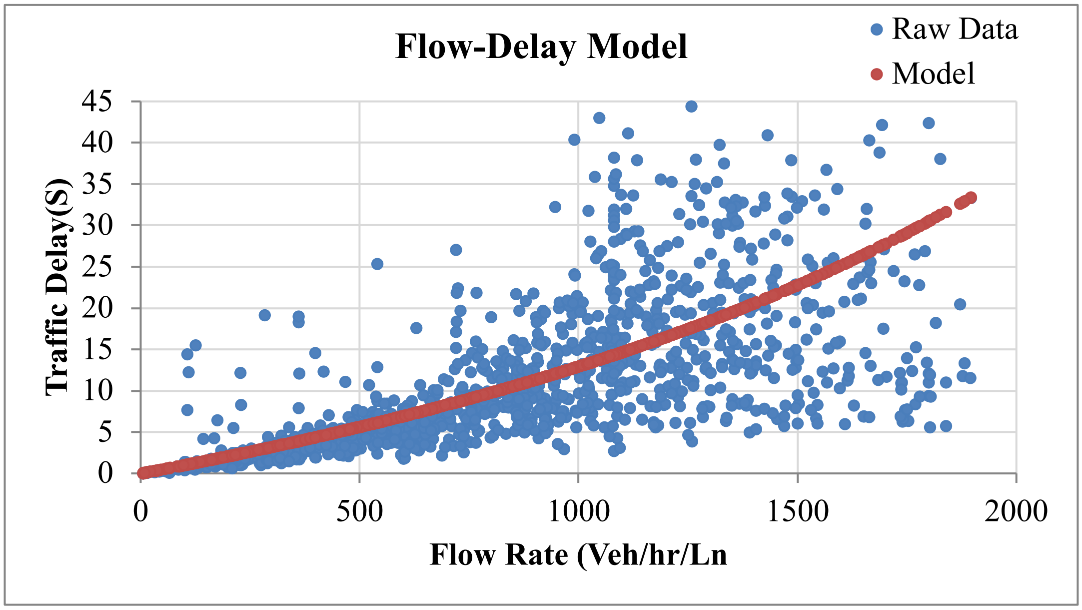

Figure 12: Flow-Delay curve for the Base Condition

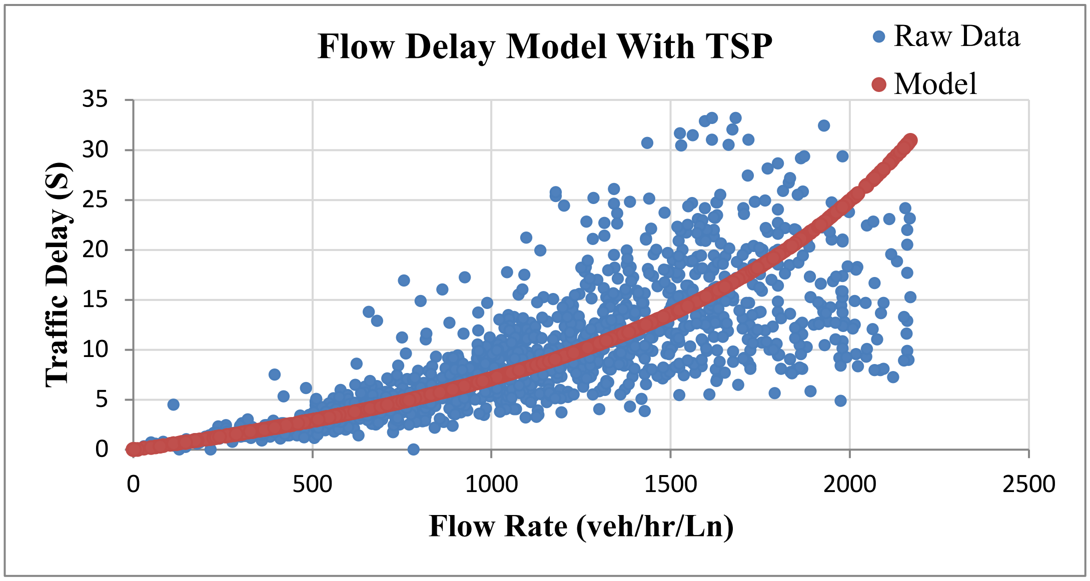

Figure 13: Flow-Delay curves for TSP Condition

4.1.2 Flow-Delay Model Comparison

The flow delay curve for both scenarios were compared and the result shown in figure 14. It can be observed that the maximum flow rate for the base scenario is 1896 vehicle/hour/lane of green time and has increased to 2163 vehicle/hour/lane of green after the implementation of TSP. This implies that TSP increased flow rate by 267 vehicle/hour/lane of green. This is because the implementation of TSP increased the speed of vehicles (as a result of green extension and red truncation) on the priority approach. The result also indicate the effectiveness of TSP on delay reduction on the priority approach as the flow delay curve for TSP scenario is below the flow delay curve for the base scenario. Based on the number of vehicles entering the link segment, it can be observed that as flow increases traffic delay also increases (meaning the more the number of vehicles entering the link segment more the delay).

