# MODELING OPERATIONAL PERFORMANCE OF URBAN ROADS WITH HETEROGENOUS TRAFFIC CONDITIONS

by

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ABSTRACT

SWAPNEEL RAO KODUPUGANTI: Modeling Operational Performance of Urban Roads with Heterogeneous Traffic Conditions (Under the guidance of DR. SRINIVAS S. PULUGURTHA)

Several urban areas in the United States have planned for new facilities to cater to the needs of users of alternative modes of transportation (e.g., public transportation, walking, and bicycling) over the next decade. As an example, the city of Charlotte has extended its current light rail transit (LRT) line (from South Charlotte to Uptown) to the University area in the northeast part of the region. Subsequently, there are plans to add more LRT routes and build pedestrian- and bicyclist-friendly infrastructure (e.g., on-street bicycle lanes, sidewalks, crosswalks, pedestrian signals, and so on). However, there is not enough evidence to justify whether such plans are instrumental in improving mobility and enhancing safety of the transportation system from a multimodal perspective. Further, there are no widely accepted methods to assess the effect of such facilities or transportation projects in terms of improved mobility and enhanced user safety. Therefore, the goal of this research is to model the operational performance of urban roads with heterogeneous traffic conditions to improve the safety, reliability, and mobility of people and goods. The objectives are

1. to collect data and comprehensively evaluate the effect of crosswalks, sidewalks, trails, greenways, on-street bicycle lanes, bus/LRT routes and stops/stations, and street network characteristics on travel time and travel time reliability (TTR) from a multimodal perspective,
2. to simulate and evaluate the influence of pedestrians, bicyclists, and public transportation system users (bus and LRT) on transportation system performance from a multimodal perspective,

3. to model and evaluate the effects on the operational performance at intersection level and corridor level by time of the day,
4. to research and examine the effects on the study corridor, parallel route, and cross-streets, and,
5. to conduct safety assessment by modeling and estimating traffic conflicts from a multimodal perspective.

First, a TTR-based approach was used to assess the effect of the LRT system on the road network within its vicinity. A four-mile stretch of the Blue Line LRT extension, which connects Old Concord Road and the University of North Carolina at Charlotte's main campus in Charlotte, North Carolina (NC), was considered as the study corridor. The raw travel time data were collected from a private data source at one-minute intervals. The average travel time (ATT), planning time (PT), buffer time (BT), buffer time index (BTI), and planning time index (PTI) were computed for each link, by day-of-the-week and time-of-day. Further, the TTR of the links on the LRT extension corridor and adjacent corridors (both the parallel route and the cross-streets) were computed for different scenarios: network without LRT, sixth month of LRT operation, twelfth month of LRT operation, and eighteenth month of LRT operation. The research revealed that the TTR of the parallel route and cross-streets was affected by the LRT system operation. Increased green signal times along N Tryon St as the LRT runs in parallel to this road, better signal coordination on this road, and the benefits associated with the alternative mode/route choice for commuters may be the reasons behind the steadiness in travel time performance measures seen due to the LRT.

Simulation-based analysis was conducted using data for a 2.5-mile corridor along the new LRT route. The traffic and signal data were obtained from the City of Charlotte

Department of Transportation (CDoT). There are no midblock or unsignalized crosswalks along the study corridor. The facilities and timings provided for pedestrians and bicycles at intersections seem to be adequate enough based on current or projected activity levels. Models were built in Vissim for the following scenarios: LRT is in operation with vehicles, LRT is in operation with vehicles and pedestrian activity, LRT is in operation with vehicles, pedestrians and bicyclist activity, change in vehicular traffic with LRT in operation with bicyclist activity and pedestrians, and increase in pedestrian and bicyclist activity with vehicles in the network. Bing maps data were used to import the network characteristics for each scenario. Vehicle delay, maximum queue length, and level of service (LOS) were used as the performance measures to evaluate the effect of the LRT on the transportation system's performance. It was found that the increase in LRT frequency has increased the vehicle delay on cross-streets while the operational performance improved on the study corridor. It was observed that a 15% or higher increase in the number of vehicles deteriorated the operational performance of the corridor. There has been not much change in the operational performance at some of the intersections, but the vehicles seem to accumulate at the intersections with additional delay during the evening peak hour. An increase in pedestrian and bicycle activity affected the overall corridor performance marginally. The intersections close to the LRT stations have had deteriorated operational performance.

Surrogate safety assessment was performed for all the hypothetical scenarios at a corridor level, and more than a 100% increase in traffic conflicts was seen with a 15% increase in vehicular traffic. A 15% increase in traffic conflicts was observed when pedestrian and bicycle count was increased by 100%.

Many growing cities are transitioning toward multimodal mobility patterns by providing infrastructure for transit users, pedestrians, and bicyclists. Planning and building infrastructure for alternative modes results in a shift in transportation demand from motorized to non-motorized traffic and increases complexities which arise due to the interaction amongst multiple models of transportation. This research proposes the use of travel time analysis and simulation framework to evaluate and understand these complex interactions and mobility patterns. The methodological framework used in this research is cross-disciplinary, transferable, and can be applied to other regions.

# DEDICATION

*To my parents (Sridhar Rao Kodupuganti and Kavitha Kodupuganti) who have always been supportive throughout my life.*

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I thank the staff of the North Carolina Department of Transportation (NCDOT), Charlotte Department of Transportation, and Regional Integrated Transportation Information System (RITIS) for their help with the data used in this research.

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| | |
|---|---|
| LRT | Light Rail Transit System |
| CDOT | Charlotte Department of Transportation |
| NCDOT | North Carolina Department of Transportation |
| TTR | Travel Time Reliability |
| BRT | Bus Rapid Transit |
| SSAM | Surrogate Safety Assessment Model |
| ATT | Average Travel Time |
| PT | Planning Time |
| BT | Buffer Time |
| PTI | Planning Time Index |
| BTI | Buffer Time Index |
| FHWA | Federal Highway Administration |
| USDOT | United States Department of Transportation |
| HOV | High Occupancy Vehicle |
| CATS | Charlotte Area Transit System |
| RITIS | Regional Integrated Transportation Information System |
| TMC IDS | Traffic Message Channel |
| TMC | Turning Movement Counts |
| WSDOT | Wisconsin Department of Transportation |
| RBC | Ring and Barrier Control |

# CHAPTER 1: INTRODUCTION

The background and motivation to conduct this research, problem statement, and research objectives are presented in this chapter.

## 1.1 Background and Motivation

Many urban areas in the United States have seen rapid population growth over the past few decades. The growth in population has had a catalytic effect on traffic congestion, air quality, and safety in such urban areas. Declining operational performance (such as traffic congestion and air quality) and safety performance are also consequences of increasing travel demand and traffic volumes on urban roads (Vuchic 2017). Congestion is considered a “negative phenomenon” (Sierpiński 2011) resulting from the increasing traffic volumes during peak hours, and it is one of the challenges almost every urban city faces today. Considering the pace at which the population and travel demand growth rates have increased, the annual delay and the forecasted nation-wide congestion costs are estimated to be around 8.3 billion hours and $192 billion in the year 2020 (Urban Utility Score Card 2015).

The construction of new roads, widening of existing roads, and improved connectivity help to mitigate and address the problems to some extent. These are long-term solutions that consume a lot of time and resources. The limited availability of rights-of-way along congested urban corridors, resource constrains (i.e., funding limitations), and the zeal to improve the sustainability of the transportation system have further motivated practitioners and researchers to explore and encourage the use of alternative modes of transportation.

Several urban areas in the United States have planned for new facilities to cater to the needs of users of alternative modes of transportation (e.g., public transportation, walking, and bicycling) over the next 30 years. Streetcar, commuter rail, and light rail transit (LRT) have been popular in urban areas since the early 19th century (Young 2015). These modes help to move a larger number of people at lower operational costs and with a higher degree of reliability. The growing concern about increasing carbon emissions has been driving transportation system managers and planners to take measures to invest in public transportation systems like LRT. The construction of LRT also leads to economic development within its vicinity. Surrounding property values could go up, while travel by such modes could be six times safer than automobile travel (Linda 2003).

## 1.2 Problem Statement

LRT is considered as the best-suited option for serving the demand in "medium-sized North American cities" (Black 1993). Transportation system managers and planners have explored constructing LRT systems from suburbs to high-density urban areas like a city's Central Business District.

In the year, 2017, around 543 million transit trips were reported across the United States by the American Public Transportation Association (APTA 2019). LRT ridership was reported to have surpassed commuter rail ridership from the year 2009. The increase in LRT ridership is three times the increase in commuter rail ridership since 1990. Additionally, the LRT can handle higher rates of travel demand (Black 1993).

The decision to implement LRT systems and decisions about the design of the system's operational attributes are made after a comprehensive transportation planning process or a feasibility study. Pedestrian and bicyclist facilities are improved to complement road infrastructure and make the LRT system more lucrative to users.

Additionally, the effectiveness of LRT systems in mitigating congestion and improving travel time must be monitored and frequently evaluated after implementation. Also, in the case of an at-grade design and operation, the LRT system would take up a significant portion of the right-of-way of existing streets, and the signal timings in the area must be adjusted to incorporate the LRT system's frequency of operation. Assessing the effect of the LRT system on near-vicinity road traffic is difficult because of its complex interaction with moving traffic. In other words, the short-term and long-term impacts of such changes on the traffic operations are uncertain, not widely explored, and need to be researched.

Typical travel demand models capture the effects of large-scale transportation projects like the LRT system in a socio-economic-spatial aspect. However, it is difficult to fully understand the effect of the LRT system on the region's traffic from typical travel demand models. In that context, providing short-term evidence of LRT systems' effect on traffic, based on travel time reliability (TTR) indices, can be considered a significant research development. However, there is not enough evidence to support that LRT systems and alternative modes of travel are instrumental in improving mobility and enhancing the safety of the transportation system from a multimodal perspective. Further, there are no widely accepted methods to assess the effect of such facilities or transportation projects on improving mobility and enhancing user safety.

There is a need to research and evaluate the effectiveness of an LRT system with associated pedestrian and bicycling facilities in reducing travel time and improving TTR on links (i.e., short segments of a corridor) within its vicinity using travel time data. Processing and analyzing travel time data and accomplishing this need does not, however, help reveal the influence of the LRT system, pedestrian activity, and bicyclist activity separately at an intersection or corridor level. Travel time data aggregated at a link level and the results might not show the interactions between different modes of travel, which could be examined through microscopic simulation.

Some unforeseen effects of the LRT system with associated pedestrian and bicycling facilities also may not be captured from the travel time-based assessment. A few effects might be intricate and understanding the influence of heterogenous traffic conditions is the key to better optimizing the LRT system. Moreover, modeling and understanding the effects allows the researchers to address any shortcomings beforehand. Microscopic simulation software like Vissim serves as a platform facilitating a detailed probing into the effects of LRT, pedestrians, and bicyclists. The findings will aid in understanding what to expect in the future and will help public agencies be prepared in advance. Therefore, there is also a need to research and evaluate the effect of the LRT system, pedestrian activity, and bicycling activity on transportation system performance along the study corridor using traffic simulation software.

## 1.3 Research Objectives

This research aims at developing a methodological framework to assess the performance of a multimodal corridor using both data-driven and simulation-based approaches. The objectives are:

- to collect data and comprehensively evaluate the effect of crosswalks, sidewalks, on-street bicycle lanes, bus/LRT routes and stops/stations, and street network characteristics on travel time and TTR from a multimodal perspective,
- to simulate and evaluate the influence of pedestrians, bicyclists, and public transportation system users (bus and LRT) on transportation system performance from a multimodal perspective,

- to model and evaluate the effects on the operational performance at intersection level and corridor level for different hypothetical scenarios during the evening peak hour,
- to research and examine the effects on the study corridor, parallel route, and cross-streets, and,
- to conduct safety assessment by modeling and estimating traffic conflicts from a multimodal perspective.

While both travel time-based performance evaluation and simulation-based evaluation serve common research interests, they facilitate investigations with complementary capabilities. The travel time-based performance evaluation helps in understanding the effects from a practical standpoint, comprehensively considering all the modes. It also sets up a platform to further probe into the analysis at more microscopic levels. On the other hand, the simulation-based approach helps in understanding the effect of LRT, pedestrian activity, bicyclist activity, and traffic, individually or combined, on the operational performance of the transportation system.

## 1.4 Organization of the Report

The remainder of the report is organized as follows. Chapter 2 presents a review of past research efforts on performance-based assessment, travel time-based assessment, simulation-based assessment, safety and conflict analysis, and limitations of previous research. Chapter 3 presents the methodological framework adopted for this research. Chapter 4 presents the data collected for this research. Chapters 5, 6 and 7 present the results of TTR-based assessment, simulation-based assessment, and surrogate safety assessment in the study corridor. Chapter 8 summarizes the conclusions of the research and scope for further work.

# CHAPTER 2: LITERATURE REVIEW

The Transportation Research Board (TRB)'s Committee on LRT defines an LRT system as "a metropolitan electric railway system characterized by its ability to operate single cars or short trains along exclusive rights of way at ground level, on aerial structures, in subways or, occasionally, in streets, and to board and discharge passengers at the track or car-floor level" (Chandler and Hoel 2004). The capability of the LRT system to alleviate congestion has been analyzed by many researchers in the past (Clark 1984, Knowles 1992, Garrett 2004). The capability of the LRT system to stimulate transit-oriented development initiatives has also been studied in the past (Arrington and Cervero 2008).

Good quality of service attracts personal vehicle users to the LRT system, thus reducing traffic congestion (Knowles 1996). On the contrary, LRT systems' capability to reduce congestion has also been questioned in some studies. Mackett and Edwards (1998) stated that the positive effect of many rail-based transit systems throughout the world on traffic congestion was less than earlier projections. This could be due to differences in methodological approaches or performance measures considered for modeling and evaluation.

A review of travel time-based and simulated-based studies to solve similar problems is presented in the next two sub-sections.

## 2.1 Performance-based Assessment of Multimodal Transit Corridors

Regional travel demand models have long been used as part of large-scale transit planning processes to determine the effect of transportation projects/improvements, such as an LRT system, on network travel times (Ewing et al. 2014). However, the outcomes from the outputs of regional travel demand models could differ from what may be observed in the real-world.

The analysis of the effect of an LRT on road traffic within its vicinity requires a comprehensive understanding of traffic and LRT signalization. Venglar et al. (1994) explored the possibility of measuring the effect of the LRT system using various factors such as delay to automobile occupants, delay to LRT users, "person-delay" at intersections, the volume-to-capacity ratio at intersections, queue lengths, the number of stops, and travel times on adjacent streets. Another measure recommended for the quantification of LRT effects is the length of the automobile queue accumulated during the passage of an LRT (Bates and Lee 1982).

Islam et al. (2016) studied the applicability of transit signal priority strategies in improving the reliability of LRT operation with less of an effect on the general traffic. They computed various measures like total travel time, total delay, and average speed to evaluate the corridor performance.

The effect of dedicated and intermittent transit lanes on arterial traffic was also studied in the past (Eichler and Daganzo 2006, Chiabaut et al. 2018, Chiabaut and Barcet 2019). As the dedicated transit lanes significantly disrupt the general traffic, Eichler and Daganzo (2006) observed that bus lanes with intermittent priority reduce the general traffic interference. Similarly, Chiabaut and Barcet (2018) proposed the use of intermittent transit lanes with transit signal priority as a better alternative to the dedicated bus transit line. Chiabaut et al. (2019) assessed whether perimeter control could be an efficient alternative to dedicated bus transit lanes. According to their findings, the perimeter control technique improved road capacity while ensuring the same transit system efficiency.

Kattan et al. (2013) studied the effect of large-scale network disruptions (due to LRT construction) on users' daily commutes. They reported a major change in mode choice during the LRT construction period. Also, driving experience, employment status, travel time, and the purpose of travel, as well as advanced traveler information, were found to significantly influence the mode choice decision-making.

## 2.2 Travel Time-based Assessment of Multimodal Transit Corridors

TTR, which provides insights into the operational improvements of arterial roads, can be used as an effective mobility performance measure (McLeod et al. 2012, Schrank et al. 2015). Studies related to the measures of the effectiveness of LRT on arterial traffic, based on TTR measures, are found to be very limited.

TTR measures include buffer measures, statistical measures, and delayed trip indicators. The United States Department of Transportation (USDOT) proposed four different measures of TTR. They are planning time (PT), planning time index (PTI), buffer time (BT), average travel time (ATT) and buffer time index (BTI). PT is the 95$^{th}$ percentile travel time, while BT and BTI are measures of trip reliability that indicate the extra time needed to be on time for 95% of the trips.

The ATT indicates the nominal level of congestion for a road segment. PT and BT indicate the variability in travel times from a road user perspective. BTI suggests the reliability of the transportation system over time. According to the report published by the Federal Highway Administration (FHWA 2006), the PTI can be used as a measure of average congestion of a corridor as it gives a clear picture of the total travel time needed for an on-time arrival in a congested condition compared to a light traffic condition.

Wakabayashi et al. (2003) studied commuters' attitudes towards TTR while considering alternative modes of transportation. They studied users' decision-making in choosing their mode after a public transportation service closure and concluded that the importance of travel time varies in the selection process. Pulugurtha et al. (2017) surveyed transportation system users' perceptions of TTR measures and monetized the value of reliability to evaluate transportation projects and alternatives.

### 2.3 Simulation-based Assessment of Multimodal Transit Corridors

Different software packages like Vissim, CORSIM and PARAMICS were used to perform simulation analysis of transportation systems in the past. The availability of the software and the features of the specific software factor in selecting for evaluating a transportation project or facility. The best and suitable software for a desired output was briefed in the research by Choa et al. (2004).

Vissim software is one of the most sophisticated simulation software and is very suitable for multimodal transit analysis, 3-D simulation and incorporating different driver behavior characteristics. Vissim and CORSIM simulation models are highly suitable for analyzing congested arterials and freeways (Ratrout and Rehman 2008).

Gomes et al. (2004) constructed and calibrated a microsimulation model in Vissim using a 15-mile stretch in Pasadena, California as the study corridor. The study corridor is a freeway with the presence of a high occupancy vehicle (HOV) lane. The steps for calibrating the model included identification of geometric features, processing traffic data, analyzing the occurrence of bottlenecks, Vissim coding, and calibration based on traffic volume. The steps were adequate to calibrate the model with relatively few modifications to driver behavior parameters in Vissim. A similar study to identify traffic bottlenecks and calibrate the network model was conducted by Ban et al. (2007) using the San Francisco Bay Area, California as the study area.

Cellular automation is an efficient microsimulation tool that uses a finite element model (Wolf 1999, Deo 2007, Gundaliya et al. 2008, Yuan et al. 2008, Tonguz et al. 2009). Deo (2007) used two-component cellular automation to model the heterogeneous motorized traffic flow. The vehicles were classified into two types (short and long) and the study was conducted for various types of roads such as the single-lane vs. multi-lane and controlled vs. uncontrolled intersections and roundabouts. Gundaliya et al. (2008) integrated cellular automation and a traffic simulation software model to analyze the operational performance of an arterial road. Input parameters such as cell size, lane width, lane length, and vehicle size were considered. Vanajakshi et al. (2009) developed a location-based travel time prediction algorithm using the Kalman Filter technique for a bus route under heterogeneous conditions. They concluded that the proposed technique is a viable option for evaluating the effect of heterogeneous traffic conditions.

Ishaque and Noland (2009) studied the interaction between pedestrians and vehicles in Vissim. In order to calibrate various parameters for pedestrians, the researchers gave the pedestrian inputs in terms of vehicles. The pedestrian input is calibrated by taking the real-world observations to replicate the flows and level of compliance observed in the pedestrians.