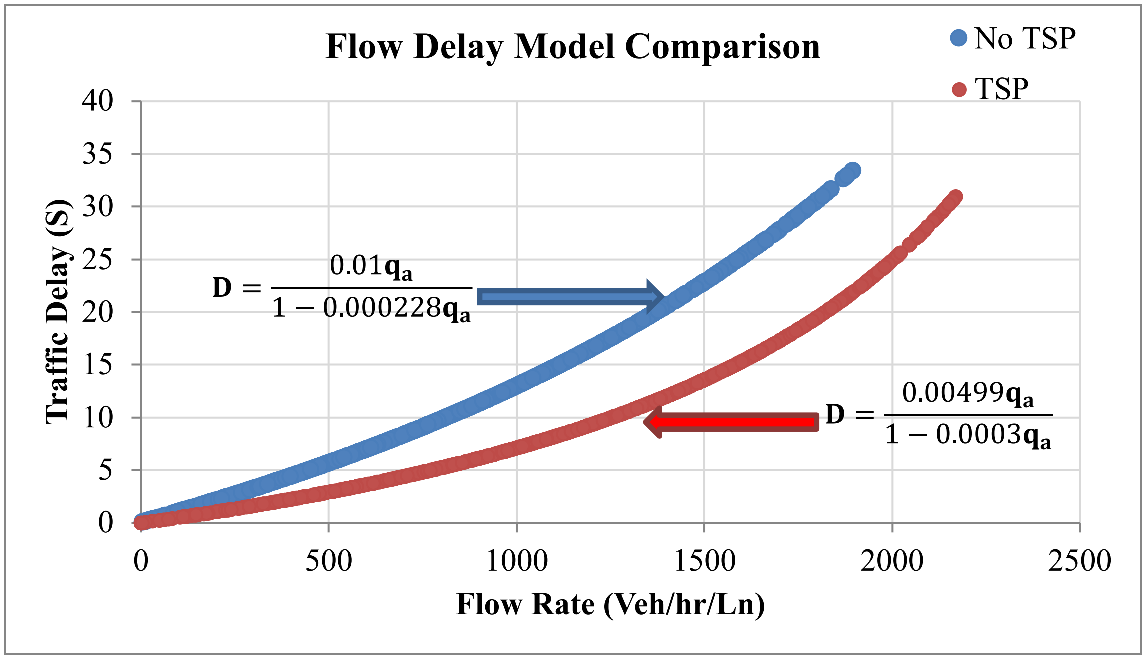

Figure 14: Flow Delay curve Comparison

4.2 Queue Delay Model

The relationship between the queue and delay at the isolated intersections based on TSP operations was evaluated. The research also developed a Queue-Delay model to predict the queue length of an intersection approach before and after the addition of TSP. This model is developed based on the microsimulation data obtained from VISSIM. Equation 9 is a queue length model included in the Highway Capacity Manual (HCM) for Two-way Stop Controlled (TWSC) intersections where the queue length is a function of traffic demand, capacity and analysis period [52].

$$Q_{95\%} \approx 900T\left[\frac{V_x}{C_{m,x}} - 1 + \sqrt{\left(\frac{V_x}{C_{m,x}} - 1\right)^2 + \frac{\left(\frac{3600}{C_{m,x}}\right)\left(\frac{V_x}{C_{m,x}}\right)}{150T}}\right]\frac{C_{m,x}}{3600} \tag{9}$$

Where

$Q_{95\%}$ is the 95th percentile queue length in vehicle is

V_x is the traffic demand for movement ‘x’ in vehicle per hour (vph)

T is the analysis period in hour (h) and

C_{mx} is the capacity of the movement ‘x’ in vph.

Tian and Kyte [53], determined that the same approach applied in predicting queues at TWSC intersections can also be applied to All-Way Stop-Controlled intersections (AWSC). According to chapter 21 of the sixth edition of HCM [52], the queue length is computed as the product of the average delay per vehicle and the flow rate of the movement of interest as presented in equation 10.

$$Q_{95\%} \approx \frac{900T}{h_d}\left[(x-1) + \sqrt{(x-1)^2 + \frac{h_d x}{150T}}\right] \tag{10}$$

Where

h_d is departure headway (secs) and ‘x’ is degree of utilization expressed as $\frac{v h_d}{3600}$ (unitless).

Box and Alroth [54], applied the methods of counting the number of standing vehicles (queue length) at 15 seconds interval and developed a model to predict delay for unsignalized intersection in terms of queue length as presented in equation 11.

$$D = \sum_{i=1}^{n} Q_i \times \frac{15}{3600} \tag{11}$$

Where D is total delay in vph and Q_i is the queue length observed in time interval ‘i’.

Tian et al [53], developed an empirical model for AWSC intersections. The model predicts the 95th percentile queue length directly from the average queue length as shown in equation 12.

$$Q_{95\%} = 1.3Q + 2.1\sqrt{Q} + \frac{Q}{Q+4.6} \tag{12}$$

Where Q is the average queue length in (veh).

Other researches on queue models have also shown that the average queue length at AWSC intersections is directly proportional to the average delay as shown in equation 13 [55] [56].

$$Q = \frac{V}{3600} \times d \tag{13}$$

Where 'V' is the traffic demand in vph and 'd' is the average delay in seconds per vehicle.

Utilizing the concept from the queue-delay relationships from precious researchers [52] [54] [53], this paper developed a queue delay model for an intersection approach for both the base and TSP condition shown in figure 15 and 16 respectively. Regression analysis was used to analyze the queue and delay data from microsimulation which resulted into power function model in the form as shown in equation 14. The developed power model for both the base condition and TSP condition with the coefficient of determination are presented in Table 2.

$$Q = d^{\alpha} \tag{14}$$

Although the queue delay models from both scenarios followed the same pattern, the maximum queue length and delay for the base condition is observed to be 69-ft and 24 secs, while queue length and delay for TSP condition is observed to be 53-ft and 20 sec respectively; showing a reduction in queue length and delay after the addition of TSP.

Table 2: Model Results

Scenario	Model	Coef.	Std. Err.	t-statistics
No TSP	α	1.33	0.017	79.72
TSP	α	1.32	0.018	72.11

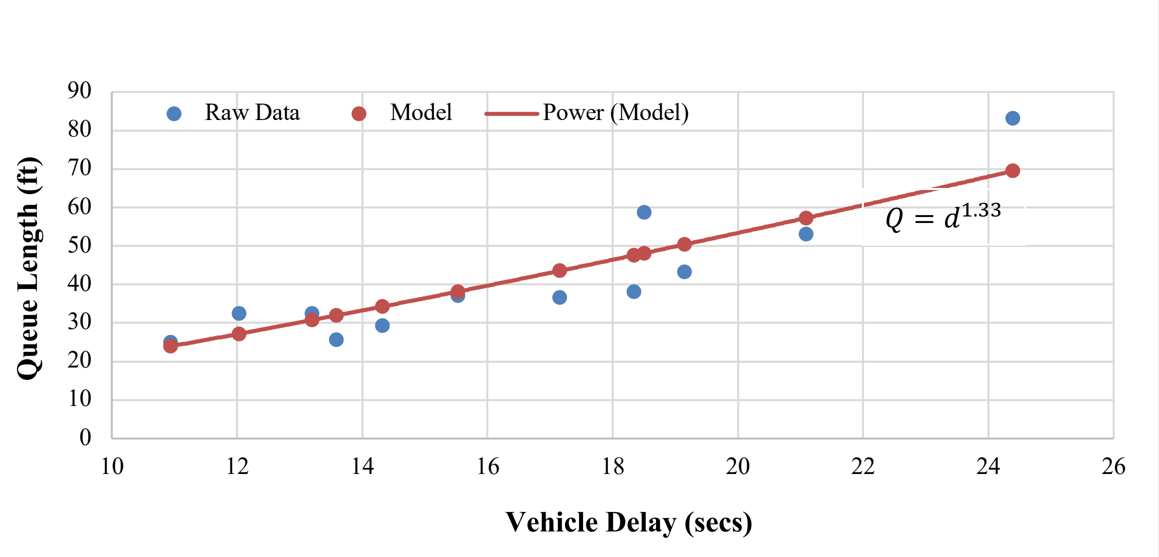

Figure 15: Queue Delay model for the Base Condition

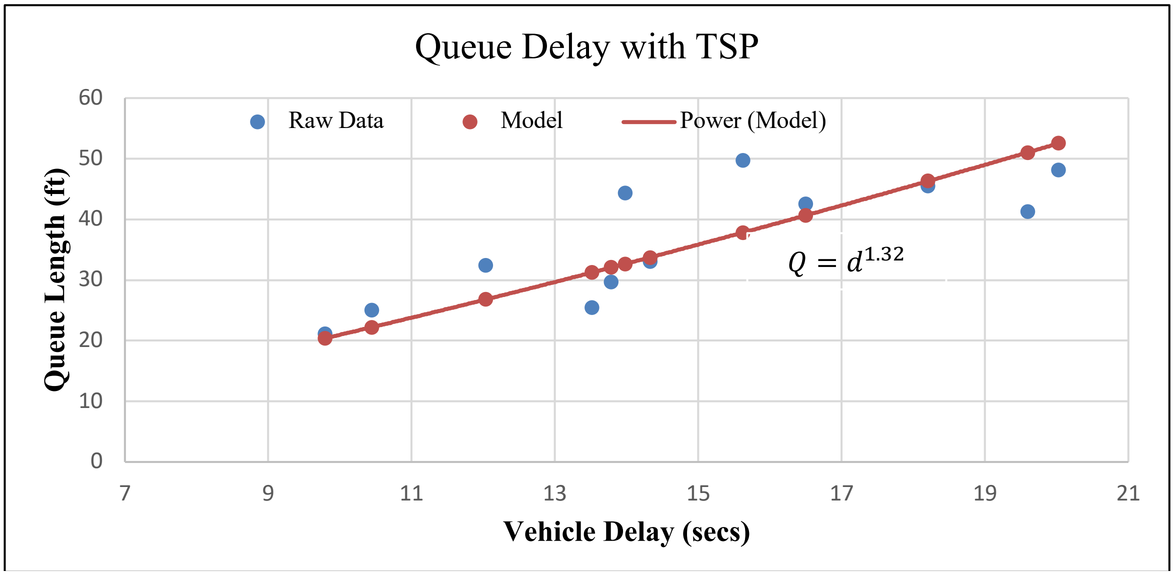

Figure 16: Queue Delay Model under TSP Condition

CHAPTER 5: MODEL RESULTS

5.1 Corridor Based Evaluation Results

All results in this research are based on the averages of 10 simulations. It was found that buses take a longer time to travel from the beginning of the link to the end of the link compared to other vehicle types. This is as a result of the dwell time at bus stops to board and alight passengers. Travel time observed from 10 and 15 seconds of priority green time were compared against the base scenario. For 15 seconds of priority green time, bus travel time was reduced by 5.1% and 10% on the WB and EB approaches of the study corridor respectively. TSP also favored other vehicle types utilizing the priority approach as they also experienced a reduction in travel time up to 4.3% and 7.3% on the WB and the EB approach respectively while on average TSP favored the general traffic on the priority approach by 4.9% on the WB approach, and 5.7% on the EB approach. For the 10 seconds of priority green travel time reduced by 4.5% and 8.1% for WB and EB approaches respectively, travel time reduced for other vehicle types up to 3.7% and 5.8% on the WB and EB approaches while on average the general traffic experienced a travel reduction up to 4.4% and 5.4% on the WB and EB approaches respectively. Based on the findings 15 seconds of priority green will yield more travel time benefits compared to 10 seconds of priority green. The research also evaluated the delay experienced by all vehicle classes on the priority approach. Buses experienced a reduction in delay up to 11.4% and 22.9% on the WB and EB approach respectively. Other vehicles on the priority approach also benefited as they experienced a delay reduction up to 8.9% and 14.4% on the WB and EB approach respectively. TSP reduced delay for the general traffic on the priority approach by 10.1% and 12.2% on the WB and EB approaches respectively.