A case study in Ocean park, New York by Mosseri et al. (2004) examined the usage of the microsimulation software in a multimodal traffic network. The area under scrutiny has high pedestrian and vehicle interactions along with the signal phasing. A small change in signal phasing can change the delay for the system user significantly at the network level. Their research also evaluated new conflict points associated with new turning movement strategies that can be incorporated in the network. Stirzaker and Hussein (2007) evaluated the benefits of transportation management strategies to maximize the utilization of road infrastructure. Simulation modeling was used, and researchers added a dedicated public transportation bus lane, a HOV lane, and a general traffic lane. Their simulation results indicated a 19% decrease in travel time along with a 68% improvement in TTR due to the addition of a bus lane to the existing roadway infrastructure.

Signal priority for public transportation affects the vehicular traffic and other modes of transportation. Yedlin and Lieberman (1981) conducted simulation studies to identify ideal conditions that benefit transit operations. In that study, several factors that could affect public transportation were considered, and interrelations were examined between the factors. The addition of a new transit system along the existing road network induces a change in the existing signal phases at a traffic signal. The most common mode of transit that are currently in practice are BRT and LRT systems.

A research by Ngan et al. (2004) focused on the transit signal priority along a corridor with BRT. The transit signal priority application is more effective when the traffic volume on the cross-streets are low, less turning movement vehicles hinder the transit movement, and when there is high transit volume and good coordination of signal timings along the peak direction of traffic flow.

Transit signal priority along the LRT corridor in Salt Lake City, Utah was examined by Zlatkovic et al. (2011). Transit signal priority addition along the two-mile corridor did not have much effect on the vehicular traffic parallel to the LRT movement. However, the vehicular traffic along the cross-streets had seen an increase in vehicle delay. The study area already had an existing LRT but signal priority for LRT was tested using microsimulation-based approach.

Transit signal priority in a connected vehicle environment was examined by Hu et al. (2015). The bus delay was expected to decrease between 55% and 75% compared to the transit signal priority with no automation.

It is important to differentiate between the operational effects on different modes of transportation due to the existing network versus when LRT is operational, and other hypothetical scenarios that can be predicted due to the addition of LRT.

### 2.4 Safety and Conflict Analysis

Surrogate Safety Assessment Model (SSAM) is a better way to analyze the traffic safety by developing traffic conflicts, which can be extracted using trajectory files from Vissim. Huang et al. (2013) used SSAM to assess the traffic conflicts at signalized intersections and compared with the real-world data. It was found that the total number of collisions and rear-end collisions correlated with conflicts the Vissim and SSAM models. A similar research related to conflict points was performed by Souleyrette and Hochstein (2012). In their research, conflict analysis for three different intersection designs were checked on a rural expressway.

Zhou et al. (2012) researched on parameters which influence the calibration of a Vissim simulation model. In their study, the importance of calibrating the parameters was presented. They developed a two-stage calibration methodology and tested their methodology on a study corridor. The errors of conflict and delay from the SSAM were promising when compared with the actual conflict points.

Wu et al. (2017) evaluated pedestrian/vehicle conflicts at signalized intersections using Vissim traffic simulation software and SSAM. They found that Vissim software underestimated the number of pedestrian/vehicle conflicts, as illegal pedestrian behavior could not be modeled with that software. Kim et al. (2019) used Vissim traffic simulation software and SSAM to mimic pedestrian and vehicular interactions. They found that the interaction between vehicles on the right-turn lanes and pedestrians in Vissim had to be addressed properly. They concluded that the effect of pedestrians on vehicular traffic at signalized intersections varies based on geometric features of the intersections.

## 2.5 Limitations of Past Research

The influence of LRT operations on road traffic, such as inducing delays at intersections and reducing the capacity of the road, was studied by a few researchers in the past. The applicability of travel time and TTR measures as well as the perceptions of users on TTR were also explored and researched in the past. TTR measures and travel time are considered as valuable measures by both practitioners and users. However, travel time and TTR measures were not explored when evaluating the influence of LRT systems on road traffic in nearby vicinities. Neither were the spatial and temporal effects due to LRT operation been widely studied in the past.

Microscopic simulation has been widely used to assess the traffic operations and management. The simulation-based models were generally run using default parameters or best guessed values in the past. Many researchers developed techniques to calibrate and validate the simulation-based models. Most of these techniques involve field data collection and using the field data for calibration of the model.

The addition of an LRT system encourages walking and bicycling to and from the stations. The new modes added to the transportation system have a potential to grow and effect the transportation system operations and traffic safety. There is a need to research the effectiveness of the system, under existing conditions as well as forecasted conditions, from a multimodal perspective. This can be done by developing hypothetical scenarios with an increase in the multimodal activity. Modeling and evaluating these scenarios helps assess the transportation system performance from traffic operations perspective and traffic safety perspective to proactively plan and implement treatments. This research aims to address these gaps.

# CHAPTER 3: METHODOLOGY

The methodological framework adopted for this research includes the following steps.

- Selecting the study corridor
- Travel time and TTR-based assessment
- Simulation-based assessment

## 3.1 Selecting the Study Corridor

Economically, the city of Charlotte, North Carolina is one of the fastest-growing cities in the United States. Affordable cost of living, growing job opportunities, and favorable weather conditions throughout the year have led to high population growth rates over the past few years (Charlotte Stories 2018). In addition to the growth in population, urban sprawl has led to increased travel demand, with a catalytic effect on mobility and congestion on roads in Charlotte. An annual congestion cost of around $770 million for the year 2014 was reported for the city (TTI 2015).

The Blue Line LRT is the Charlotte region's first LRT service. It is 18.9 miles long and extends from I-485 at South Boulevard to the University of North Carolina (UNC) Charlotte's main campus. The first section was opened in November 2007 and runs from I-485 at South Boulevard to Uptown Charlotte. This section is 9.6 miles long with 15 stations and seven park and ride facilities. The second section from uptown Charlotte to UNC Charlotte's main campus was opened in March 2018 (Figure 1). This extended section is 9.3 miles long with 11 stations and four park and ride facilities. Weekday service operates from 5:26 AM to 1:26 AM. The service is available every 7.5 minutes during weekday rush hour and every 15 minutes during non-peak hours CATS 2018).

Plans are also being discussed to expand the bus transportation network and/or commuter rail, streetcar, or LRT service by the year 2030, in conjunction with improved access to various land uses across the city (CATS 2019). Further, various action plans are being proposed and implemented across the city of Charlotte for pedestrians and bicyclists. These plans encompass pedestrian facilities (CDoT 2017a), bicyclist facilities (CDoT 2017b), and shared mobility facilities (CDoT 2018).

A four-mile stretch of the new extension that connects Old Concord Rd and UNC Charlotte's main campus, running through the N Tryon St median, was considered for travel time and TTR analysis. The commuters who use the N Tryon St (US 29) corridor may expect an extra delay due to LRT operation. They may shift to alternative routes. Therefore, I-85 parallel route within the vicinity of the Blue Line LRT was also considered for analysis and modeling. The Blue Line LRT contains many at-grade crossings. To understand the effect of signal cycle adjustments on accommodating the LRT, locations near vicinity cross-streets within a mile of the N Tryon St, such as University City Blvd, E WT Harris Blvd, E Mallard Creek Church Rd, and I-485, were also selected for travel time-based analysis. Figure 2 shows the study (LRT) corridor, parallel routes, and cross-streets for travel time and TTR analysis.

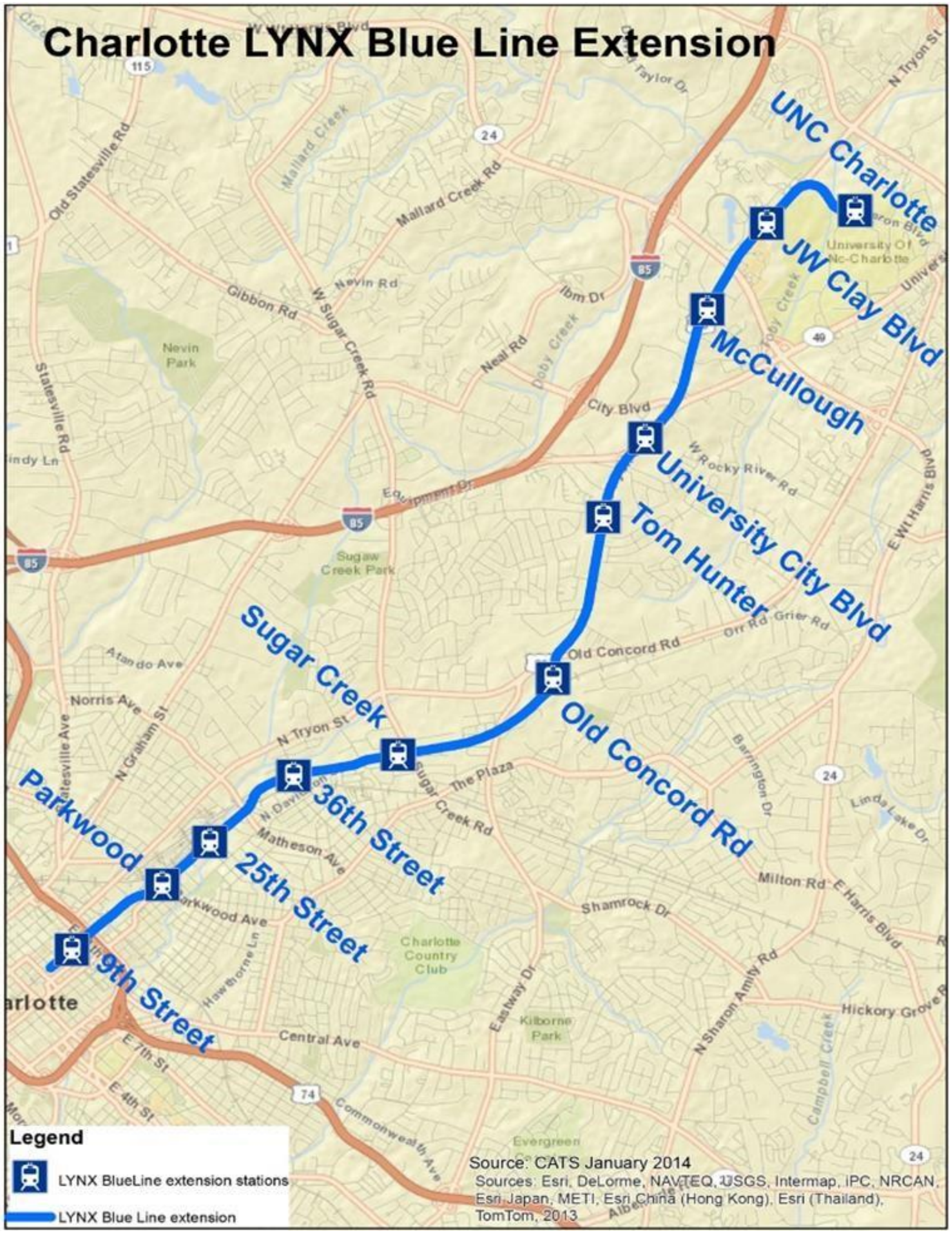



Figure 1. Blue Line LRT, Charlotte, North Carolina

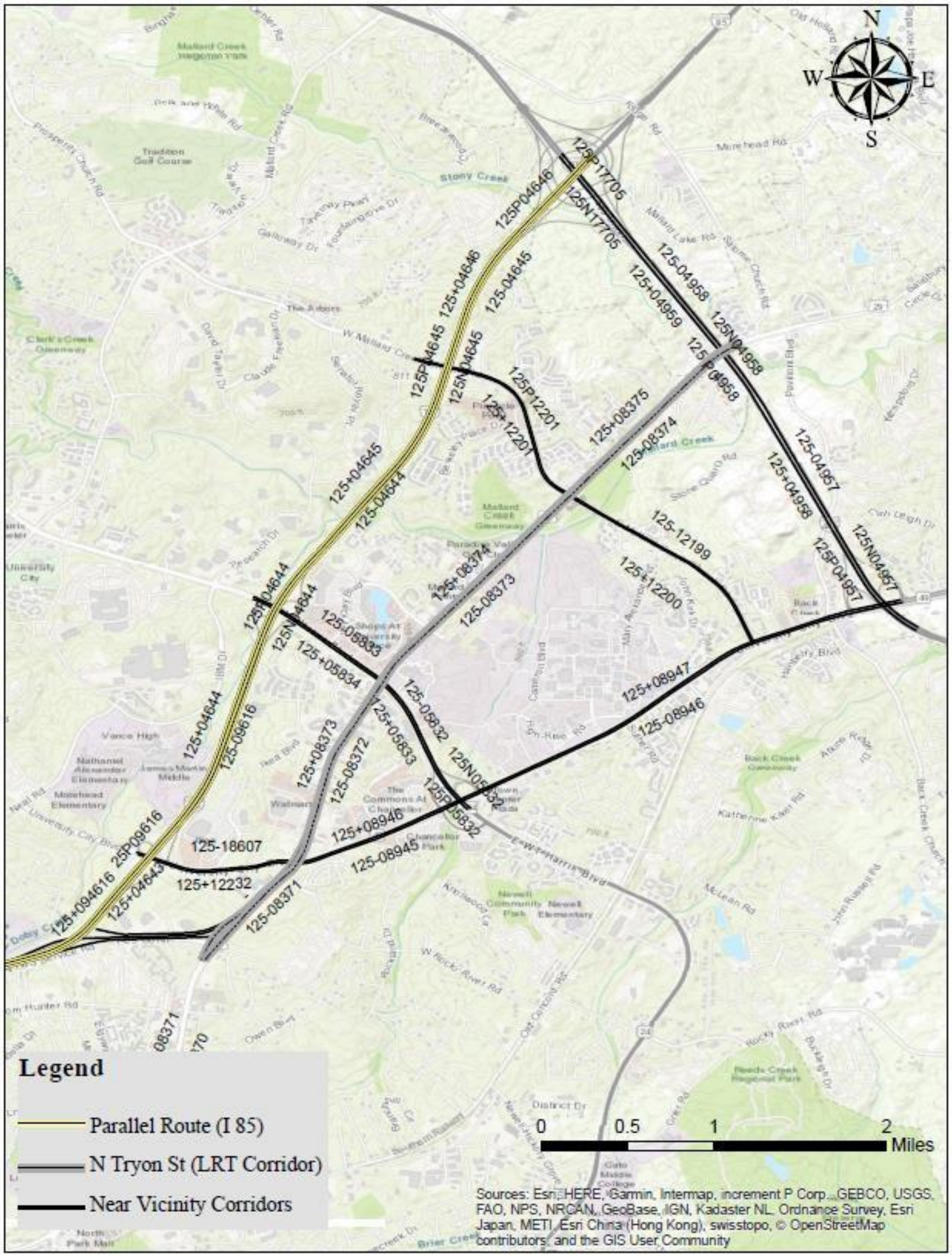



Figure 2. Study Area with Selected Links

A part of the four-mile stretch was used to model the effect of pedestrians, bicyclists, and LRT on road operational performance measures such as delay, queue length, and LOS at the intersection level. This section is 2.5 miles long, with nine intersections, and it extends from University City Blvd until UNC Charlotte on N Tryon St. The nine intersections (cross-streets) from north to south in geographical order are University City Blvd, University Pointe Blvd, McCullough Dr, Ken Hoffman Dr, E WT Harris Blvd, J M Keynes Dr, JW Clay Blvd, Institute Cir, and E Mallard Creek Church Rd. Of these intersections, University City Blvd and E WT Harris Blvd are major cross-streets. They are grade-separated intersections, while the other seven are at-grade intersections. On-street bicycle lanes, pedestrian crosswalks and sidewalks, and park and ride facilities are also provided along the selected study corridor. Chapter 3.3 discusses the geometric characteristics at all the intersections.

## 3.2 Travel Time and Travel Time Reliability (TTR)-based Assessment

This step involves the travel time and TTR-based assessments from a multimodal perspective. It considers crosswalks, sidewalks, trails, greenways, on-street bicycle lanes, bus/LRT routes and stops/stations, street network characteristics, and traffic conditions to comprehensively evaluate and assess their effect on travel time and TTR at the link and corridor levels.

Figure 3 represents the methodological framework adopted for the TTR-based assessment of the transportation network (including the LRT system).

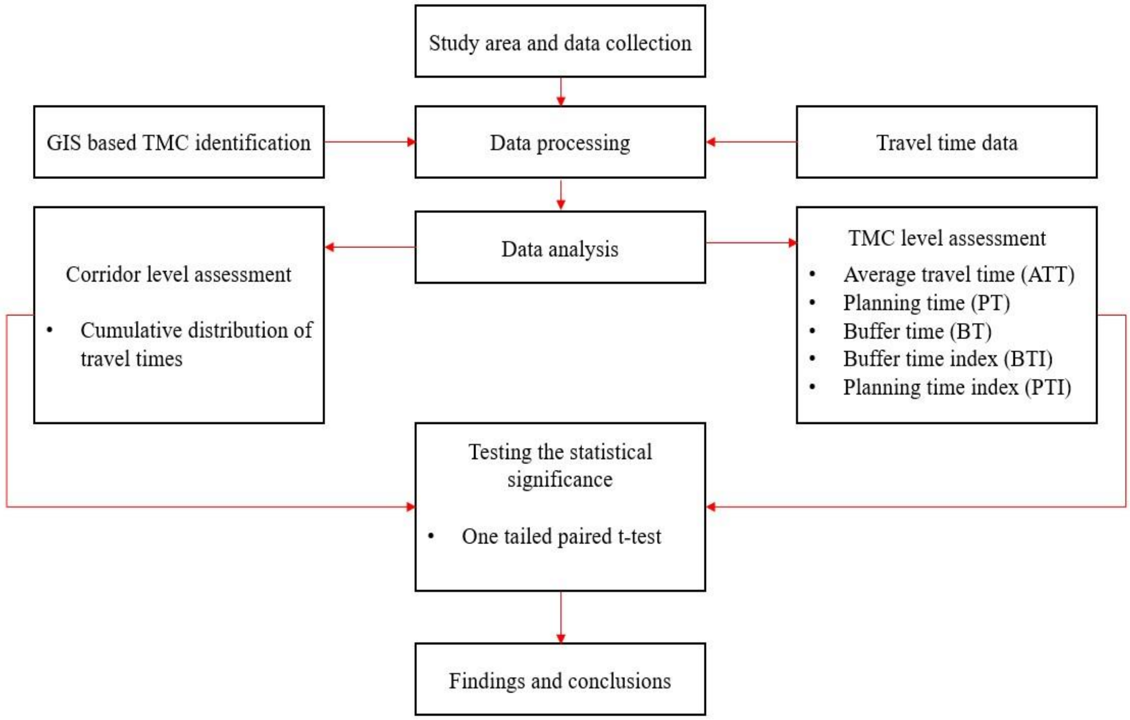



Figure 3. Methodological Framework for TTR-based Assessment

Four different scenarios—network with LRT, the sixth month of LRT operation, the twelfth month of LRT operation, and the eighteenth month of LRT operation—were considered in the TTR analysis. Travel time data for March 2018 are considered as representing the network with LRT analysis period.

The Blue Line LRT extension was open to the public as of March 16, 2018. Travel time data for September of 2018, March of 2019, and September of 2019 represent the sixth month of LRT operation, the twelfth month of LRT operation, and the eighteenth month of LRT operation, respectively.

The raw minute-wise travel time data were collected from the Regional Integrated Transportation Information System (RITIS) website, with support from the North Carolina Department of Transportation (NCDOT). The data corresponding to each link are coded with a single identification code: namely, a Traffic Message Channel (TMC) ID. The data contain nine-digit link (TMC) IDs, unique segment identification numbers (for example, 125+08373). The data processing is carried out at two levels: link identification and the computation of TTR indices.

## 3.3 Simulation-based Assessment

### *3.3.1 Network Development*

For the simulation-based assessment, the geometric changes along the study corridor are used as inputs for modeling. Many geometric changes were made to the study corridor during and after LRT construction to accommodate traffic and to make sure that the traffic flow was disturbed as little as possible.

Figures 4 through 13 show the geometric conditions during the years 2018 and 2019 (LRT was constructed and serving users). On-street bicycle lanes were added in some areas during the year 2017. They were then painted green in the year 2018. This illustrates the emphasis on improving heterogeneous conditions at selected intersections along the LRT study corridor.

A brief description of each intersection and geometric conditions before, during, and after the construction of the LRT system using aerial images is provided next.

#### *3.3.1.1 N Tryon St & University City Blvd Intersection*

University City Blvd is a major intersection along with E WT Harris Blvd and E Mallard Creek Church Rd. There is no direct interaction between the LRT and road traffic at University City Blvd intersection, as the LRT system is grade-separated at this intersection. Two through lanes were there along with one left-turn lane and one right-turn lane in the southbound direction in the year 2016. Later in the year 2017, three through lanes, one left-turn lane, an on-street bicycle lane, and one right-turn lane were observed.

There were no changes in the northbound direction. Figure 4 shows an aerial image of the intersection in the year 2018.


Figure 4. N Tryon St & University City Blvd Intersection

*3.3.1.2 N Tryon St & University Pointe Blvd Intersection*

There was only one left-turn lane, two through lanes, and one right-turn lane in the northbound direction on N Tryon St in the year 2016 during the construction phase. Later, two left-turn lanes, two through lanes, an on-street bicycle lane, and one right-turn lane were added in the year 2017. Similarly, one left-turn lane, one through lane, and one shared through/right-turn lane are in the southbound direction in the year 2016, later becoming one left-turn lane, two through lanes, one shared through/right-turn lane, and an on-street bicycle lane in 2018. Figure 5 shows an aerial image of the intersection in the year 2018.


Figure 5. N Tryon St & University Pointe Blvd Intersection

*3.3.1.3 N Tryon St & McCullough Dr Intersection*

There were no lane additions at the McCullough Dr intersection. However, there is one left-turn lane, two through lanes, and one right-turn lane in the year 2016 in the northbound direction, becoming two left-turn lanes, one through lane, and one right-turn lane. Additionally, on-street bicycle lanes were also added in the northbound and southbound directions on N Tryon St in the year 2017. No changes were made to the cross-streets. Figure 6 shows an aerial image of the intersection in the year 2018.


Figure 6. N Tryon St & McCullough Dr Intersection

*3.3.1.4 N Tryon St & Ken Hoffman Dr Intersection*

There are no significant changes in the lane configurations at the Ken Hoffman Dr intersection. However, on-street bicycle lanes were added in the southbound and northbound directions during the year 2018. Figure 7 shows an aerial image of the intersection in the year 2018.

*3.3.1.5 N Tryon St & E WT Harris Blvd Intersection*

There is no direct interaction between the LRT and road traffic at E WT Harris Blvd intersection, as the LRT system is grade-separated at this intersection. There are some lane changes between the before and after scenarios. An additional lane was added in both northbound and southbound directions. There were two left-turn lanes, one through lane, and one shared through/right-turn lane during the before period. After the lane addition, there were two left-turn lanes, two through lanes, and one right-turn lane, as well as on-street bicycle lanes in both directions. Figure 8 shows an aerial image of the intersection in the year 2018.


Figure 7. N Tryon St & Ken Hoffman Dr Intersection


Figure 8. N Tryon St & E WT Harris Blvd Intersection

*3.3.1.6 N Tryon St & J M Keynes Dr Intersection*

There were no additional lanes added in the northbound direction on N Tryon St. However, on street bicycle lanes were added in the northbound and southbound directions. An additional lane was added in the southbound direction on N Tryon St to the existing left-turn lane, through lane, and shared through/right-turn lane, making it one left-turn lane, two through lanes, and one shared through/right-turn lane. The length of the left-turn lane was increased from the year 2016 to 2017. Figure 9 shows an aerial image of the intersection in the year 2018.


Figure 9. N Tryon St & J M Keynes Dr Intersection

*<u>3.3.1.7 N Tryon St & JW Clay Blvd Intersection</u>*

The intersection at JW Clay Blvd had three lanes in the southbound direction in the year 2016 with one left-turn lane, one through lane and one shared through/right-turn lane. An additional lane was added after the LRT construction in the year 2017 in the southbound direction, making it one left turn lane, two through lanes, and one shared through/right-turn lane. There were no changes in the configuration of the side streets. However, an on-street bicycle lane was added in the northbound and southbound directions on N Tryon St in the year 2017. Figure 10 shows an aerial image of this intersection in the year 2018.


Figure 10. N Tryon St & JW Clay Blvd Intersection

*3.3.1.8 N Tryon St & Institute Circle Intersection*

Institute Cir is the last intersection after which the LRT turns into UNC Charlotte's main campus, deflecting away from N Tryon St. There were no lane changes on cross-streets. There were no lane changes in the northbound direction. However, there were three lanes in the year 2016 in the southbound direction comprising one left-turn lane, one through lane, and one through/right-turn lane; an additional lane was added in the year 2017, making it one left-turn lane, two through lanes, and one through/right-turn lane. An on-street bicycle lane was also added in the northbound direction from 2017 to 2018. Figure 11 shows an aerial image of this intersection in the year 2018.


Figure 11. N Tryon St & Institute Cir Intersection

*<u>3.3.1.9 N Tryon St & E Mallard Creek Church Rd Intersection</u>*

Figure 12 shows an aerial image of the intersection at E Mallard Creek Church Rd in the year 2018. The LRT does not extend to this intersection. However, it was considered as a part of the study corridor due to its proximity to the area of interest. There are no changes at this intersection between the pre-construction, during-construction, or post-construction scenarios.

Figure 12. N Tryon St & E Mallard Creek Church Rd Intersection

*3.3.2 Calibration Parameters and External modules*

Table 1 shows the selected calibration parameters that are used for modeling. The speed limits on the arterial sections in the study corridor and the vehicle speed data observed in field were used to develop the speed distribution curves. The speed distribution curves are developed for each individual speed limit observed along the study. The speed distribution curves used for modeling are shown in Figure A1 (appendix).

Table 1. Values of the Selected Calibration Parameters

| Parameter | Vissim Settings |
|---|---|
| Speed limits in the corridor | 35,45 mph (study corridor). 20,45 mph (cross-streets) |
| Lane following model | Wiedemann 74 Car-following model |
| Vehicle composition | Car, 0.97(3D simulation models)<br>HGV, 0.03 |
| Pedestrian composition | Man, Woman |
| Look ahead distance (max.) | 820.21 ft |
| Standstill distance for static obstacles | 1.64 ft |
| Wiedemann 74 Average Standstill distance | 6.56 ft |
| Wiedemann 74: Additive part of safety distance | 2.00 ft |
| Wiedemann 74: Multiplicative part of safety distance | 3.00 ft |
| Maximum deceleration | -13.12 ft/s$^2$ |

Wiedemann 74 car-following model and lane-following model was used for developing the model. This car-following model is a psycho-physical car-following model, best suited for urban arterial corridors All the intersections used in the analysis are arterials and Wiedemann 74 model best replicates the car-following and lane-following behaviors. The vehicle composition provided in the default Vissim model replicate European traffic conditions which effect the overall operational performance of the system. Vissim provides an open source of 600 vehicle models to account for the vehicle composition via 3D vehicle models. This feature is used in Vissim to replicate the vehicles observed in the study corridor.

Pedestrians in the model are generally classified based on the gender: man and woman. All other parameters are fixed based on the visual inspection and by using the field observations. Many combinations of values for different parameters in Vissim were explored while running the initial simulation models to get a balanced set of values. The calibrated model developed in Vissim was for the year 2018 and includes LRT in operation. Modeling of these diverse geometric conditions was done in Vissim. Some minor approaches on the intersections in the study corridor have shared lanes while other minor approaches have exclusive turning lanes. All the major approaches have an exclusive bicycle lane which are considered in the simulation model.

After the model is calibrated, the pedestrians and bicycles are introduced into the model. The introduction of non-motorist traffic did not change any calibration settings for the vehicular traffic in the model. An external signal control with detectors is provided for the LRT. The algorithm for the external signal controller ("vap") and visual validation of the external signal controller is discussed in the next sub-section. Scenario 1 (vehicular traffic with LRT addition) is the base model. The introduction of LRT, pedestrians and bicycles required addition of external signal controllers. Initially, the signal phasing of these new modes were tried to be programed in Vissim, with no external signal controllers. While programing them in Vissim, with no external signal controllers, the LRT did not replicate the on-field observed characteristics. And, at some intersections, the priority for LRT turned on but it was always active and the communication between the signal controllers and detectors was lost. Hence, the external modules were used to develop the logic for LRT, pedestrians and bicycles which are explained in the section 3.2.2.1

*3.2.2.1 Visvap external module for LRT modeling*

The presence of LRT in the network requires assuring priority for LRT at at-grade intersections. The priority for LRT may be provided using detection through transit signal priority module in the Vissim signal controller. While doing this operation in Vissim, the call-in detectors would detect the presence of LRT, but the call-out detector sometimes fails to indicate the signal controller that the LRT has crossed. This lack of communication between the call-out detector and signal controller would not mimic real-world conditions all the time. Hence, an external Visvap module with signal interchanges is used to provide the transit signal priority. The "vap" file generated from the external module has two signal interchanges. The first interchange is for when LRT is detected by the detectors. The second interchange is when there is no LRT presence.

Each at-grade intersection with LRT needs a check-in and check-out detector for detection of LRT. The check-in detector calls in the signal controller to operate in the first signal interchange, whereas the check-out detector calls in the signal controller to operate in the second signal interchange. Figure 13 shows the flowchart of how the LRT external module operates. The external module helps replicate the real-world scenario with LRT.

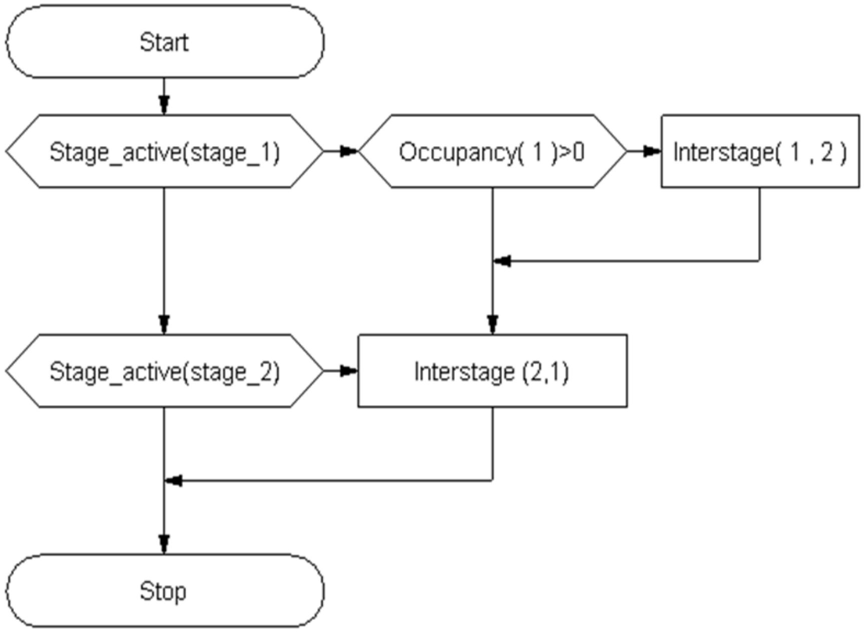



Figure 13. Flowchart of Visvap Algorithm for Transit Signal Priority

Entry detector was placed at a distance of 1000 feet from the next signal. The detector slot number is then tied up to the coding in the VAP file. An exit detector is also placed to indicate the signal controller of the crossing of the LRT.

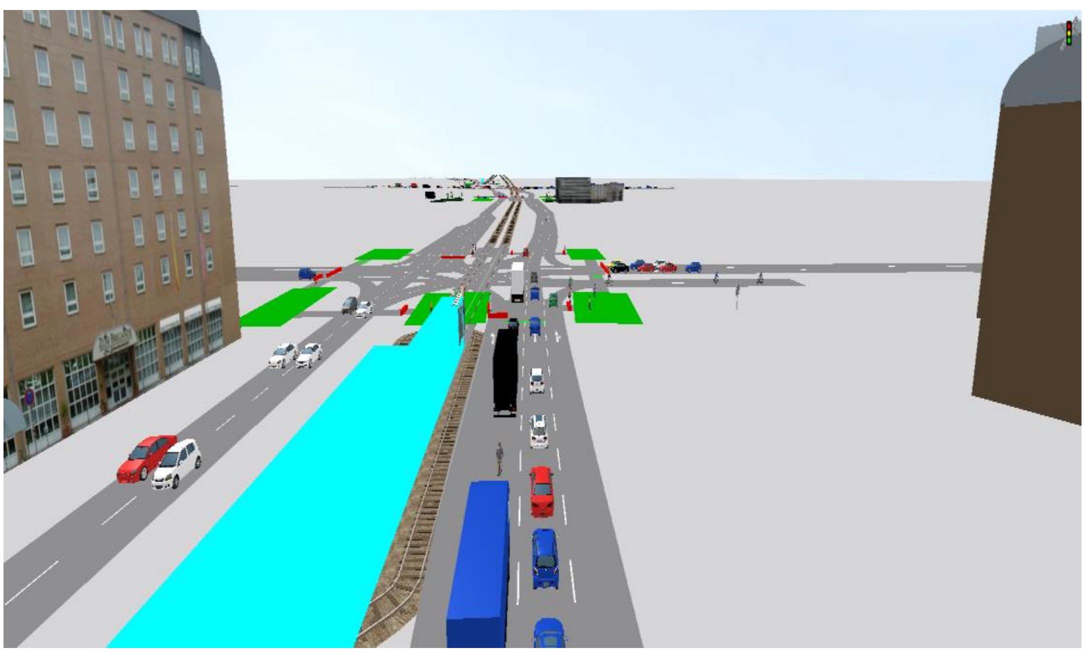


Figure 14. Transit Signal Priority Activation - LRT Detection (Interstage 1)

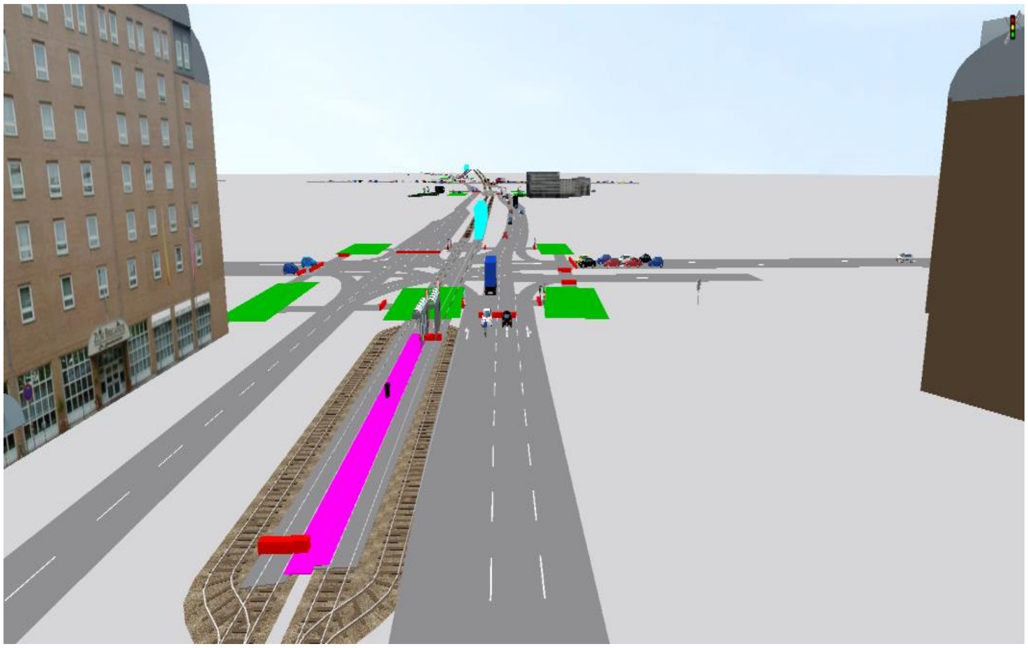


Figure 15. Transit Signal Priority Deactivation (Interstage 2)

Figure 14 and Figure 15 shows how the signal priority for LRT functions in the simulation model. The northbound through and southbound through signals are active in interstage 1 when the presence detector detects the LRT. The interstage 2 is active once the LRT crosses the intersection. Figure 15 starts interstage 2 where southbound left-turning movement gets the green.

The trajectory/path of LRT intersects with the pedestrian movement. The LRT movement is prioritized over the pedestrian movement by defining conflict points and enabling LRT the priority over the pedestrians.

*3.2.2.2 Viswalk external module for pedestrians*

The signal priority/ boarding-alighting of pedestrians at the LRT stations can be modelled using the Viswalk external module. In the current network, the pedestrian crossings are only modeled near the intersections. There are no mid-block pedestrian crossing locations in the network.

Pedestrian signals are provided as observed in the field. But a countdown pedestrian signal could not be provided in the model. Therefore, pedestrians tend to cross when there is green signal for pedestrian movement, and the pedestrians might be only halfway through the path of their route while the signal turns red. To ensure that there are no pedestrian conflicts with vehicles, priority is provided to pedestrians over vehicles. Simultaneously, priority for LRT is provided over pedestrians where their paths cross. Figure 16 shows the conflict zones, and the priorities provided for all movements at an intersection in the network.

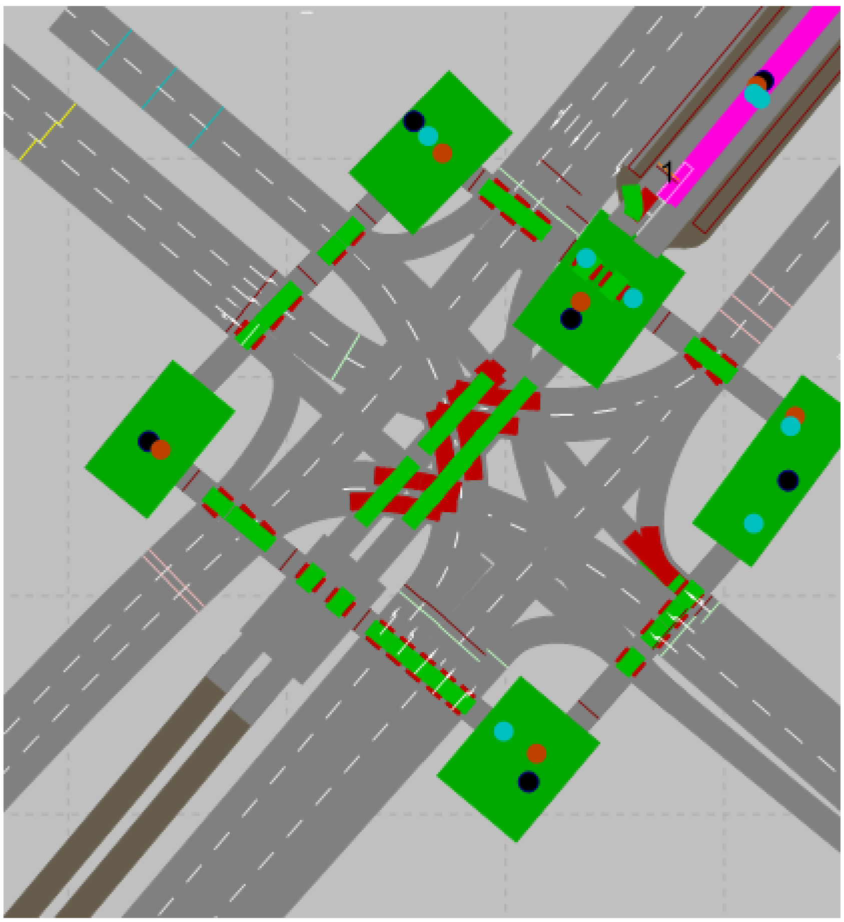


Figure 16. LRT, Pedestrians and Vehicle Priority as Seen in the Study Area

## 3.3 SSAM-based Assessment

SSAM is a software developed by the Federal Highway Administration (FHWA) to do a traffic conflict analysis on roads. The trajectory files developed in the simulation software is processed in the SSAM software which generates outputs in terms of conflict points. Researchers tend to develop different simulation models for a same location and do the operational performance and safety analysis to recommend their changes. In this research, the trajectory files for all hypothetical scenarios are developed in Vissim and are run in SSAM.