5.1.1 Late Bus Recovery

This study has also evaluated the amount of bus lateness that can be recovered at bus stop level after the implementation of TSP. Bus lateness before and after TSP was evaluated, and analyzed for all 7 bus stops in each direction of the priority approach. Results from evaluation show that bus lateness increases as the bus travel across major intersections. The result in figure 17 showed that there is a progressive increase of bus lateness from stop 1 which is located towards the beginning of the study segment to stop 7 which is located towards the end of the study segment this means that bus lateness increases as the bus travel across intersections. TSP recovered bus lateness up to 25.21% to 43.1% on the average. Lateness of the buses at bus stop is dependent on the bus dwell times at each stop. For the research bus dwell times vary from approximately 1 minute to approximately 4 minutes as observed on the field. Longer dwell times were mostly as a result of disabled and elderly people boarding and alighting the bus.

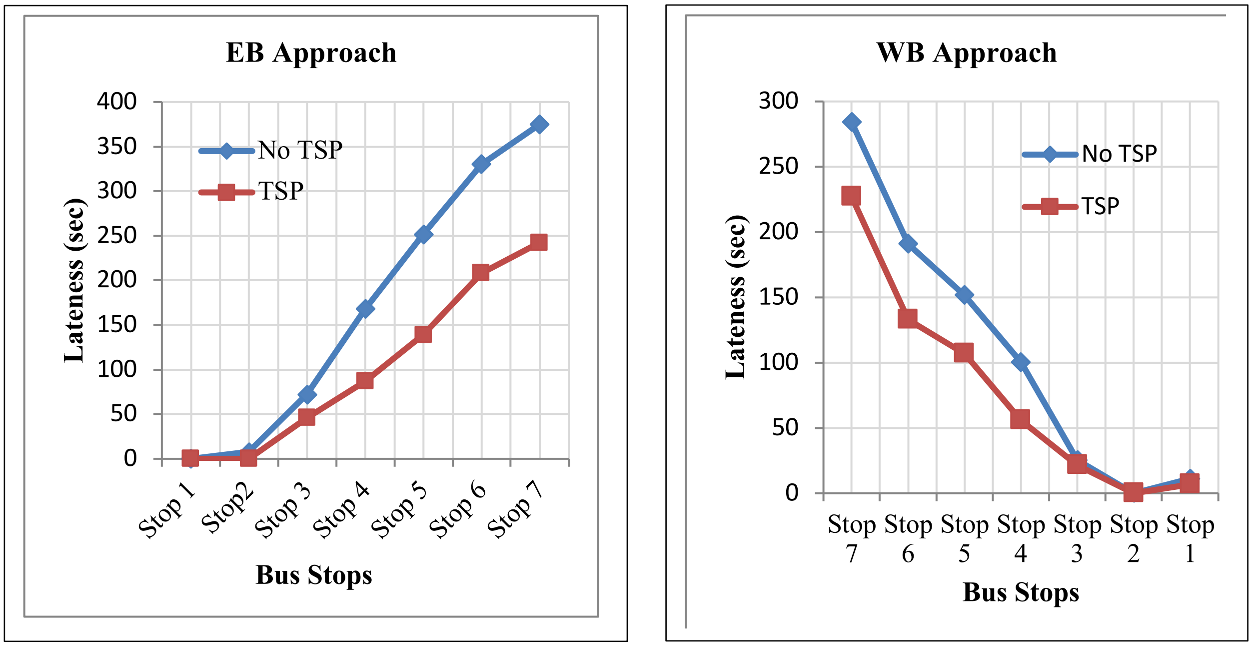

Figure 17: Late Bus Recovery on the priority Approaches

Simulation results showed an increase in side street delay after the addition of TSP as presented in figure 18. This increase in delay is a result of the reduction of the green time for the side street phases to return an early green for the priority phase; however the side street phases are allowed to at least use up their minimum green time before a return of an early green to the priority approach. Vehicles on the side street experienced an average increase in delay up to 15.9%.