Time to collision (TTC) is the minimum time-to-collision value observed during the conflict. It is the projected time until two vehicles would collide if they continue to go in the same collision path with no change in the speed and direction. A TTC value is defined for each time step during the conflict event. A conflict event is concluded if the TTC value is greater than the critical threshold value. This value is recorded in seconds.

The time differential between when the leading vehicle occupied this location and the trailing vehicle arrived is the post-encroachment time (PET) . A value of zero indicates a collision. A post-encroachment time is associated with each time step during a conflict. The PET values are recorded in seconds.

Studies by Sayed et al. (1994) and Hayward (1972) suggested usage of TTC values of 1.5 seconds, and Svensson and Hyden (1987) suggested usage of PET value of 5 seconds on urban arterial corridors in SSAM. TTC is set at 1.5 seconds and PET value is set at 5.0 seconds for all the hypothetical scenarios. TTC values greater than 1.5 seconds are not considered as they are not considered to be severe enough.

The trajectory files were developed for five random simulation seeds and the conflicts are presented as an average of the five simulation runs for all the hypothetical scenarios developed in simulation analysis.

# CHAPTER 4: DATA COLLECTION

The data collected for modeling and evaluation are discussed in this chapter.

## 4.1 Travel Time-based Assessment Data Collection

Geo-referencing of the links was done using four well-defined points (start latitude, start longitude, end latitude, and end longitude). The exact coordinates of these points were obtained from the RITIS database. These points were transferred to the street map of North Carolina. A buffer of one mile was created along N Tryon St, and all the links within the one-mile buffer were identified.

The commuters who use the N Tryon St (US-29) corridor may expect an extra delay due to the LRT operation. They may shift to alternative routes. Therefore, the I-85 parallel route within the vicinity of the LRT system was also considered. The LRT system contains many at-grade crossings. To understand the effect of signal cycle adjustments to accommodate the LRT, the near vicinity cross-streets within a mile of the N Tryon St, such as University City Blvd, W T Harris Blvd, Mallard Creek Church Rd, and I-485, were also selected for travel time analysis. The study links considered are shown in Figure 2.

The TTR for different hours of the day and days of the week was first examined. These patterns help in determining the peak and off-peak hours of the day and the peak day of the week. In this research, for weekdays, morning peak (7:00 AM – 8:00 AM), afternoon (12:00 PM – 1:00 PM), evening peak (5:00 PM – 6:00 PM), and the evening (8:00 PM – 9:00 PM) were considered.

Various percentile based TTR measures were considered to assess the effect of the LRT system on transportation system performance. All these measures were derived from the travel time distributions (for example, as shown in Figure 17).

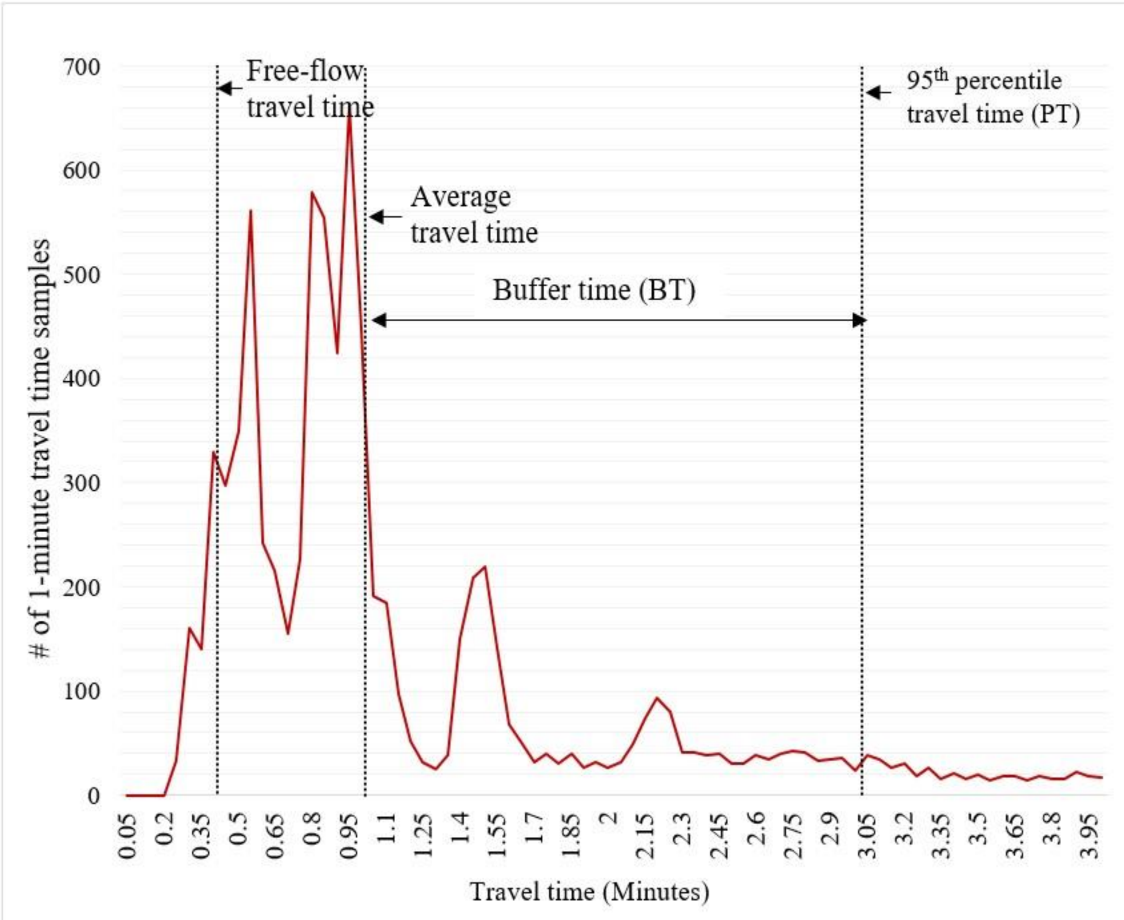



Figure 17. Travel Time Distribution - N Tryon St

The ATT, the free-flow travel time, and the 95th percentile travel time were computed for each link by aggregating data by day of the week and time of day using Microsoft SQL. The 95th percentile travel time indicates that 95% of the time, the performance of the study segment will not be worse than the values associated with the 95th percentile travel time. PT is directly computed from the travel time data. BT is the difference between the PT and the ATT, as shown in Equation 1. It indicates the extra travel that users add to their ATT to ensure on-time arrival at their destination.

$$BT = PT - ATT \tag{1}$$

PTI and BTI are widely used for the performance evaluation of transportation systems. PTI is the ratio of the 95th percentile travel time to the free-flow travel time. PTI is computed using Equation 2. It compares the near-worst travel time with the ideal travel time.

$$PTI = \frac{PT}{Free\text{-}flow\ travel\ time} \quad (2)$$

The BT divided by the ATT gives the BTI. It indicates the size of BT as a percentage of the ATT (Equation 3).

$$BTI = \frac{BT}{ATT} \quad (3)$$

An LRT system with dedicated right-of-way and signal priority influences the arterial street traffic. Figure 18 shows the interaction of the LRT system with moving traffic, pedestrian activity, and bicyclist activity. In this research, the initial assessment of TTR was carried out at the link level, as it can capture the effect of the LRT system on a specific segment of the road. Moreover, route level aggregation may only provide the overall effect of TTR along the selected study corridor. As this study proposes a methodological framework for the assessment of the effect from a multimodal perspective on the road traffic within its vicinity, the initial assessment was performed at the disaggregated level. The link-level analysis was followed by corridor-level travel time distribution analysis. As the lengths of the link are not the same, data normalization was carried out by dividing the travel time with the length of each link. The measures of TTR (i.e., ATT, PT, BT, BTI, and PTI) are derived from these distributions.

Figure 18. Interaction of the LRT System with the Moving Traffic, On-street Bicycle Lane, and Pedestrian Crosswalks

The statistical significance of the change in travel time performance measures (ATT, PT, BT, BTI, and PTI) over different phases of LRT operation was evaluated using one-tail paired t-tests. The analysis was performed at a 95% confidence level. The null hypothesis assumes zero mean difference in the travel time performance measure between the network without LRT and the selected operational phase. The alternate hypothesis assumes that the mean difference between the selected performance measures is less than zero.

The proposed duration of time considered for the TTR analysis are before LRT, sixth month after LRT, twelfth month after LRT, and eighteen months after LRT.

4.2 Simulation-based Assessment Data Collection

Geometric characteristics like the taper lengths, lane widths, lengths of left- and right-turn lanes, and width and length of on-street bicycle lanes were captured using Google Earth for the year 2018. Transit data such as the frequency of trains in an hour, the number of cars on the train, and the duration of time the train stops at a station were collected manually for year 2018.

Turning movement counts, pedestrian counts, bicyclist counts, and signal timing details were collected for simulation modeling and analysis. They are discussed next.

*4.2.1 Turning Movement Counts*

The vehicular volumes and turning movement counts were obtained from the CDoT. They are typically collected every two years for each intersection. The turning movement counts for all the intersections on the study corridor were requested for years 2012 to 2018. Turning movement counts for all the intersections were available for 2018. Appropriate calibration methods were used to validate the precision of collected and estimated turning movement counts data.

The data obtained from CDoT were not collected on the same day for all the intersections, which can probably be attributed to the limited availability of resources. Hence, there were some errors while trying to balance the vehicular volumes. To minimize the balancing errors, the data were segregated into three periods: morning peak period (7:00 AM – 9:00 AM), evening peak period (4:00 PM – 7:00 PM), and off-peak period (10:00 AM – 12:00 PM). Vehicular volume balancing was performed to track inaccuracies in vehicular volumes throughout the study corridor.

*4.2.2 Vehicular Volume Balancing*

Balancing vehicular volumes is a cumbersome process, especially at a corridor level. The turning movement counts at the selected nine intersections were not collected on the same day. Hence, the collected data might be prone to vehicular volume imbalances as the numbers might be slightly different on the very next day. To obtain realistic numbers, the average vehicular volumes of a peak period (for example, 4:00 PM – 7:00 PM) were used as hourly vehicular volumes.

The Wisconsin Department of Transportation (WsDOT) has developed a tool to minimize the imbalances and adjust the corresponding vehicular volumes along the corridor (WsDOT 2019). The vehicular volumes for all the intersections (by approach and turning movement direction) are fed into the macro-enabled Excel spreadsheet tool as raw data. The vehicles already in the network, vehicles entering the network, vehicles exiting the network, and vehicles making U-turns are all required to balance the vehicular volumes. These vehicular volumes are initially balanced using the vehicular volume balancing tool. The difference in the entering and exiting vehicular volumes at two successive intersections is distributed proportionally based on their corresponding vehicular volumes. The tool runs multiple iterations (maximum of 500) adjusting the vehicular volumes until the differences in vehicular volumes are minimal. In spite of applying the process, vehicular volume imbalances persist in most of the cases, but they are lower in magnitudes. These imbalances are further adjusted manually to improve the degree of precision (WsDOT 2019).

WsDOT has also provided acceptable values that serve as benchmarks to tally the final remaining errors. This error is defined as Equation 4.

$$Error = \sqrt{\frac{(Raw\ volume - Balanced\ volume)^2}{Raw\ Volume}} \tag{4}$$

The vehicular volume balancing tools state that an error of less than 3.0 is considered highly acceptable, whereas 3.0 to 4.9 is considered acceptable. Any error greater than 5.0 necessitates further refinement. The balancing at the corridor level in this research was performed with minimal errors using the abovementioned procedure. A maximum error of 4.2 was reported for the study corridor.

Missing data in the vehicular volumes at intersections along the study corridor were projected based on the available vehicular volumes from adjacent intersections. The year 2018 was considered as a base scenario because of the availability of vehicular volume data for all the selected intersections. Vehicular volume ratios were calculated for the intersections for the year 2018. These ratios were then used to project any missing data for the two previous years.

Table 2 summarizes the vehicle inputs at the routing decision points in the network. These vehicle inputs are for the evening peak period used for the initial model development. The vehicular volumes are kept consistent for all the scenarios except for two scenarios where the vehicular volumes are changed. For these two scenarios, 15% increase/ decrease to the existing vehicular volumes are provided.

Table 2. Traffic Volume Inputs

| Location | Hourly Traffic volume |
|---|---|
| N Tryon St & University City Blvd (NB) | 802 |
| N Tryon St & University City Blvd (EB) | 713 |
| N Tryon St & University City Blvd (WB) | 1115 |
| N Tryon St & University Pointe Blvd (EB) | 289 |
| N Tryon St & University Pointe Blvd (WB) | 223 |
| N Tryon St & McCullough Dr (EB) | 112 |
| N Tryon St & McCullough Dr (WB) | 444 |
| N Tryon St & Ken Hoffmann Dr (EB) | 239 |
| N Tryon St & Ken Hoffmann Dr (WB) | 198 |
| N Tryon St & E WT Harris Blvd (EB) | 1894 |
| N Tryon St & E WT Harris Blvd (WB) | 1758 |
| N Tryon St & J M Keynes Dr (EB) | 114 |
| N Tryon St & J M Keynes Dr (WB) | 40 |
| N Tryon St & JW Clay Blvd (EB) | 285 |
| N Tryon St & JW Clay Blvd (WB) | 221 |
| N Tryon St & Institute Cir (EB) | 435 |
| N Tryon St & Institute Cir (WB) | 253 |
| N Tryon St & Mallard Creek Church Rd (SB) | 861 |
| N Tryon St & Mallard Creek Church Rd (EB) | 1476 |
| N Tryon St & Mallard Creek Church Rd (WB) | 1030 |

*.4.2.3 Pedestrian and Bicyclist Counts*

Pedestrian counts were collected manually at intersections with possible interactions between pedestrians and other modes of transportation after the LRT is in operation. Among all the intersections, pedestrian counts were the highest at JW Clay Blvd, followed by Institute Cir and McCullough Dr. The increase in pedestrian counts can be attributed to people walking toward the LRT station from the university or the residential communities in close vicinity. The LRT parking deck at N Tryon St & JW Clay Blvd also adds to the pedestrian counts. It is situated across the street from the station. This is the only station in the selected study corridor with park and ride facility. Bicyclist counts were low as opposed to an expected increase in activity after the LRT is in operation.

### *4.2.4 Signal Timings*

The traffic phasing patterns and signal timings for selected intersections were obtained from the CDoT. The signal controllers for the intersections in the study corridor are of Ring and Barrier Controller (RBC) type. This controller is typically designed by allocating phases in a continuous loop termed as the “ring”, with the “barrier” being phased with conflicting movements. In other words, the ring represents the continuous phases that are operated in the desired order while the barrier is used to separate the conflicting phases at an intersection. The interval and clearance time are used to separate the vehicular movements in time. The data obtained from the CDoT comprised the phases and their corresponding timings for patterns allocated differently during different times of the day. The evening peak period signal timings pattern were used for all the scenarios in this study.

# CHAPTER 5: TRAVEL TIME-BASED ASSESSMENT RESULTS

TTR-based assessment is done at two levels, the first one being at link level and the second one is at the corridor level.

## 5.1 Travel Time Reliability (TTR) at Link Level

Initially, the ATT and the PT were estimated for the study corridor (N Tryon St), I-85 (parallel route), and other cross-streets in the near vicinity. The BT, BTI, and PTI were computed for the selected peak and off-peak periods of the day. This section demonstrates the link-level TTR assessment of selected corridors during different phases of LRT operation.

### *5.1.1 Effect on the Study Corridor (N Tryon St)*

The TTR assessment was carried out on twelve different links along the N Tryon St for four different phases of LRT operation. The selected links are shown in Figure 2. The TTR assessment of 125+08371 (a sample link) for a typical weekday evening peak hour is illustrated in Figure 19. From Figure 19, there is a trend of worsening TTR over different phases of LRT operation. The effect is at a maximum during the eighteenth month of LRT operation.

Further, for each selected link, the researchers computed the ratio between the travel time performance measure for (a) the analysis phase and (b) the network without the LRT phase. A ratio greater than one indicates a decrease in the TTR measure, while a ratio value less than one indicates an improvement. The analysis performed for N Tryon St on a typical weekday morning peak hour is summarized in Table 3. The column corresponding to the network without LRT shows the TTR measures, and the change in TTR during different phases is shown with ratios.

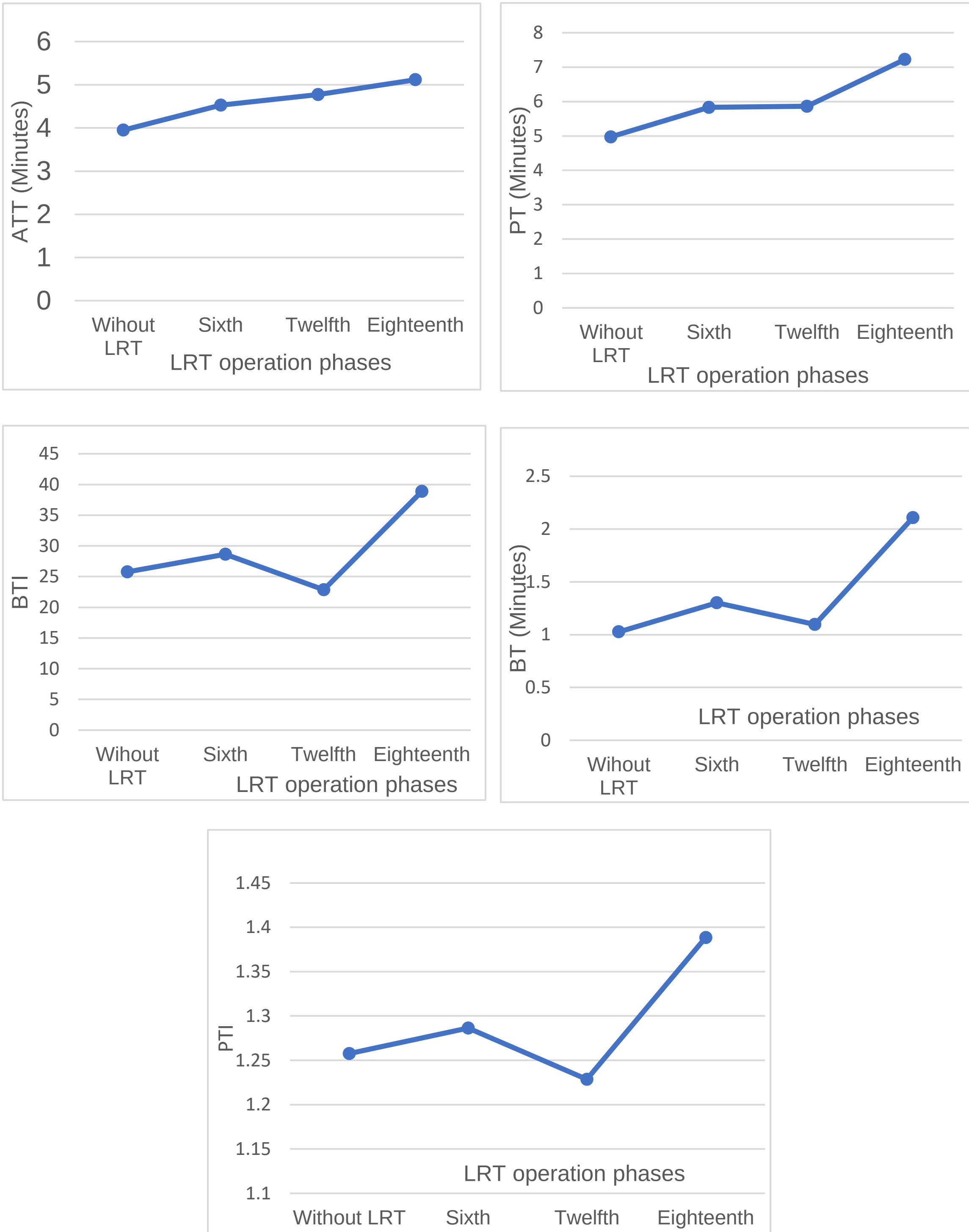



Figure 19. TTR of 125+08371 - Different Phases of LRT Operation

The green shaded cells indicate a ratio of less than one, which indicates an improvement in the performance measure after the operation of the LRT began. The red color cells indicate a decrease in the TTR measure compared to the system without LRT.

For example, the ratio of ATT during the sixth month of LRT operation divided by the ATT for the network without the LRT, in Table 3, is reported as 0.94 for link ID - 125+08371. This implies a 6% decrease in the ATT during the sixth month of the LRT operation when compared to the network without the LRT condition.

In Table 3, there exists a trend of improvement in TTR for many links during the sixth month of LRT operation. However, a few links showed a decrease in the performance. While looking into the twelfth month of LRT operation, many links showed an improvement in reliability compared to the sixth month of operation. During the eighteenth month of operation, the majority of the links showed a decrease in TTR. A consistent improvement in TTR was observed on 125+08373 and 125+08374 during different phases of LRT operation.

A significant improvement in travel time performance measures is observed on some of the links on N Tryon St during the evening peak hour, as illustrated in Table 4. However, a trend of deterioration in performance is observed on some of the links during different phases of LRT operation. The delay associated with the at-grade LRT system crossings can be considered one primary reason behind the increase in travel time on those links. Moreover, one can also see a very consistent deterioration in travel time performance measures on link ID 125+08372 during different phases of the LRT operation. The delay associated with the left-turn movements to parking decks and significant trip attractions, or to the university area and other public offices in the vicinity, may have influenced the travel time performance on 125+08372.

Overall, the maximum variability is observed in the case of buffer measures (BT and BTI) during different phases of LRT operation compared to the network without LRT.

### *5.1.2 Effect on the Parallel Route (I-85)*

The TTR assessment was carried out on sixteen different links along the parallel route for four different phases of LRT operation. The results from analysis for the I-85 parallel route for a typical morning peak hour are shown in Table 5. From the link-level TTR assessment of the parallel route, a substantial adverse effect on TTR was observed during the morning peak during all the selected analysis periods compared to the network without LRT. When looking into the twelfth and eighteenth month of operation, the buffer measure notably worsened in all the selected segments.

Similar to the morning peak hour, TTR measures showed a consistent trend of worsening on the I-85 parallel route in the evening peak hour for all the phases of LRT operation (Table 6). Also, the degree of change is higher in the evening peak hour compared to the morning peak hour.

### *5.1.3 Effect on the Near Vicinity Cross-streets*

A similar analysis was performed on 42 links along the selected near vicinity cross-streets, and the results are shown in Table 7 and Table 8. There is a trend of decrease in travel time performance measures on some of the cross-street links during the sixth month of LRT operation. However, the majority of the links showed an improvement in TTR during the twelfth month of LRT operation compared to the network without LRT. Finally, the analysis for the eighteenth month of LRT operation showed a trend of worsening reliability for most of the links during both the morning and evening peak periods.

Overall, the link-level analysis indicates that many links on the study corridor clearly showed an improvement, while the TTR worsened in some of them during many operating scenarios, compared to the network without the LRT system in operation. To avoid delays at signalized intersections due to LRT system operation, the results clearly exhibit a trend of parallel route choice during the morning and evening hours. The worsening in TTR on the parallel route links indicates the same.

Table 3. TTR Measures: N Tryon St (Morning Peak)

| Link | Length (miles) | TTR for the network without LRT | | | | | Ratio of TTR values for network with and without LRT | | | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | | | | | Sixth month | | | | | Twelfth month | | | | | Eighteenth month | | | | |
| | | ATT | PT | BT | BTI | PTI | ATT | PT | BT | BTI | PTI | ATT | PT | BT | BTI | PTI | ATT | PT | BT | BTI | PTI |
| 125+08371 | 1.77 | 4.22 | 5.36 | 1.14 | 27.04 | 1.27 | 0.94 | 0.90 | 0.76 | 0.79 | 0.96 | 0.95 | 0.90 | 0.72 | 0.75 | 0.95 | 0.98 | 1.04 | 1.26 | 1.22 | 1.05 |
| 125+08372 | 0.35 | 0.83 | 1.11 | 0.27 | 32.63 | 1.33 | 1.14 | 1.34 | 1.95 | 1.63 | 1.15 | 1.17 | 1.28 | 1.62 | 1.39 | 1.10 | 1.10 | 1.33 | 2.01 | 1.74 | 1.18 |
| 125+08373 | 1.08 | 3.49 | 4.52 | 1.03 | 29.31 | 1.29 | 0.83 | 0.81 | 0.77 | 0.93 | 0.98 | 0.84 | 0.84 | 0.81 | 0.95 | 0.99 | 0.76 | 0.75 | 0.73 | 0.96 | 0.99 |
| 125+08374 | 1.39 | 3.42 | 4.38 | 0.96 | 28.29 | 1.28 | 0.89 | 0.89 | 0.90 | 1.00 | 1.00 | 0.88 | 0.87 | 0.87 | 0.96 | 0.99 | 0.93 | 0.91 | 0.82 | 0.88 | 0.97 |
| 125+08375 | 0.93 | 1.48 | 1.84 | 0.36 | 24.26 | 1.24 | 1.01 | 1.04 | 1.19 | 1.20 | 1.04 | 0.97 | 0.96 | 0.92 | 0.95 | 0.99 | 1.01 | 1.06 | 1.28 | 1.26 | 1.05 |
| 125-08370 | 1.70 | 3.51 | 4.25 | 0.74 | 20.60 | 1.21 | 1.03 | 1.02 | 0.95 | 0.93 | 0.99 | 1.08 | 1.16 | 1.51 | 1.42 | 1.07 | 1.16 | 1.19 | 1.34 | 1.12 | 1.02 |
| 125-08371 | 0.43 | 0.94 | 1.27 | 0.33 | 33.26 | 1.33 | 0.96 | 0.97 | 0.98 | 1.03 | 1.01 | 1.05 | 1.06 | 1.09 | 1.02 | 1.01 | 1.04 | 1.20 | 1.64 | 1.60 | 1.15 |
| 125-08372 | 1.10 | 2.75 | 3.82 | 1.07 | 38.26 | 1.38 | 1.14 | 1.27 | 1.61 | 1.44 | 1.12 | 1.08 | 1.10 | 1.15 | 1.07 | 1.02 | 0.99 | 0.96 | 0.87 | 0.88 | 0.97 |
| 125-08373 | 1.38 | 3.06 | 3.97 | 0.92 | 29.87 | 1.30 | 1.01 | 0.96 | 0.79 | 0.79 | 0.95 | 0.97 | 0.93 | 0.82 | 0.85 | 0.97 | 0.98 | 1.00 | 1.08 | 1.10 | 1.02 |
| 125-08374 | 0.80 | 1.27 | 1.64 | 0.37 | 28.95 | 1.29 | 1.00 | 1.05 | 1.22 | 1.20 | 1.05 | 0.97 | 0.92 | 0.79 | 0.82 | 0.96 | 1.01 | 1.09 | 1.37 | 1.33 | 1.07 |
| 125N08375 | 0.27 | 0.37 | 0.43 | 0.06 | 16.40 | 1.16 | 1.09 | 1.19 | 1.76 | 1.60 | 1.08 | 1.04 | 1.05 | 1.11 | 1.07 | 1.01 | 1.12 | 1.19 | 1.57 | 1.38 | 1.05 |
| 125P08375 | 0.26 | 0.42 | 0.52 | 0.10 | 24.44 | 1.24 | 1.00 | 1.04 | 1.17 | 1.18 | 1.04 | 0.97 | 0.95 | 0.89 | 0.92 | 0.98 | 1.01 | 1.06 | 1.27 | 1.25 | 1.05 |

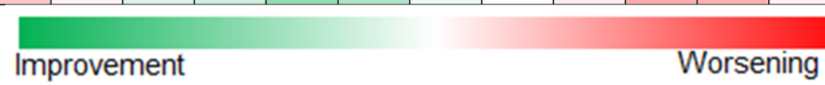


Table 4. TTR Measures: N Tryon St (Evening Peak)

| Link | Length (miles) | TTR for the network without LRT | | | | | Ratio of TTR values for network with and without LRT | | | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | | | | | Sixth month | | | | | Twelfth month | | | | | Eighteenth month | | | | |
| | | ATT | PT | BT | BTI | PTI | ATT | PT | BT | BTI | PTI | ATT | PT | BT | BTI | PTI | ATT | PT | BT | BTI | PTI |
| 125+08371 | 1.77 | 3.95 | 4.98 | 1.03 | 25.76 | 1.26 | 1.15 | 1.17 | 1.27 | 1.11 | 1.02 | 1.21 | 1.18 | 1.07 | 0.89 | 0.98 | 1.30 | 1.45 | 2.06 | 1.51 | 1.10 |
| 125+08372 | 0.35 | 0.76 | 1.01 | 0.25 | 32.48 | 1.32 | 1.27 | 1.25 | 1.19 | 0.94 | 0.98 | 1.27 | 1.36 | 1.62 | 1.27 | 1.07 | 1.50 | 1.87 | 3.01 | 1.98 | 1.24 |
| 125+08373 | 1.08 | 3.09 | 4.50 | 1.40 | 44.85 | 1.45 | 1.15 | 1.12 | 1.05 | 0.90 | 0.97 | 1.08 | 1.05 | 0.99 | 0.91 | 0.97 | 1.17 | 1.13 | 1.05 | 0.89 | 0.97 |
| 125+08374 | 1.39 | 4.83 | 7.44 | 2.60 | 50.91 | 1.51 | 1.04 | 1.19 | 1.47 | 1.41 | 1.14 | 0.90 | 0.97 | 1.10 | 1.11 | 1.04 | 1.10 | 1.27 | 1.58 | 1.35 | 1.12 |
| 125+08375 | 0.93 | 1.73 | 2.24 | 0.51 | 29.66 | 1.30 | 0.95 | 0.93 | 0.89 | 0.92 | 0.98 | 0.96 | 0.95 | 0.93 | 0.97 | 0.99 | 1.02 | 1.16 | 1.64 | 1.52 | 1.12 |
| 125-08370 | 1.70 | 5.14 | 7.08 | 1.94 | 36.65 | 1.37 | 0.91 | 0.82 | 0.56 | 0.63 | 0.90 | 0.92 | 0.84 | 0.63 | 0.70 | 0.92 | 0.94 | 0.92 | 0.85 | 0.91 | 0.98 |
| 125-08371 | 0.43 | 0.98 | 1.35 | 0.37 | 37.43 | 1.37 | 1.02 | 1.01 | 0.97 | 0.97 | 0.99 | 0.97 | 1.04 | 1.22 | 1.28 | 1.08 | 0.98 | 1.02 | 1.13 | 1.15 | 1.04 |
| 125-08372 | 1.10 | 4.17 | 5.23 | 1.07 | 25.42 | 1.25 | 0.93 | 1.02 | 1.39 | 1.52 | 1.10 | 0.84 | 0.90 | 1.14 | 1.38 | 1.08 | 0.79 | 0.82 | 0.95 | 1.19 | 1.04 |
| 125-08373 | 1.38 | 4.20 | 5.47 | 1.27 | 30.24 | 1.30 | 0.94 | 0.93 | 0.88 | 0.92 | 0.98 | 0.91 | 0.89 | 0.81 | 0.89 | 0.97 | 0.91 | 0.96 | 1.12 | 1.20 | 1.05 |
| 125-08374 | 0.80 | 1.39 | 1.91 | 0.52 | 37.69 | 1.38 | 0.96 | 0.92 | 0.81 | 0.84 | 0.96 | 0.93 | 0.86 | 0.66 | 0.71 | 0.92 | 0.98 | 1.03 | 1.18 | 1.20 | 1.06 |
| 125N08375 | 0.27 | 0.42 | 0.51 | 0.09 | 20.64 | 1.21 | 0.96 | 0.95 | 0.90 | 0.95 | 0.99 | 0.91 | 0.90 | 0.85 | 0.93 | 0.99 | 0.95 | 0.97 | 1.06 | 1.12 | 1.02 |
| 125P08375 | 0.26 | 0.49 | 0.63 | 0.14 | 29.21 | 1.29 | 0.95 | 0.93 | 0.89 | 0.92 | 0.98 | 0.96 | 0.95 | 0.95 | 0.98 | 1.00 | 1.02 | 1.16 | 1.65 | 1.53 | 1.12 |

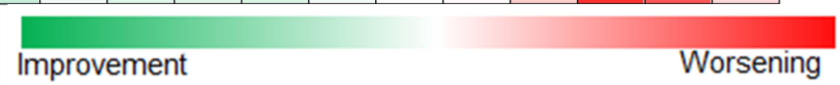


Table 5. TTR Measures: I-85 Parallel Route (Morning Peak)

| Link | Length (miles) | TTR for the network without LRT | | | | | Ratio of TTR values for network with and without LRT | | | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | | | | | Sixth month | | | | | Twelfth month | | | | | Eighteenth month | | | | |
| | | ATT | PT | BT | BTI | PTI | ATT | PT | BT | BTI | PTI | ATT | PT | BT | BTI | PTI | ATT | PT | BT | BTI | PTI |
| 125+04644 | 1.00 | 0.87 | 0.91 | 0.04 | 5.15 | 1.05 | 1.02 | 1.06 | 1.80 | 1.75 | 1.04 | 1.00 | 1.02 | 1.26 | 1.27 | 1.01 | 0.99 | 1.01 | 1.36 | 1.38 | 1.02 |
| 125+04645 | 1.04 | 0.93 | 0.98 | 0.05 | 5.75 | 1.06 | 1.00 | 1.02 | 1.41 | 1.42 | 1.02 | 1.00 | 1.01 | 1.20 | 1.20 | 1.01 | 0.99 | 1.01 | 1.35 | 1.37 | 1.02 |
| 125+04646 | 0.39 | 0.35 | 0.37 | 0.02 | 5.66 | 1.06 | 1.00 | 1.02 | 1.39 | 1.39 | 1.02 | 1.00 | 1.01 | 1.14 | 1.14 | 1.01 | 0.99 | 1.01 | 1.33 | 1.34 | 1.02 |
| 125+09616 | 0.29 | 0.25 | 0.26 | 0.01 | 5.30 | 1.05 | 1.01 | 1.04 | 1.58 | 1.57 | 1.03 | 1.01 | 1.03 | 1.43 | 1.42 | 1.02 | 1.00 | 1.01 | 1.20 | 1.21 | 1.01 |
| 125-04643 | 0.36 | 0.44 | 0.86 | 0.43 | 78.62 | 1.79 | 0.95 | 0.74 | 0.52 | 0.64 | 0.84 | 1.22 | 1.20 | 1.19 | 0.98 | 0.99 | 1.26 | 1.49 | 1.73 | 1.25 | 1.11 |
| 125-04644 | 1.16 | 1.08 | 1.39 | 0.32 | 26.35 | 1.26 | 1.04 | 1.09 | 1.28 | 1.28 | 1.06 | 1.07 | 1.20 | 1.65 | 1.48 | 1.10 | 1.16 | 1.60 | 3.12 | 2.65 | 1.34 |
| 125-04645 | 0.60 | 0.53 | 0.64 | 0.10 | 18.18 | 1.18 | 1.17 | 1.67 | 4.28 | 2.61 | 1.25 | 1.01 | 1.04 | 1.23 | 1.22 | 1.03 | 1.09 | 1.29 | 2.35 | 2.09 | 1.17 |
| 125-09616 | 1.04 | 1.11 | 1.98 | 0.87 | 63.66 | 1.64 | 0.98 | 0.81 | 0.60 | 0.69 | 0.88 | 1.22 | 1.32 | 1.45 | 1.20 | 1.08 | 1.32 | 1.88 | 2.60 | 1.86 | 1.34 |
| 125N04644 | 0.47 | 0.43 | 0.56 | 0.13 | 26.70 | 1.27 | 1.04 | 1.09 | 1.27 | 1.27 | 1.06 | 1.07 | 1.20 | 1.64 | 1.47 | 1.10 | 1.16 | 1.60 | 3.07 | 2.60 | 1.34 |
| 125N04645 | 0.53 | 0.48 | 0.57 | 0.09 | 18.07 | 1.18 | 1.17 | 1.67 | 4.32 | 2.63 | 1.25 | 1.01 | 1.04 | 1.21 | 1.21 | 1.03 | 1.09 | 1.30 | 2.37 | 2.11 | 1.17 |
| 125N04646 | 1.07 | 0.95 | 1.01 | 0.07 | 6.89 | 1.07 | 1.12 | 1.73 | 10.54 | 7.22 | 1.40 | 1.01 | 1.08 | 2.23 | 2.16 | 1.07 | 1.06 | 1.32 | 5.09 | 4.63 | 1.23 |
| 125N09616 | 0.53 | 0.57 | 1.01 | 0.44 | 63.31 | 1.63 | 0.98 | 0.81 | 0.61 | 0.70 | 0.88 | 1.22 | 1.32 | 1.46 | 1.21 | 1.08 | 1.32 | 1.89 | 2.61 | 1.87 | 1.34 |
| 125P04644 | 0.59 | 0.51 | 0.54 | 0.03 | 4.91 | 1.05 | 1.02 | 1.06 | 1.89 | 1.84 | 1.04 | 1.00 | 1.02 | 1.35 | 1.35 | 1.02 | 0.99 | 1.01 | 1.30 | 1.32 | 1.01 |
| 125P04645 | 0.53 | 0.47 | 0.49 | 0.03 | 5.47 | 1.05 | 1.00 | 1.03 | 1.54 | 1.55 | 1.03 | 1.00 | 1.01 | 1.27 | 1.28 | 1.01 | 0.99 | 1.01 | 1.45 | 1.47 | 1.02 |
| 125P04646 | 1.09 | 0.96 | 1.02 | 0.06 | 5.85 | 1.06 | 1.00 | 1.02 | 1.43 | 1.44 | 1.02 | 1.00 | 1.01 | 1.17 | 1.17 | 1.01 | 0.99 | 1.01 | 1.27 | 1.28 | 1.02 |
| 125P09616 | 0.59 | 0.50 | 0.53 | 0.03 | 5.97 | 1.06 | 1.01 | 1.03 | 1.42 | 1.40 | 1.02 | 1.01 | 1.02 | 1.21 | 1.20 | 1.01 | 1.00 | 1.01 | 1.17 | 1.17 | 1.01 |