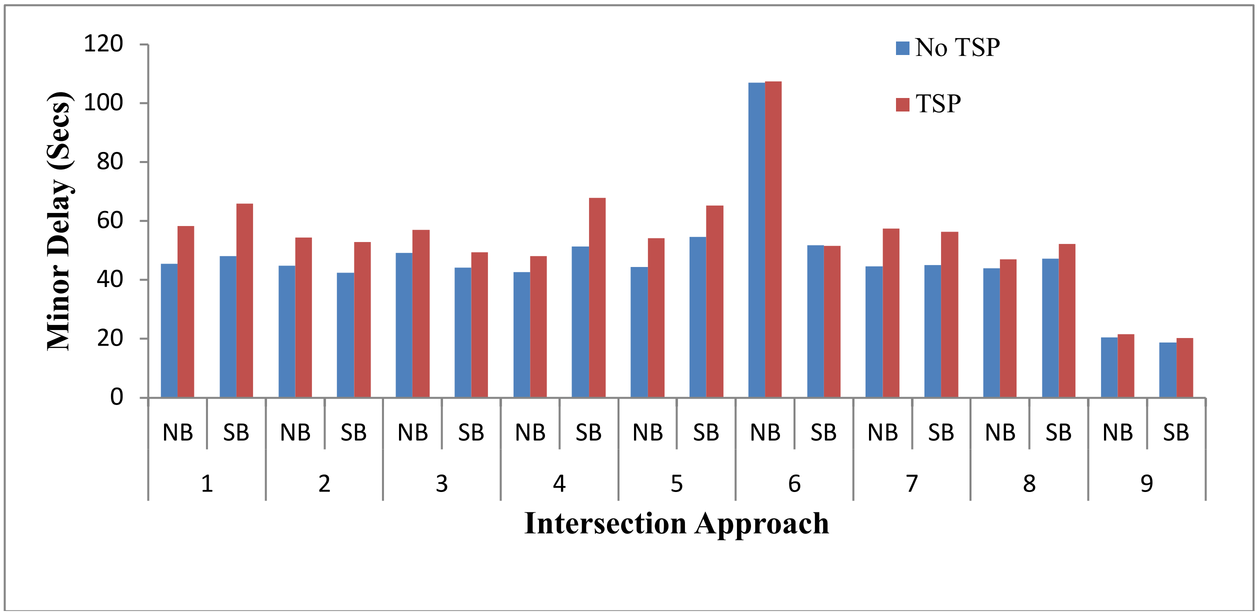

Figure 18: Impact of TSP on the Side Street Traffic

5.1.2 Impact of TSP on Control Delay and Level of Service (LOS)

This study also evaluated the impact TSP on control delay and LOS. Although TSP will increase the control delay, the LOS may not be affected. Table 3 shows the control delay and level of service for all 9 intersections within the study segment. All intersection show an increase in control delay but no change in the level of service after implementation of TSP except for one intersection which showed an increase in control delay and a change in LOS from C to D. This may be because this intersection has very high traffic volume compared to other intersections in the study segment.

Table 3: Comparison of Existing (base) Model and TSP Model Control Delay and LOS

Intersection of Gallatin Pike and…	Intersection Delay & LOS					
	Base	LOS	Base + TSP	LOS	% Increase	% Reduction
Alta Loma	27.3	C	31.13	C	14.0	
Unnamed	21.47	C	21.51	C	0.2	
Rivergate	34.1	C	42.39	D	24.3	
Cude Lane	21.33	C	23.3	C	9.2	
Shepherd Hills	20.91	C	21.36	C	2.2	
Conference Dr	24.79	C	26.06	C	5.1	
Liberty	17.07	B	17.85	B	4.6	
North Side	17.67	B	18.45	B	4.4	
2284-2282 TN6	7.98	A	7.97	A		0.1

5.2 Isolated Intersection Based Evaluation Results

This study further utilized both the green extension and red truncation active priority strategies evaluate the impact of TSP on isolated intersections. Simulation results show a significant reduction in bus delay for all three intersections and it can be observed that other vehicles utilizing the priority approaches experienced a reduction in delay. Buses on the priority approach experienced a delay reduction ranging from 34% to 76%, see figure 19. Other vehicles experienced an average delay reduction ranging from 3% to 9%. Result illustrated in figure 20 shows an increase in vehicle delay for the crossing street traffic (minor streets) ranging from 0.1% to 18%. This means that TSP may not favor traffic on the crossing street.