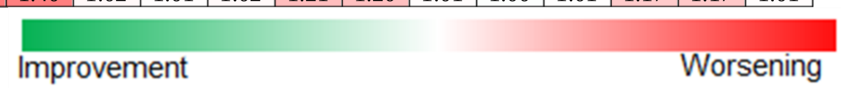


Table 6. TTR Measures: I-85 Parallel Route (Evening Peak)

| Link | Length (miles) | TTR for the network without LRT | | | | | Ratio of TTR values for network with and without LRT | | | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | | | | | Sixth month | | | | | Twelfth month | | | | | Eighteenth month | | | | |
| | | ATT | PT | BT | BTI | PTI | ATT | PT | BT | BTI | PTI | ATT | PT | BT | BTI | PTI | ATT | PT | BT | BTI | PTI |
| 125+04644 | 1.00 | 1.16 | 1.98 | 0.82 | 64.38 | 1.64 | 0.99 | 0.88 | 0.73 | 0.74 | 0.90 | 1.17 | 1.69 | 2.42 | 1.75 | 1.29 | 1.14 | 1.25 | 1.40 | 1.11 | 1.04 |
| 125+04645 | 1.04 | 1.39 | 2.04 | 0.65 | 44.56 | 1.45 | 0.93 | 0.90 | 0.84 | 0.90 | 0.97 | 1.00 | 1.11 | 1.34 | 1.23 | 1.07 | 1.02 | 1.16 | 1.47 | 1.20 | 1.06 |
| 125+04646 | 0.39 | 0.39 | 0.45 | 0.06 | 14.59 | 1.15 | 0.99 | 1.02 | 1.21 | 1.23 | 1.03 | 0.99 | 1.07 | 1.59 | 1.60 | 1.08 | 1.30 | 3.32 | 16.77 | 5.88 | 1.62 |
| 125+09616 | 0.29 | 0.26 | 0.33 | 0.07 | 25.07 | 1.25 | 1.12 | 1.30 | 1.95 | 1.32 | 1.06 | 1.26 | 2.16 | 5.49 | 3.69 | 1.54 | 1.29 | 2.50 | 6.98 | 3.94 | 1.59 |
| 125-04643 | 0.36 | 0.34 | 0.36 | 0.03 | 7.88 | 1.08 | 1.19 | 1.83 | 9.95 | 4.88 | 1.28 | 1.12 | 2.01 | 13.34 | 9.72 | 1.64 | 1.09 | 1.69 | 9.22 | 6.94 | 1.43 |
| 125-04644 | 1.16 | 1.00 | 1.06 | 0.06 | 5.76 | 1.06 | 1.03 | 1.17 | 3.61 | 3.20 | 1.12 | 1.00 | 1.03 | 1.54 | 1.54 | 1.03 | 0.99 | 1.01 | 1.32 | 1.33 | 1.02 |
| 125-04645 | 0.60 | 0.52 | 0.55 | 0.03 | 6.03 | 1.06 | 1.00 | 1.04 | 1.58 | 1.57 | 1.03 | 1.00 | 1.06 | 1.99 | 1.98 | 1.06 | 0.99 | 1.00 | 1.22 | 1.24 | 1.01 |
| 125-09616 | 1.04 | 0.90 | 0.97 | 0.06 | 7.17 | 1.07 | 1.26 | 2.19 | 15.21 | 6.21 | 1.35 | 1.04 | 1.36 | 5.85 | 5.19 | 1.28 | 1.02 | 1.24 | 4.24 | 3.83 | 1.19 |
| 125N04644 | 0.47 | 0.40 | 0.42 | 0.02 | 5.95 | 1.06 | 1.03 | 1.18 | 3.57 | 3.18 | 1.12 | 1.00 | 1.03 | 1.49 | 1.49 | 1.03 | 0.99 | 1.01 | 1.28 | 1.29 | 1.02 |
| 125N04645 | 0.53 | 0.46 | 0.49 | 0.03 | 5.69 | 1.06 | 1.00 | 1.04 | 1.65 | 1.65 | 1.03 | 1.00 | 1.06 | 2.08 | 2.07 | 1.06 | 0.99 | 1.00 | 1.24 | 1.25 | 1.01 |
| 125N04646 | 1.07 | 0.94 | 0.99 | 0.06 | 5.95 | 1.06 | 1.01 | 1.04 | 1.59 | 1.58 | 1.03 | 1.00 | 1.04 | 1.75 | 1.74 | 1.04 | 0.99 | 1.02 | 1.50 | 1.50 | 1.03 |
| 125N09616 | 0.53 | 0.46 | 0.49 | 0.03 | 6.93 | 1.07 | 1.26 | 2.20 | 15.77 | 6.44 | 1.35 | 1.04 | 1.37 | 6.10 | 5.42 | 1.29 | 1.02 | 1.24 | 4.37 | 3.93 | 1.19 |
| 125P04644 | 0.59 | 0.68 | 1.17 | 0.49 | 64.27 | 1.64 | 0.99 | 0.88 | 0.73 | 0.74 | 0.90 | 1.17 | 1.69 | 2.42 | 1.75 | 1.29 | 1.14 | 1.25 | 1.40 | 1.11 | 1.04 |
| 125P04645 | 0.53 | 0.70 | 1.03 | 0.33 | 44.57 | 1.45 | 0.93 | 0.90 | 0.84 | 0.90 | 0.97 | 1.00 | 1.10 | 1.33 | 1.23 | 1.07 | 1.01 | 1.16 | 1.47 | 1.20 | 1.06 |
| 125P04646 | 1.09 | 1.09 | 1.26 | 0.17 | 14.80 | 1.15 | 0.99 | 1.02 | 1.22 | 1.25 | 1.03 | 1.00 | 1.07 | 1.60 | 1.61 | 1.08 | 1.30 | 3.32 | 16.57 | 5.82 | 1.62 |
| 125P09616 | 0.59 | 0.52 | 0.66 | 0.14 | 25.32 | 1.25 | 1.12 | 1.30 | 1.95 | 1.32 | 1.07 | 1.26 | 2.17 | 5.48 | 3.68 | 1.54 | 1.29 | 2.50 | 6.94 | 3.91 | 1.59 |

Improvement — Worsening

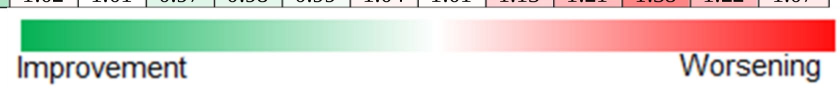
Table 7. TTR Measures: Near Vicinity Cross-streets (Morning Peak)

| Link | Length (miles) | TTR for the network without LRT | | | | | Ratio of TTR values for network with and without LRT | | | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | | | | | Sixth month | | | | | Twelfth month | | | | | Eighteenth month | | | | |
| | | ATT | PT | BT | BTI | PTI | ATT | PT | BT | BTI | PTI | ATT | PT | BT | BTI | PTI | ATT | PT | BT | BTI | PTI |
| 125+05832 | 0.44 | 0.53 | 0.60 | 0.08 | 15.01 | 1.15 | 1.01 | 1.01 | 1.04 | 1.02 | 1.00 | 0.99 | 0.95 | 0.70 | 0.71 | 0.96 | 1.04 | 1.07 | 1.29 | 1.22 | 1.03 |
| 125+05833 | 0.51 | 0.92 | 1.20 | 0.29 | 31.87 | 1.32 | 1.12 | 1.27 | 1.75 | 1.49 | 1.12 | 0.93 | 0.91 | 0.84 | 0.89 | 0.97 | 1.08 | 1.25 | 1.80 | 1.58 | 1.14 |
| 125+05834 | 0.52 | 1.05 | 1.43 | 0.39 | 37.08 | 1.37 | 1.05 | 1.03 | 0.97 | 0.92 | 0.98 | 0.93 | 0.88 | 0.74 | 0.79 | 0.94 | 1.05 | 1.07 | 1.10 | 1.04 | 1.01 |
| 125+08947 | 2.04 | 4.09 | 4.73 | 0.64 | 15.06 | 1.15 | 1.02 | 1.06 | 1.34 | 1.35 | 1.05 | 0.96 | 0.97 | 1.02 | 1.08 | 1.01 | 0.99 | 1.11 | 1.87 | 1.92 | 1.12 |
| 125+12200 | 1.24 | 2.14 | 2.59 | 0.45 | 20.58 | 1.21 | 1.04 | 1.06 | 1.13 | 1.09 | 1.01 | 1.00 | 0.97 | 0.82 | 0.82 | 0.97 | 1.08 | 1.09 | 1.15 | 1.06 | 1.01 |
| 125+12201 | 0.87 | 1.68 | 2.38 | 0.70 | 39.29 | 1.39 | 0.91 | 0.81 | 0.55 | 0.62 | 0.89 | 0.87 | 0.73 | 0.41 | 0.49 | 0.86 | 0.91 | 0.82 | 0.62 | 0.71 | 0.92 |
| 125+12232 | 0.57 | 1.07 | 1.44 | 0.38 | 35.05 | 1.35 | 0.92 | 0.87 | 0.73 | 0.80 | 0.95 | 0.95 | 0.88 | 0.69 | 0.73 | 0.93 | 0.98 | 1.00 | 1.06 | 1.06 | 1.01 |
| 125+12233 | 0.59 | 0.98 | 1.21 | 0.23 | 22.96 | 1.23 | 0.92 | 0.96 | 1.15 | 1.21 | 1.04 | 0.96 | 0.97 | 1.01 | 1.07 | 1.01 | 0.95 | 1.00 | 1.24 | 1.33 | 1.06 |
| 125-04957 | 0.96 | 0.82 | 0.87 | 0.05 | 6.50 | 1.07 | 1.01 | 1.06 | 1.72 | 1.69 | 1.04 | 1.00 | 1.01 | 1.20 | 1.20 | 1.01 | 1.01 | 1.03 | 1.42 | 1.41 | 1.02 |
| 125-04958 | 0.28 | 0.23 | 0.24 | 0.01 | 5.80 | 1.06 | 1.01 | 1.05 | 1.78 | 1.76 | 1.04 | 1.01 | 1.04 | 1.52 | 1.51 | 1.03 | 1.01 | 1.05 | 1.61 | 1.59 | 1.03 |
| 125-05831 | 0.49 | 0.59 | 0.69 | 0.09 | 15.60 | 1.16 | 0.97 | 0.96 | 0.85 | 0.89 | 0.99 | 1.03 | 1.24 | 2.51 | 1.99 | 1.13 | 1.00 | 1.04 | 1.30 | 1.32 | 1.04 |
| 125-05832 | 0.50 | 0.64 | 0.75 | 0.10 | 15.85 | 1.16 | 0.99 | 1.03 | 1.29 | 1.31 | 1.04 | 0.95 | 0.93 | 0.77 | 0.80 | 0.97 | 0.98 | 0.99 | 1.08 | 1.11 | 1.01 |
| 125-05833 | 0.53 | 1.17 | 1.55 | 0.38 | 32.24 | 1.32 | 0.96 | 1.01 | 1.18 | 1.24 | 1.06 | 0.88 | 0.86 | 0.81 | 0.91 | 0.98 | 1.02 | 1.10 | 1.32 | 1.30 | 1.07 |
| 125-08945 | 0.67 | 1.44 | 1.76 | 0.32 | 22.31 | 1.22 | 0.87 | 0.88 | 0.90 | 1.01 | 1.00 | 0.91 | 0.92 | 0.96 | 1.04 | 1.01 | 1.01 | 1.12 | 1.63 | 1.56 | 1.10 |
| 125-08946 | 2.03 | 3.58 | 4.68 | 1.09 | 29.57 | 1.30 | 0.97 | 0.92 | 0.75 | 0.80 | 0.95 | 1.01 | 0.93 | 0.67 | 0.66 | 0.92 | 1.08 | 1.03 | 0.89 | 0.84 | 0.96 |
| 125-12199 | 1.24 | 2.48 | 2.96 | 0.48 | 18.86 | 1.19 | 0.90 | 0.90 | 0.91 | 1.03 | 1.00 | 0.86 | 0.83 | 0.70 | 0.83 | 0.97 | 0.92 | 0.93 | 0.99 | 1.07 | 1.01 |
| 125-12200 | 0.84 | 1.62 | 2.07 | 0.45 | 27.31 | 1.27 | 0.96 | 1.00 | 1.16 | 1.21 | 1.04 | 0.87 | 0.86 | 0.84 | 0.97 | 0.99 | 0.89 | 0.92 | 1.05 | 1.17 | 1.04 |
| 125-12232 | 0.60 | 0.96 | 1.23 | 0.27 | 26.65 | 1.27 | 0.97 | 0.92 | 0.70 | 0.74 | 0.94 | 1.03 | 0.99 | 0.86 | 0.86 | 0.97 | 1.00 | 0.94 | 0.74 | 0.74 | 0.94 |
| 125-18607 | 0.56 | 1.27 | 1.71 | 0.44 | 33.78 | 1.34 | 1.05 | 1.06 | 1.09 | 1.03 | 1.01 | 1.06 | 1.03 | 0.97 | 0.93 | 0.98 | 1.07 | 1.17 | 1.45 | 1.32 | 1.08 |
| 125N04957 | 0.78 | 0.67 | 0.71 | 0.04 | 6.34 | 1.06 | 1.01 | 1.06 | 1.81 | 1.78 | 1.05 | 1.00 | 1.02 | 1.26 | 1.26 | 1.02 | 1.01 | 1.03 | 1.42 | 1.41 | 1.02 |
| 125N04958 | 0.62 | 0.52 | 0.54 | 0.03 | 5.36 | 1.05 | 1.01 | 1.05 | 1.82 | 1.79 | 1.04 | 1.01 | 1.04 | 1.64 | 1.63 | 1.03 | 1.01 | 1.06 | 1.87 | 1.85 | 1.04 |
| 125N05832 | 0.46 | 0.59 | 0.69 | 0.09 | 15.61 | 1.16 | 0.99 | 1.03 | 1.30 | 1.31 | 1.04 | 0.95 | 0.93 | 0.76 | 0.79 | 0.97 | 0.98 | 0.99 | 1.08 | 1.10 | 1.01 |
| 125N05834 | 0.21 | 0.43 | 0.56 | 0.13 | 29.06 | 1.29 | 0.92 | 0.93 | 0.96 | 1.05 | 1.01 | 0.87 | 0.89 | 0.95 | 1.10 | 1.02 | 0.95 | 0.95 | 0.93 | 0.96 | 0.99 |
| 125N08947 | 0.31 | 0.52 | 0.72 | 0.20 | 35.23 | 1.35 | 0.95 | 0.99 | 1.08 | 1.08 | 1.02 | 0.91 | 0.80 | 0.49 | 0.53 | 0.88 | 1.04 | 1.11 | 1.30 | 1.15 | 1.04 |
| 125N12201 | 0.24 | 0.45 | 0.54 | 0.09 | 20.35 | 1.20 | 0.95 | 1.00 | 1.25 | 1.32 | 1.05 | 0.92 | 0.92 | 0.92 | 1.00 | 1.00 | 0.97 | 1.07 | 1.55 | 1.57 | 1.10 |
| 125N12232 | 0.19 | 0.31 | 0.41 | 0.10 | 30.84 | 1.31 | 0.98 | 0.91 | 0.70 | 0.74 | 0.94 | 1.01 | 0.95 | 0.76 | 0.76 | 0.94 | 0.99 | 0.90 | 0.64 | 0.64 | 0.91 |
| 125P04957 | 0.38 | 0.33 | 0.39 | 0.06 | 17.18 | 1.17 | 1.07 | 1.52 | 4.10 | 3.18 | 1.32 | 0.99 | 0.94 | 0.65 | 0.67 | 0.95 | 1.05 | 1.30 | 2.77 | 2.44 | 1.21 |
| 125P05832 | 0.50 | 0.61 | 0.70 | 0.09 | 14.69 | 1.15 | 1.00 | 1.01 | 1.04 | 1.02 | 1.00 | 0.99 | 0.95 | 0.70 | 0.71 | 0.96 | 1.04 | 1.07 | 1.30 | 1.23 | 1.03 |
| 125P05834 | 0.20 | 0.40 | 0.55 | 0.15 | 36.83 | 1.37 | 1.05 | 1.02 | 0.95 | 0.90 | 0.97 | 0.94 | 0.88 | 0.73 | 0.78 | 0.94 | 1.05 | 1.06 | 1.09 | 1.03 | 1.01 |