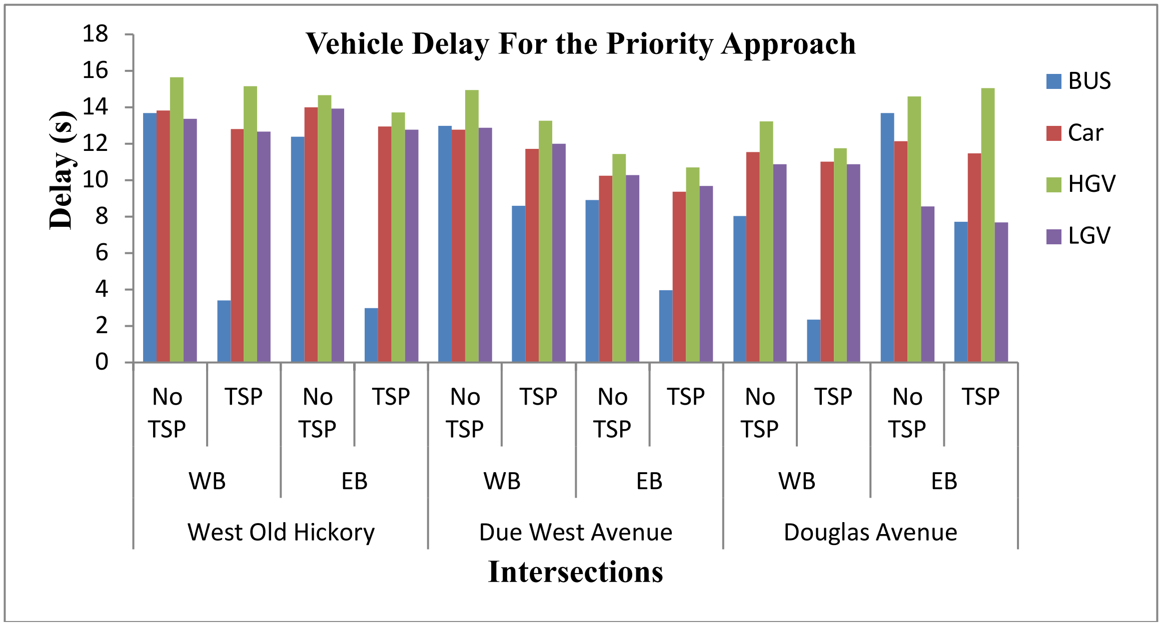

Figure 19: Vehicles delay on the approaches with Transit Signal Priority

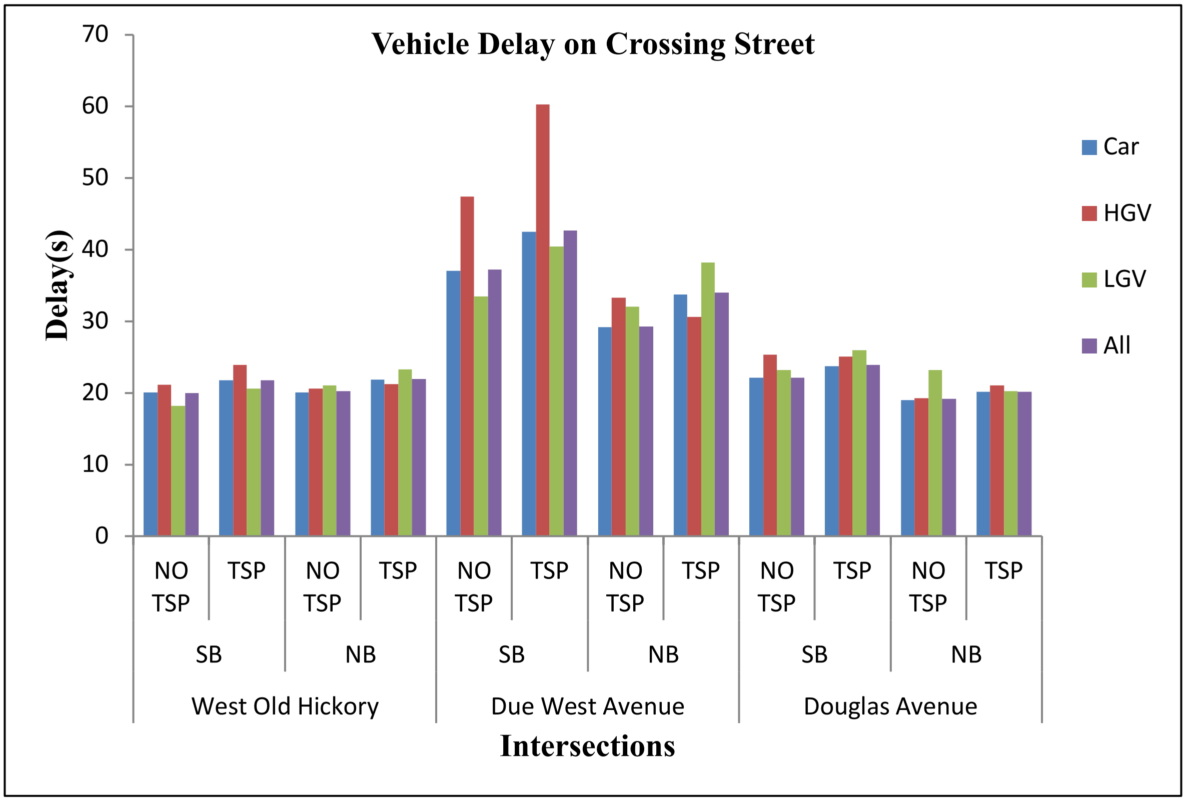

Figure 20: Vehicles delay on the Minor Street Approach

The results in the Table 4 show TSP has little or no effect on overall intersection delay. All intersection delays approximately remained the same before and after implementing TSP. The LOS for the three intersections did not change after TSP implying that TSP may not affect the overall LOS under medium traffic conditions.

Table 4: Isolated Intersection Delay and LOS

Intersection	Field Signal Timing		LOS
	No TSP	TSP	
West Old Hickory	15.03	15.26	B
Due West Ave	14.71	14.95	B
Douglas Ave	14.78	14.71	B

CHAPTER 6: CONCLUSION

This study has evaluated TSP benefits on an urban arterial corridor, by modelling a section of Gallatin Pike corridor which is a busy bus route surrounded by business centers and offices. This study also evaluated TSP benefits on isolated intersections with the aim of evaluating the performance of TSP when signalized intersections are analyzed in isolation. For both the corridor based and isolated intersection scenarios, this study focused on the effectiveness of TSP on transit vehicle operation particularly buses, in terms of bus delay and travel times, bus schedule adherence, side street delay, control delay and LOS.

This study employed unconditional green extension and red truncation active priority strategy, developed in VAP language and tied to VISSIM signal controller. The TSP logic is developed such that buses located 75 meters away from the intersection are detected and given priority, however buses will not be given priority upon reaching the intersection when the signal is red unless other conflicting phases have at least used up there minimum green time. Corridor and intersection geometry were developed in VISSIM and was further calibrated to closely match field conditions.

From the corridor based analysis, it was observed that TSP will yield great benefits in bus travel time reduction, and will not only benefit buses alone but also favor other vehicle types using the bus route. The study also considered evaluating travel time reduction with different priority green time and has observed that 15 seconds of priority green time will yield greater travel time benefits compared to 10 seconds of priority green. It was also observed that travel time for buses reduced by 5.1% to 10%, while other vehicle types experienced a travel time reduction of 4.3% to 7.3%. Buses also experienced an 11.4% to 22.9% reduction in delay while delay for other vehicle types reduced by 8.9% to 14.4%. Each bus stop in the study segment was also analyzed and it was observed that TSP will recover bus lateness up to 25.21% to 43.1% on the average. It was also discovered that TSP may not benefit the crossing street traffic as they experienced an increase in delay up to 15.9%. From the analysis of isolated intersection, it was discovered that TSP reduce bus delays up to 34% to 76%, and on the average reduce delay for other vehicles on the priority approach up to 3% to 9%, while side street experienced an increase in delay up to 0.1% to 18% when signalized intersections are analyzed in isolation. Results from both scenarios show the effectiveness of TSP to reduce bus delays and improve travel times, with an improvement in bus schedule adherence. It was also observed that under medium traffic condition TSP may increase control delay but not LOS, however there may be an increase in control delay and LOS under high traffic condition.

Finally, this research developed a flow-delay and a queue-delay model under interrupted flow condition in a mixed traffic environment. The flow delay model will predict delay even under TSP conditions and the queue-delay model will predict queue length for an amount of traffic delay per vehicle; i.e. it linearizes queue length against delay for an intersection approach. It was observed that the shape of the flow-delay curve for uninterrupted flow is similar to that of the flow-delay curve for interrupted flow developed in this research. Although they follow the same pattern and shape, it should be noted that the pattern of the curve may be influenced by location of the study area, traffic volume data, vehicle composition and types, among other factors.

REFERENCES

[1] Garrow M. and Machemehl R., "Development and Evaluation of Transit Signal Priority Strategies," 1997.

[2] Feng W., Figliozzi M. and and and Bertini R., "Empirical Evaluation of Transit Signal Priority through Fusion of Heterogeneous Transit and Traffic Signal Data and Novel Performance Measures," *Transportation Research Record: Journal of the Transportation Research Board,* no. 2488, p. 20–31, 2015.

[3] Altun S. and Furth P., "Schedulling Buses to Take Advantage of Transit Signal Priority," *Transportation Research Record: Journal of the Transportation Research Board,* no. 2111, pp. 50-59, 2009.

[4] Tindale-Oliver & Associates Inc., "Transit Signal Priority Implementation Guidance," Florida Department of Transportation, Tallahassee Florida, 2014.

[5] Smith H., Hemily B., Ivanovic M. and Fleming G., Transit Signal Priority: A planning and Implementation Handbook, 2005.

[6] Papageorgiou G., Damianou P., Pitsillides A., Aphamis T., Charalambous D. and Ioannou P., "Modelling and Simulation of Transportation Systems:A Scenario Planning Approach," *ATKAAF,* 2009.

[7] Adams B. and Yu L., "An Evaluation of Traffic Simulation Models for Supporting ITS Development," *Center for Transportation Training and Research,* 2000.

[8] Kamdar V., "Evaluating the Transit Signal Priority Impacts along the U.S. 1 Corridor in Northern Virginia," Northern Virginia, 2004.

[9] Metropolitan Government of Nashville and Davidson County, "Nashville Strategic Transit Master Plan Final Report," Metropolitan Government of Nashville and Davidson County, Nashville Tennessee.

[10] Rakha H. and Ahn K., "Transit Signal Priority Project– Phase II – Simulation Study Results," Virginia Transportation Research Council, Charlottesville, Virginia, 2006.

[11] Kittelson & Associates Inc., " Bus Rapid Transit Practitioner’s Guide," Transportation Research Board, Washington D.C., 2007.

[12] B. J., "Nashville is one of the fastest growing U.S. cities," 18 January 2018. [Online]. Available: http://www.crossville-chronicle.com/news/lifestyles/nashville-is-one-of-the-fastest-growing-u-s-cities/article_36b20ff4-fc82-11e7-907b-5738e23c2d36.html. [Accessed 27 August 2018].

[13] Ward G., "How many people are really moving to Nashville every day?," Nashville Tennessee, 2016.

[14] Vanasse Hangen Brustlin Inc., "Bus Priority Treatment Guidelines," Metropolitan Washington Council of Governments, Washington D.C., 2010.

[15] The Center for Transit-Oriented Development, "Transit Corridors and TOD:Connecting the Dots is Important," Federal Transit Administration, Washington D.C, 2010.

[16] Truong L., Currie G. and and Majid S., "Analytical and simulation approaches to understand combined," *Transportation Research Part C: Emerging Technologies,* vol. 74, pp. 275-294, 2017.

[17] Hedden C., Kopp C. and AICP, "Transit Signal Priority Systems Application and Technology Investigation," Cambridge Systematics, Inc., New York, 2009.

[18] Burak C., Altun S. and Lane B., "Queue Jump Lane, Transit Signal Priority and Stop Location Evaluation of Transit Preferential Treatments Using Microsimulation," *Transportation Research Record: Journal of the Transportation Research Board,* vol. 2533, p. 39–49, 2015.

[19] Guangwei Z. and Gan A., "Design of Transit Signal Priority at Signalized Intersections with Queue Jumper Lanes," *Journal of Public Transportation,* vol. 12, no. 4, 2009.

[20] Cambridge Systematic, Inc, "An Asset Management Framework for the Interstate Highway System," 2009.

[21] Ahmed B., "Exploring new bus priority methods at isolated vehicle actuated junctions," *Transportation Research Procedia,* vol. 4, p. 391 – 406, 2014.

[22] Guler S. and Menendez M., "Analytical formulation and empirical evaluation of pre-signals for bus priority," *Transportation Research Part B: Methodological,* vol. 64, pp. 41-53, 2014.

[23] Baker R.J., Collura J., Dale J., Head L., Hemily B., Ivanovic M., Jarzab J., McCormick D., Obenberger J., Smith L. and Stoppenhagen G., "An Overview of TRansit Signal Priority," 2002.

[24] Ahmad H. Alomari, Haitham Al-Deek, Adrian Sandt, John H. Rogers, Jr. and and Omar Hussain, "Regional Evaluation of Bus Rapid Transit With and Without Transit Signal Priority," *Transportation Research Record: Journal of the Transportation Research Board,* p. 46–59, 2016.