Improvement — Worsening

Table 8. TTR Measures: Near Vicinity Cross-streets (Evening Peak)

| Link | Length (miles) | TTR for the network without LRT | | | | | Ratio of TTR values for network with and without LRT | | | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | | | | | Sixth month | | | | | Twelfth month | | | | | Eighteenth month | | | | |
| | | ATT | PT | BT | BTI | PTI | ATT | PT | BT | BTI | PTI | ATT | PT | BT | BTI | PTI | ATT | PT | BT | BTI | PTI |
| 125+05832 | 0.44 | 0.55 | 0.65 | 0.09 | 16.61 | 1.17 | 0.96 | 0.94 | 0.85 | 0.91 | 0.99 | 0.94 | 0.96 | 1.04 | 1.11 | 1.02 | 1.03 | 1.38 | 3.43 | 3.09 | 1.30 |
| 125+05833 | 0.51 | 1.52 | 3.26 | 1.74 | 88.64 | 1.89 | 0.84 | 0.72 | 0.62 | 0.85 | 0.93 | 0.87 | 0.83 | 0.80 | 1.11 | 1.05 | 1.17 | 1.24 | 1.30 | 1.20 | 1.09 |
| 125+05834 | 0.52 | 1.68 | 2.48 | 0.80 | 45.92 | 1.46 | 0.91 | 0.91 | 0.90 | 1.01 | 1.00 | 0.97 | 0.98 | 0.99 | 1.03 | 1.01 | 1.13 | 1.21 | 1.38 | 1.21 | 1.06 |
| 125+08947 | 2.04 | 7.42 | 10.47 | 3.05 | 37.32 | 1.37 | 0.96 | 1.10 | 1.43 | 1.49 | 1.13 | 0.83 | 0.91 | 1.11 | 1.31 | 1.08 | 0.96 | 1.01 | 1.12 | 1.17 | 1.05 |
| 125+12200 | 1.24 | 2.82 | 3.40 | 0.58 | 20.18 | 1.20 | 0.93 | 0.95 | 1.08 | 1.15 | 1.03 | 0.88 | 0.89 | 0.90 | 1.05 | 1.01 | 0.90 | 0.93 | 1.07 | 1.19 | 1.03 |
| 125+12201 | 0.87 | 2.09 | 2.85 | 0.76 | 35.36 | 1.35 | 0.90 | 0.94 | 1.05 | 1.15 | 1.04 | 0.94 | 1.14 | 1.70 | 1.64 | 1.17 | 0.84 | 0.80 | 0.69 | 0.82 | 0.95 |
| 125+12232 | 0.57 | 1.30 | 1.81 | 0.51 | 39.43 | 1.39 | 0.97 | 0.94 | 0.86 | 0.89 | 0.97 | 1.07 | 1.13 | 1.28 | 1.21 | 1.06 | 1.10 | 1.16 | 1.33 | 1.19 | 1.05 |
| 125+12233 | 0.59 | 0.98 | 1.36 | 0.39 | 38.52 | 1.39 | 0.99 | 1.02 | 1.10 | 1.02 | 1.01 | 1.02 | 0.97 | 0.84 | 0.83 | 0.95 | 1.05 | 1.09 | 1.18 | 1.09 | 1.02 |
| 125-04957 | 0.96 | 0.99 | 1.47 | 0.47 | 46.55 | 1.47 | 0.94 | 0.90 | 0.83 | 0.84 | 0.95 | 1.09 | 1.21 | 1.47 | 1.19 | 1.06 | 1.13 | 1.02 | 0.79 | 0.65 | 0.89 |
| 125-04958 | 0.28 | 0.27 | 0.40 | 0.13 | 46.10 | 1.46 | 0.98 | 0.92 | 0.79 | 0.74 | 0.92 | 1.11 | 1.39 | 1.97 | 1.54 | 1.17 | 1.24 | 1.29 | 1.39 | 1.07 | 1.02 |
| 125-05831 | 0.49 | 0.62 | 0.73 | 0.11 | 18.09 | 1.18 | 1.00 | 1.00 | 1.04 | 1.01 | 1.00 | 1.02 | 1.01 | 0.92 | 0.89 | 0.98 | 1.03 | 1.13 | 1.67 | 1.58 | 1.09 |
| 125-05832 | 0.50 | 0.70 | 0.85 | 0.16 | 22.60 | 1.23 | 0.98 | 0.95 | 0.81 | 0.82 | 0.97 | 0.99 | 0.97 | 0.89 | 0.90 | 0.98 | 1.03 | 1.11 | 1.46 | 1.42 | 1.08 |
| 125-05833 | 0.53 | 2.01 | 2.98 | 0.97 | 47.97 | 1.48 | 1.05 | 1.13 | 1.30 | 1.21 | 1.07 | 1.04 | 1.14 | 1.35 | 1.28 | 1.09 | 1.43 | 1.58 | 1.90 | 1.31 | 1.10 |
| 125-08945 | 0.67 | 1.74 | 2.24 | 0.50 | 28.69 | 1.29 | 0.95 | 0.95 | 0.95 | 1.00 | 1.00 | 0.96 | 0.94 | 0.89 | 0.92 | 0.98 | 1.02 | 1.14 | 1.56 | 1.52 | 1.11 |
| 125-08946 | 2.03 | 5.36 | 6.32 | 0.96 | 17.89 | 1.18 | 1.03 | 1.21 | 2.22 | 2.10 | 1.17 | 0.94 | 0.94 | 0.96 | 1.02 | 1.00 | 1.04 | 1.14 | 1.71 | 1.62 | 1.09 |
| 125-12199 | 1.24 | 2.93 | 3.87 | 0.93 | 30.80 | 1.31 | 0.90 | 0.83 | 0.62 | 0.71 | 0.93 | 0.88 | 0.82 | 0.61 | 0.72 | 0.93 | 0.92 | 0.98 | 1.16 | 1.26 | 1.06 |
| 125-12200 | 0.84 | 1.83 | 2.60 | 0.77 | 41.31 | 1.41 | 0.89 | 0.85 | 0.75 | 0.84 | 0.95 | 0.88 | 0.87 | 0.83 | 0.95 | 0.99 | 0.91 | 0.91 | 0.93 | 1.00 | 1.00 |
| 125-12232 | 0.60 | 1.00 | 1.31 | 0.32 | 31.17 | 1.31 | 1.00 | 0.97 | 0.84 | 0.82 | 0.96 | 1.08 | 1.11 | 1.18 | 1.11 | 1.03 | 1.14 | 1.19 | 1.36 | 1.19 | 1.05 |
| 125-18607 | 0.56 | 1.61 | 2.16 | 0.55 | 33.92 | 1.34 | 1.08 | 1.16 | 1.41 | 1.29 | 1.07 | 1.06 | 1.11 | 1.27 | 1.18 | 1.05 | 1.15 | 1.32 | 1.83 | 1.61 | 1.15 |
| 125N04957 | 0.78 | 0.81 | 1.20 | 0.39 | 46.91 | 1.47 | 0.94 | 0.91 | 0.83 | 0.85 | 0.95 | 1.09 | 1.21 | 1.47 | 1.19 | 1.06 | 1.13 | 1.02 | 0.78 | 0.65 | 0.89 |
| 125N04958 | 0.62 | 0.60 | 0.89 | 0.29 | 45.75 | 1.46 | 0.98 | 0.92 | 0.79 | 0.74 | 0.92 | 1.11 | 1.40 | 1.99 | 1.56 | 1.17 | 1.24 | 1.29 | 1.40 | 1.08 | 1.03 |
| 125N05832 | 0.46 | 0.64 | 0.79 | 0.15 | 22.94 | 1.23 | 0.98 | 0.95 | 0.81 | 0.82 | 0.97 | 0.99 | 0.97 | 0.87 | 0.89 | 0.98 | 1.03 | 1.11 | 1.43 | 1.39 | 1.07 |
| 125N05834 | 0.21 | 0.62 | 0.85 | 0.23 | 37.56 | 1.38 | 0.97 | 1.06 | 1.30 | 1.26 | 1.07 | 0.81 | 0.82 | 0.84 | 1.01 | 1.00 | 1.17 | 1.52 | 2.45 | 1.94 | 1.26 |
| 125N08947 | 0.31 | 0.48 | 0.55 | 0.07 | 14.34 | 1.14 | 1.03 | 0.99 | 0.74 | 0.71 | 0.96 | 1.02 | 0.99 | 0.79 | 0.77 | 0.97 | 1.02 | 1.05 | 1.24 | 1.20 | 1.02 |
| 125N12201 | 0.24 | 0.60 | 0.79 | 0.19 | 27.29 | 1.27 | 0.83 | 0.81 | 0.73 | 0.98 | 1.00 | 0.79 | 0.79 | 0.80 | 1.10 | 1.02 | 0.99 | 1.07 | 1.32 | 1.46 | 1.10 |
| 125N12232 | 0.19 | 0.32 | 0.42 | 0.10 | 31.61 | 1.32 | 1.00 | 0.96 | 0.84 | 0.82 | 0.96 | 1.08 | 1.10 | 1.17 | 1.10 | 1.02 | 1.14 | 1.19 | 1.33 | 1.16 | 1.04 |
| 125P04957 | 0.38 | 0.32 | 0.34 | 0.02 | 7.57 | 1.08 | 1.01 | 1.01 | 1.11 | 1.10 | 1.01 | 1.00 | 1.01 | 1.08 | 1.08 | 1.01 | 0.99 | 1.00 | 1.14 | 1.15 | 1.01 |
| 125P05832 | 0.50 | 0.64 | 0.75 | 0.11 | 16.59 | 1.17 | 0.96 | 0.93 | 0.81 | 0.86 | 0.98 | 0.94 | 0.95 | 1.01 | 1.08 | 1.01 | 1.03 | 1.38 | 3.41 | 3.08 | 1.30 |
| 125P05834 | 0.20 | 0.64 | 0.95 | 0.31 | 45.74 | 1.46 | 0.91 | 0.91 | 0.91 | 1.02 | 1.01 | 0.97 | 0.98 | 0.99 | 1.04 | 1.01 | 1.13 | 1.21 | 1.38 | 1.22 | 1.07 |



## 5.2 Corridor-Level Analysis

To compare the overall effect of LRT on TTR measures from a multimodal perspective, cumulative frequency diagrams were plotted at an aggregate level. Considering the cumulative distribution of travel times in a corridor is useful for analyzing the variations in travel times. It helps visualize the travel time trends for multiple time periods in a single graph. Most importantly, it provides the magnitude of travel times along with the distribution of travel times in a specific time period. The variability in travel times can be visualized and interpreted from the cumulative distribution function for travel time. Data normalization was carried out by dividing the travel time by the length of each link.

### *5.2.1 Effect on the Study Corridor (N Tryon St)*

The cumulative distribution of travel times per mile for N Tryon St during the analysis period is shown in Figure 20. The cumulative distribution of travel times along N Tryon St showed a similar pattern, but the central tendency shifted during different time periods. For example, in the morning peak hour, there is little difference in travel time along the study corridor for different phases of LRT operation. A shift in the cumulative travel times can be seen in the afternoon, specifically while looking into the twelfth month of LRT operation. Similarly, an improvement in travel times can be seen in the evening peak hour after the LRT was opened for complete service. The median travel time ranges from 1.5–2.5 minutes/mile in all the selected hours of analysis.

### *5.2.2 Effect on the Parallel Route (I-85)*

A corridor-level analysis was also performed for the I-85 parallel route (Figure 21). The travel time distributions for morning peak hour substantiate the results obtained from the link-level analysis. The $50^{th}$ percentile travel time is found to be approximately one minute/mile in all the selected scenarios. However, an overall shift in distribution was also observed beyond the 50th percentile normalized travel time for morning and evening peak periods. A deterioration in the PT or the 95th percentile travel time as well as buffer measures (the difference between ATT and PT) was observed, similar to observations in the link-level analysis. However, a shift in travel time distribution was observed beyond the 50th percentile during the morning and evening peak hours. The travel time is observed to be at a minimum before opening of the LRT for service. Overall, the results obtained indicate that the parallel route (I-85), a freeway, is more reliable for daily commutes and is still the first-choice preference for daily commutes in the study region.

*5.2.3 Effect on the Near Vicinity Cross-streets*

The results obtained for the cross-street analysis are shown in Figure 22. The travel time distribution for cross-streets follows a similar pattern during the morning peak and afternoon peak hours. The corridor-level travel time is at a minimum for the twelfth month of LRT operation when considering the morning peak hour. The median travel time ranges from 1.5 to 2 minutes/mile in the morning, afternoon, and evening peak periods, whereas the median travel time during the evening is ~one minute/mile. The high dispersion (high variability) in the distribution can be observed in all the selected scenarios.

One point that arises from the corridor-level analysis is the difference in morning and evening peak commutes in the study region. In general, there is a significant difference in travel time patterns between the morning peak and evening peak. In Charlotte, North Carolina, the majority of people seeking to travel during rush hours use personal cars. In general, the peak evening commute happens between 3:00 PM and 7:00 PM. Based on working hours, an uneven trip distribution is possible during this entire peak period, rather than commuters favoring a single peak hour. Besides, the variations in normalized travel times were observed to be minimal during 12:00 PM – 1:00 PM and 8:00 PM – 9:00 PM for the selected categories of roads in the TTR assessment.