[25] Illinois Department of Transportation and Civiltech Engineering Inc., "The Cermak Road Bus Priority Project Final Report," Chicago IL, 1998.

[26] Boje B.F. and Nookala M., "Signal Priority for Buses: An Operational Test at Louisiana Avenue, Minneapolis," *Compendium of Technical Papers for the 66th ITE Annual Meeting,* pp. 309-313, 1996.

[27] Duncan W. and Mirabdal J., "Transit Preferential Streets Program in San Francisco," *Compendium of Technical Papers for the 66th ITE Annual Meeting,* pp. 314-318., 1996.

[28] Tindale-Oliver & Associates, Inc., "Transit Signal Priority Implementation Guidance," Florida Department of Transportation, Tallahassee, FLorida, 2014.

[29] Peterangelo J., "Coordination Key to Bus System Improvements," Public Policy Forum, 2015.

[30] Gardner K., D’Souza C., Hounsell N. and Shrestha B., "Review of Bus Priority at Traffic Signals around the World," 2009.

[31] Kittelson & Associates Inc., "Bus Rapid Transit Practitioner’s Guide," Transportation Research Board, Washington, D.C., 2007.

[32] Furth P. and Muller T., "Conditional Bus Priority at Signalized Intersections:Better Service Quality with Less Traffic Disruption," *Transportation Research Record,* no. 1731, pp. 23-30, 2000.

[33] Shireen C. and Robert N., "Effectiveness of Bus Signal Priority," Tampa, Florida, 2002.

[34] Griffin S., "Transit Signal Priority," [Online]. Available: https://slideplayer.com/slide/8301054/. [Accessed 5 June 2018].

[35] Guler S., Gayah V. and Menendez M., "Bus priority at signalized intersections with single-lane approaches: A novel pre-signal strategy," *Transportation Research Part C,* 2015.

[36] Guler S. Ilgin and Monica Menendez, "Analytical formulation and empirical evaluation of pre-signals for bus priority," *Transportation Research Part B,* 2014.

[37] Wu J. and Hounsell N., "Bus Priority Using pre-signals," *Transportation Research Part A,* 1998.

[38] Liu H., Zhang J. and Cheng D., "Analytical Approach to Evaluating Transit Signal Priority," *Journal of Transportation Systems Engineering and Information Technology,* vol. 8, no. 2, pp. 48-57., 2008.

[39] Alomari A., Al-Deek H., Sandt A., Rogers J. and Hussain O., "Regional Evaluation of Bus Rapid Transit with and Without Transit Signal Priority," *Transportation Research Record: Journal of the Transportation Research Board,* p. 46–59, 2016.

[40] Papageorgiou G., Damianou P., Pitsillides A., Thrasos A. and Ioannou P., "A Microscopic Traffic Simulation Model for Transportation Planning in Cyprus," 2006.

[41] Boxill S. and Yu L., "An Evaluation of Traffic Simulation Models for Supporting ITS Development," Southwest Region University Transportation Center, Texas, 2000.

[42] Kotusevski G. and HawickK K., "A Review of Traffic Simulation Software," Computer Science Institute of Information and Mathematical Sciences, Auckland, New Zealand, 2009.

[43] Cambridge Systematics Inc., "Oakland Park Boulevard Transit Corridor," Florida Department of Transportation District IV, Florida, 2011.

[44] Miovision, "Miovision Scout," [Online]. Available: https://miovision.com/. [Accessed July 2018].

[45] Fellendorf M. and Vortisch P., "Microscopic Traffic Flow Simulator VISSIM," in *Fundamentals of Traffic Simulation*, vol. 145, International Series in Operations Research & Management Science, 2010.

[46] Priya H., Shankar R., Prasad C. and Reddy T., "Evaluation of Area Traffic Management Measures Using Microscopic Simulation Model," *Procedia - Social and Behavioral Sciences,* vol. 104, pp. 815-824, 2013.

[47] Akçelik R., "Speed-Flow Models for Uninterrupted Traffic Facilities," Akcelik & Associates Pty Ltd, 2003.

[48] Sharma H., Swami M. and Swami B., "Speed-Flow Analysis for Interrupted Oversaturated Traffic Flow with Heterogeneous Structure for Urban Roads," *International Journal for Traffic and Transport Engineering,* vol. 2, no. 2, p. 142 – 152, 2012.

[49] Roux J. and Bester C., "Speed-Flow Relationships on Cape Town Freeways," *21st Annual South African Transport Conference South Africa,* 15 - 19 July 2002.

[50] "Trip Generation, 8th edition: An ITE Informational report," Institute of Transportation Engineers, Washington DC, 2008.

[51] Roess R., Prassas E. and McShane W., Traffic Engineering, Fourth edition, Fourth ed., 2011.

[52] "Highway Capacity Manual, Sixth Edition: A Guide for Multimodal Mobility Analysis," Transportation Research Board, Washington, D.C., 2016.

[53] Tian z. and Kyte M., "Queue Length Models for All-Way Stop-Controlled intersections," *Transportation Research Record: Journal of the Transportation Research Board,* vol. Transportation Research Board of the National Academics, no. 1988, pp. 63-66, 2006.

[54] Box C. and Willard A., "Warrants for Traffic Control Signals," *Traffic Engineering,* December 1967.

[55] Kyte M. and Marek J., "Estimating Capacity and Delay at Single-Lane Approach, All-Way Stop-Controlled Intersections," *Transportation Research Record: Journal of the Transportation Research Board,* no. 1225, pp. 73-82, 1989.

[56] Wu N., "An Approximation for the Distribution of Queue Lengths at Unsignalized Intersections," *Proc., 2nd International Symposium on Highway Capacity,* vol. 2, p. 717–736, 1994.