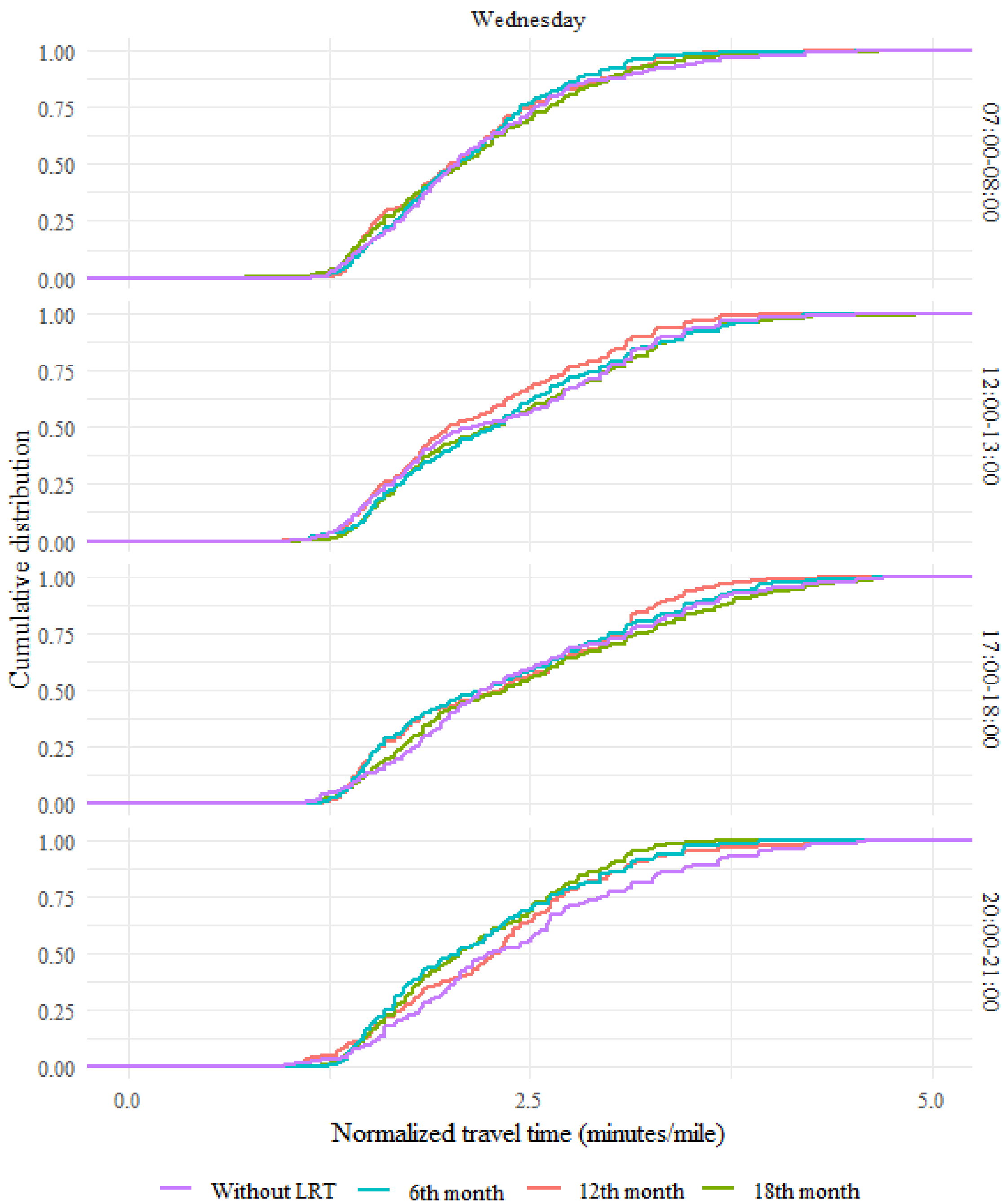



Figure 20. Cumulative Distribution of Travel Times: N Tryon St

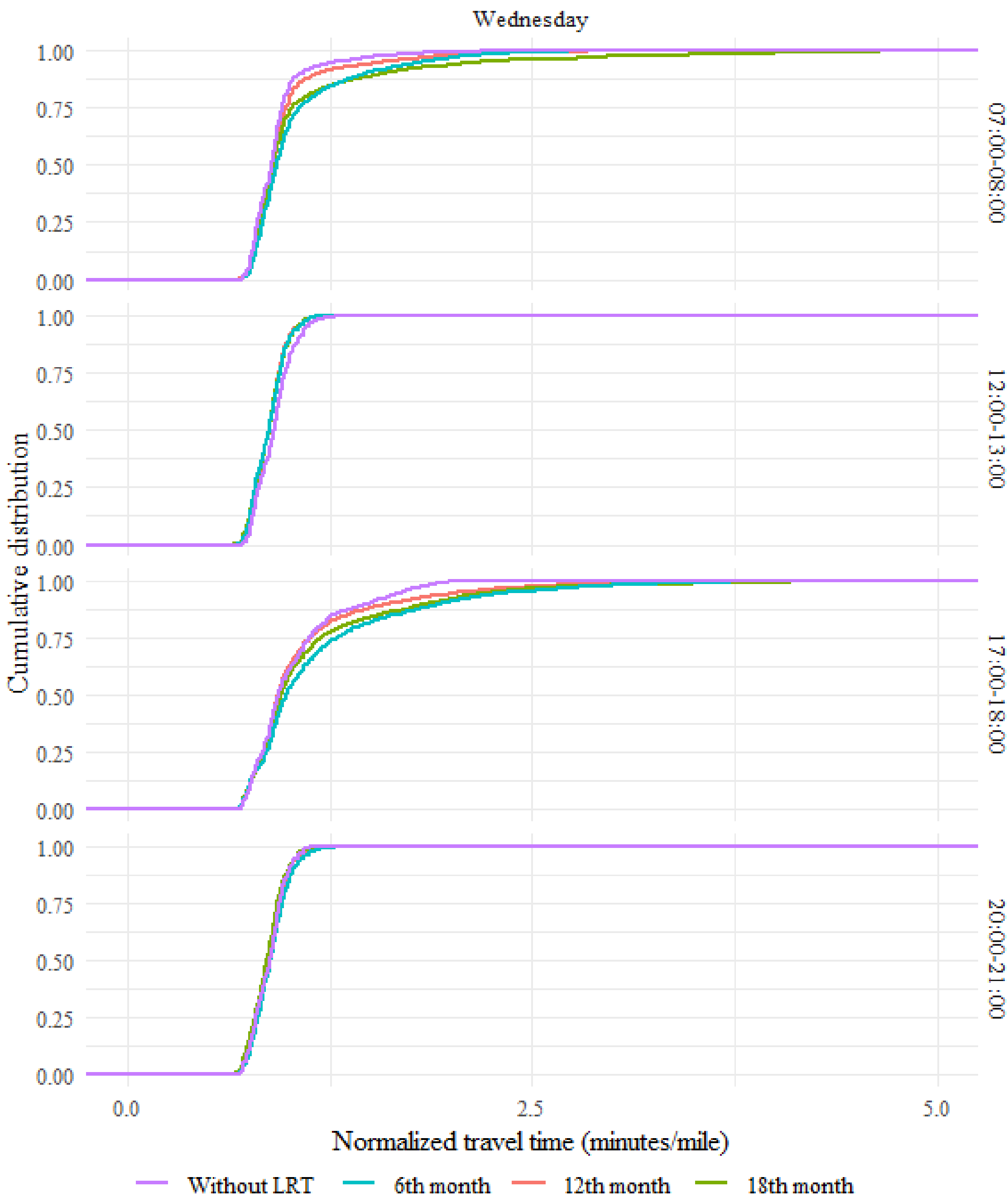



Figure 21. Cumulative Distribution of Travel Times: I-85 Parallel Route

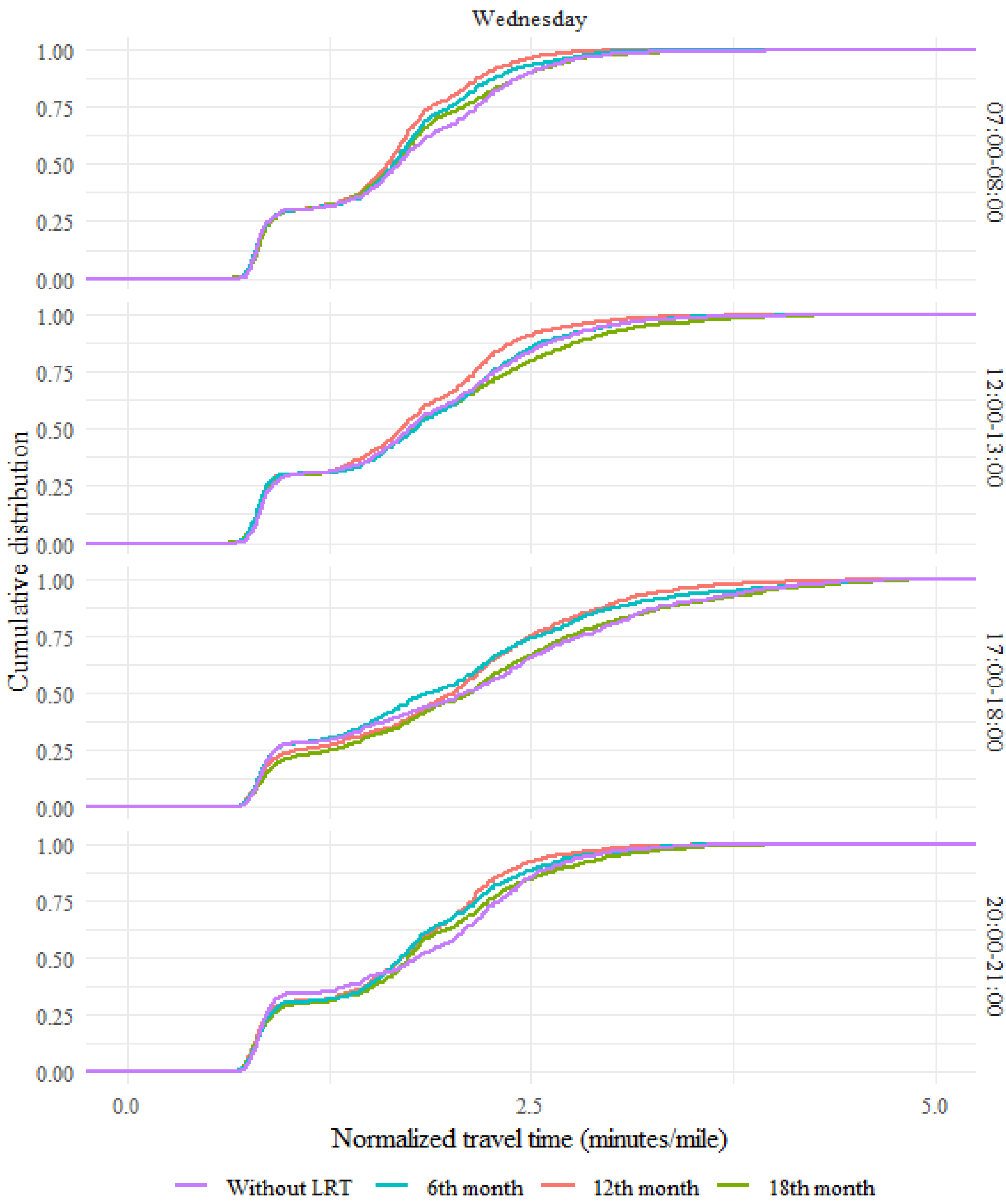



Figure 22. Cumulative Distribution of Travel Times: Near Vicinity Cross-streets

5.2.4 Testing the Statistical Significance

To understand the statistical significance of changes in TTR measures (ATT, PT, BT, BTI, and PTI), a paired t-test analysis was conducted at a 95% confidence level. Generally, the one-tail paired t-test is used for before-and-after comparisons of the same subject matter. The null hypothesis is H0: TTR measure remained the same during a phase of LRT operation compared to the network without the LRT (for example, BT for a network without LRT minus BT for the testing phase of LRT is equal to 0). The alternate hypothesis is H1: TTR measure decreased during a phase of LRT operation (for example, BT for a network without LRT minus BT for the testing phase of LRT is less than 0). The mathematical representations of the null and alternate hypotheses are shown as equations 5 and 6.

$$H_0\colon TTR_d = 0 \tag{5}$$

$$H_1\colon TTR_d < 0 \tag{6}$$

In these equations, $TTR_d$ is the difference in the selected TTR measure over different phases of LRT operation compared to the network without LRT.

The test results for the entire study area are summarized in Table 9. The statistical significance of the variations in travel time performance measures was found to be particularly less in the case of N Tryon St with LRT). The results obtained are insignificant in majority of cases in the morning and evening peak periods. Moreover, there exists a statistically significant improvement in TTR during the afternoon and evening in the study corridor in different phases of LRT operation. It can be considered as a good indication as there is an improvement in the TTR during different phases of LRT operation in the N Tryon St after opening LRT for complete service. A balance between the travel time lost due to frequent lane closures and the benefits associated with the parallel route choice for commuters may be considered as the reason behind such a result.

While looking into the parallel route, as observed in the link-level and corridor-level analysis, there is a clear trend of a worsening in TTR. In most cases, there is a statistically significant worsening in TTR at a 95% confidence level. In the case of cross-street links, the change in reliability is found to be marginal compared to the parallel route. While considering the morning peak hour, PTI showed statistically significant deterioration in all the LRT operation scenarios

Table 9. Results: Statistical Analysis

| TTR measure | Scenario | Study Corridor | | | | Parallel Route | | | | Near Vicinity Cross-streets | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | M | A | E | N | M | A | E | N | M | A | E | N |
| ATT | Network without LRT: Sixth month of operation | 0.25 | 0.06 | 0.39 | < 0.05 | < 0.05 | 0.25 | 0.11 | 0.17 | 0.05 | < 0.05 | < 0.05 | 0.05 |
| | Network without LRT: Twelfth month of operation | 0.23 | < 0.05 | 0.26 | < 0.05 | < 0.05 | < 0.05 | < 0.05 | < 0.05 | < 0.05 | < 0.05 | < 0.05 | < 0.05 |
| | Network without LRT: Eighteenth month of operation | 0.33 | 0.16 | 0.30 | < 0.05 | < 0.05 | < 0.05 | < 0.05 | < 0.05 | 0.45 | < 0.05 | 0.11 | 0.45 |
| PT | Network without LRT: Sixth month of operation | 0.42 | < 0.05 | 0.32 | < 0.05 | 0.15 | < 0.05 | 0.08 | < 0.05 | 0.25 | 0.08 | 0.47 | 0.25 |
| | Network without LRT: Twelfth month of operation | 0.28 | < 0.05 | 0.23 | < 0.05 | < 0.05 | < 0.05 | < 0.05 | 0.44 | < 0.05 | < 0.05 | 0.25 | < 0.05 |
| | Network without LRT: Eighteenth month | 0.42 | 0.26 | 0.10 | < 0.05 | < 0.05 | < 0.05 | < 0.05 | < 0.05 | 0.06 | 0.16 | < 0.05 | 0.06 |
| BT | Network without LRT: Sixth month of operation | 0.37 | < 0.05 | 0.31 | < 0.05 | 0.19 | < 0.05 | 0.07 | < 0.05 | 0.43 | 0.19 | 0.22 | 0.43 |
| | Network without LRT: Twelfth month of operation | 0.39 | < 0.05 | 0.30 | < 0.05 | < 0.05 | < 0.05 | < 0.05 | < 0.05 | < 0.05 | 0.16 | 0.06 | < 0.05 |
| | Network without LRT: Eighteenth month | 0.11 | 0.33 | < 0.05 | < 0.05 | < 0.05 | < 0.05 | < 0.05 | < 0.05 | < 0.05 | 0.16 | < 0.05 | < 0.05 |
| BTI | Network without LRT: Sixth month of operation | 0.06 | 0.21 | 0.48 | < 0.05 | 0.17 | < 0.05 | < 0.05 | < 0.05 | 0.15 | 0.29 | 0.45 | 0.15 |
| | Network without LRT: Twelfth month of operation | 0.43 | < 0.05 | 0.50 | < 0.05 | < 0.05 | < 0.05 | < 0.05 | < 0.05 | < 0.05 | 0.22 | < 0.05 | < 0.05 |
| | Network without LRT: Eighteenth month | < 0.05 | 0.05 | < 0.05 | 0.06 | < 0.05 | < 0.05 | < 0.05 | < 0.05 | < 0.05 | < 0.05 | < 0.05 | < 0.05 |
| PTI | Network without LRT: Sixth month of operation | 0.06 | 0.21 | 0.48 | < 0.05 | 0.17 | < 0.05 | < 0.05 | < 0.05 | 0.15 | 0.29 | 0.45 | 0.15 |
| | Network without LRT: Twelfth month of operation | 0.43 | < 0.05 | 0.50 | < 0.05 | < 0.05 | < 0.05 | < 0.05 | < 0.05 | < 0.05 | 0.22 | < 0.05 | < 0.05 |
| | Network without LRT: Eighteenth month | < 0.05 | 0.05 | < 0.05 | 0.06 | < 0.05 | < 0.05 | < 0.05 | < 0.05 | < 0.05 | < 0.05 | < 0.05 | < 0.05 |

Notes: Grey shaded cells indicate worsening at a 95% confidence level. M: morning peak (7:00 AM–8:00 AM), A: afternoon (12:00 PM–1:00 PM), E: evening peak (5:00 PM–6:00PM), N: nighttime (8:00 PM–9:00 PM)

# CHAPTER 6: SIMULATION-BASED ASSESSMENT RESULTS

The results from simulation-based assessment are discussed in this chapter.

## 6.1 Vissim model development

Maps were used in the background of Vissim to build the model and replicate the geographical offsets between traffic signals. The cross-streets, however, were modeled only for relatively shorter lengths, as the influence on N Tryon St was the focus of this research.

The signals at all the intersections are RBC type, which allows the designers to design different phase timings for each intersection during different times of the day. As discussed earlier, the pedestrian activity is considerably higher at three intersections, Institute Cir, JW Clay Blvd, and J M Keynes Dr, compared to the other intersections on the study corridor. Pedestrian crosswalks are available at all the signalized intersections along the corridor with provision for pedestrian signal timing as well. The pedestrian signal is phased such that pedestrians' movement is parallel to the traffic to avoid movement conflicts.

The LRT is designed to run parallel to N Tryon St, and it is segregated as a public transit line, which helps differentiate it from regular vehicular traffic. This also allows the modeler to assign traffic signal priority to the LRT by placing detectors at each at-grade intersection. While this is advantageous to the through and right-turning movements that run parallel to the LRT system on N Tryon St, the vehicles on the cross-streets experience added delays and difficulties, as they also have to yield to the pedestrians crossing N Tryon St in the given green time. This might also mean that the pedestrians crossing N Tryon St must wait for two cycles to cross safely sometimes.

The priority rules were defined such that any right-turning vehicle will have to yield to through traffic at an intersection. Pedestrians were given priority over vehicles and bicycles for simulating traffic conditions using the Vissim traffic simulation software.

The turning movement count data obtained from the CDoT were balanced using the macro file developed by the WsDOT. There are 20 locations with vehicle inputs in the network.

Input parameters such as the vehicular volumes were allocated at each cross-street and each end of the study corridor. Based on the balanced vehicular volumes, the routes were allocated from each major route. Based on the percentage of the allocated route, the percentages and their corresponding origin and destinations were input. The three major intersections (University City Blvd, E WT Harris Blvd, and E Mallard Creek Church Rd) were taken as control points for assigning the “static vehicle routes” in Vissim. The vehicle compositions were allocated as 3% heavy vehicles (trucks and buses) and 97% cars (with most of the cars in the sedan class).

To reflect the speeds of the vehicles in the arterial corridor, travel time and speed data were used to generate cumulative distribution function curves (S-curves) and are reflected in the speed distribution of the vehicles. The desired speed distributions were allocated by the direction of travel (southbound and northbound) in the Vissim traffic simulation software.

## 6.2 Calibrating the model and validation

Simulation models were generated using Vissim for 2018 analytical scenario. The model was calibrated by comparing the simulated number of vehicles and the vehicular volumes input into Vissim. The percentage differences were observed to be less than 15%. Visual observations were used to ensure that the model would run as expected in the field. These observations were also used to build nodes for capturing data for each approach and at intersection levels.

The results presented are for the evening peak period (4:00 PM – 7:00 PM). The simulation is set to run for a total of 75 minutes, of which the last 60 minutes are considered to generate outputs. The evening peak hour had the worst vehicular traffic in the study corridor. Hence, the operational performance in the study corridor was only analyzed during the evening peak period. They were generated using five different random seed numbers. The average of the five random seed numbers was used for tabulations and interpretations.

The vehicular volumes observed versus the vehicular volumes expected by the data collection points for the initial model (2018) is used to validate the model. Validation using vehicular volumes ensures that the static vehicle routes provided in the network are performing as expected based on field observations. In addition, the model is also validated by using the travel times at the link level. The entire simulation network has its links divided into four links – two in the northbound direction and two in the southbound direction. The ATT during the evening peak hour for these links are compared with the travel time for the observed vehicles in the simulation. The values were checked, and multiple calibration parameters were tweaked to set the model which would give desirable travel times. The final calibration parameters used to develop the calibrated model are summarized in Table 1. The volume validation for Scenario 1 and travel times for four links are shown in Table A2 (appendix). The simulation volumes for Scenario 1 were found to be within 5% of the observed volume in the corridor. Figure 23 shows the aerial image of Scenario 1.

Figure 23 Aerial Image of the Simulation Network in 3D

6.3 Hypothetical scenarios

Several hypothetical scenarios were developed to understand the effect of heterogenous traffic conditions on operational performance of vehicles. They are listed next.

- Vehicular traffic with LRT (Scenario 1)
- Vehicular traffic with LRT and pedestrians (Scenario 2)
- Vehicular traffic with LRT, pedestrians, and bicycles (Scenario 3)
- Increase in vehicular traffic with LRT, pedestrians, and bicycles (Scenario 4)
- Decrease in vehicular traffic with LRT, pedestrians, and bicycles (Scenario 5)
- Vehicular traffic with LRT and increase in pedestrians with bicycles (Scenario 6)
- Change in LRT frequency (Scenario 7 and Scenario 8)

*6.3.1 Vehicular Traffic with LRT*

Based on field observations, the expected wait time for an LRT train to arrive is between 7 and 8 minutes during the peak hour. Therefore, a frequency of 8 is possible in the peak hour with a difference in departure time of 420 seconds between two consecutive LRT departures.

One park and ride facility was available along the study corridor. It is situated at the N Tryon St & JW Clay Blvd intersection. The park and ride facility at this intersection has 800 parking spaces to attract commuters. An increase in pedestrian activity was observed due to the addition of the park and ride facility and the LRT system. To encourage more pedestrian traffic and bicyclists in the area, an additional five feet of on-street bicycle lanes were also added along the shoulder on N Tryon St along with provision for scooters at the pedestrian waiting areas at intersections. However, pedestrian activity and bicyclist activity were ignored in this scenario. Only LRT trains were assumed to operate in this scenario.

*6.3.2 Vehicular Traffic with LRT and Pedestrians*

After the LRT came into operation, the pedestrian counts increased significantly at some intersections. With a park and ride facility of over 800 parking spaces at N Tryon St & JW Clay Blvd intersection and several residential communities being situated within a half-mile radius of the LRT stations, the pedestrian counts at Institute Cir, JW Clay Blvd, and J M Keynes Dr intersections were affected. Also, there are transit bus stops within the close vicinity (a half-mile) of the LRT stations, driving the pedestrian counts to go up further, as expected. The pedestrian counts were collected 45 days after the LRT came into operation. Additional pedestrian data were collected using count boards at selected intersections for every 15-minute interval during the morning and evening peak hours. This data was collected in November 2018, which is about eight months after the LRT came into operation, to capture any missing numbers.

While collecting pedestrian data at the selected intersections, it was observed that most of the pedestrians follow a platoon movement, possibly because the pedestrian crossing is driven by the train timings. It was also observed that there is minimal to no signal timing preemption for pedestrians. The pedestrians typically use the same green time assigned to the vehicular movement. There is no mid-block or unsignalized crosswalks along the study corridor. Multiple models were developed with the CDoT data, observed pedestrian data, and extrapolated pedestrian data at the selected intersections to evaluate the effect of pedestrian activity on transportation system performance.

Pedestrian waiting area and pedestrian boarding/ alighting LRT is only located at McCullough station and JW Clay station. Pedestrian waiting area is added to the model. Due to the unavailability of pedestrian boarding/ alighting data, the boarding/ alighting data was fed into the model based on the assumed values. But these values do not tend to change the operational performance characteristics that are intended to be captured in the model.

*6.3.3 Vehicular Traffic with LRT, Pedestrians and Bicycles*

No data were previously recorded dedicated to bicycle counts. The only bicycle data available came through the observations made during pedestrian data collection. Though on-street bicycle lanes were constructed in the year 2018, bicycle counts along the corridor were minimal. These counts were mostly observed at the intersections. The bicyclists were observed to use the green time assigned to the vehicle movement and pedestrians. Multiple models were developed in the research with the observed and extrapolated bicyclist count data at the selected intersections to evaluate the effect of bicyclist activity on transportation system performance.

*6.3.4 Increase in Vehicular Traffic with LRT, Pedestrians, and Bicycles*

A hypothetical scenario with an increase in the vehicular volume by 15% was developed. The pedestrian counts and bicycle counts were kept same as of the previous scenario. This scenario is used to check the effect of change in the vehicle delay due to an increase in the vehicular volume. Simultaneously, the operational performance of pedestrians is also checked due to the increase in vehicular volume.

*6.3.5 Decrease in Vehicular Traffic with LRT, Pedestrians, and Bicycles*

Due to the increase in the multi-modal activity, there could be a shift in the user behavior toward public transportation system. This would lead to a decrease in the vehicular traffic. A hypothetical scenario with decrease in the vehicular volume by 15% was developed. The pedestrian counts and bicycle counts were kept same as of the previous scenario. This scenario is used to check the effect of change in the vehicle delay due to a decrease in the vehicular volume. Simultaneously, the operational performance of pedestrians is also checked due to the decrease in vehicular volume.

*6.3.6 Vehicular Traffic with LRT and Increase in Pedestrians and Bicycles*

A hypothetical scenario with an increase in pedestrian and bicycle activity were developed in this scenario by keeping the vehicular volume constant. The pedestrian and bicycle volumes were increased by 100% in the third hypothetical scenario. This scenario is used to check a further increase in pedestrian and bicycle activity on the operational performance of vehicles. Simultaneously, the operational performance of pedestrians and bicycles are also examined.

The study area has no mid-block locations with pedestrian crossings and bicycle activity due to higher speed limits. But there are few locations which have a conflicting movement for vehicles with pedestrians and bicycles (particularly at residential complexes and shuttle bus stations). However, the data and its effect on intersection performance measures was minimal.

### *6.3.7 Change in LRT Frequency*

A change in LRT frequency can affect the operational performance of the corridor and at an intersection level. The operational performance of vehicles based on the turning movement at the intersection is captured and the movements which benefit from the transit signal priority are focused on. Along with the improvement of operations, there could be change in safety at the intersections. Hence for only this scenario, along with performing SSAM, the types of collisions are also analyzed (rear-end, sideswipe or angle collisions).

## 6.4 Results from Simulation-based Analysis

The operational performance of vehicles is captured using vehicle delay, queue length, queue length (max), level of service (LOS), and average walking speed of pedestrians at the intersection. The pedestrian performance is captured by evaluating performance of the pedestrian areas. Pedestrian LOS could not be captured, but the walking speed of pedestrians along with total number of stops for all the pedestrians are captured. The average walking speed for pedestrians and total number of stops are compared between all the scenarios to identify the effect of an increase in heterogeneous traffic conditions on pedestrians. Although bicycles were also in the simulations, the bicycle volumes are low. The operational performance of bicycles was not captured. Also, the presence of bicycles did affect the operational performance of vehicles.

### *6.4.1 Vehicle Delay*

The vehicle delay is captured at an intersection level. Figures 24 to 30 show the delay at corridor level at all the links. The figures show the effect of increase/decrease in vehicle delay at upstream/ downstream intersections. Also, the segments in the figures with no color indicate that there is no vehicle going on at the time of the simulation run when the network performance was captured. The segments are classified into three categories with average vehicle delays ranging from 0.-

25.00, 25.01-60.00, >60.01. It should be noted that the evaluation is based on the spot vehicular volumes. The snapshots, hence, are taken exactly at 3600 seconds of the simulation run for all scenarios.

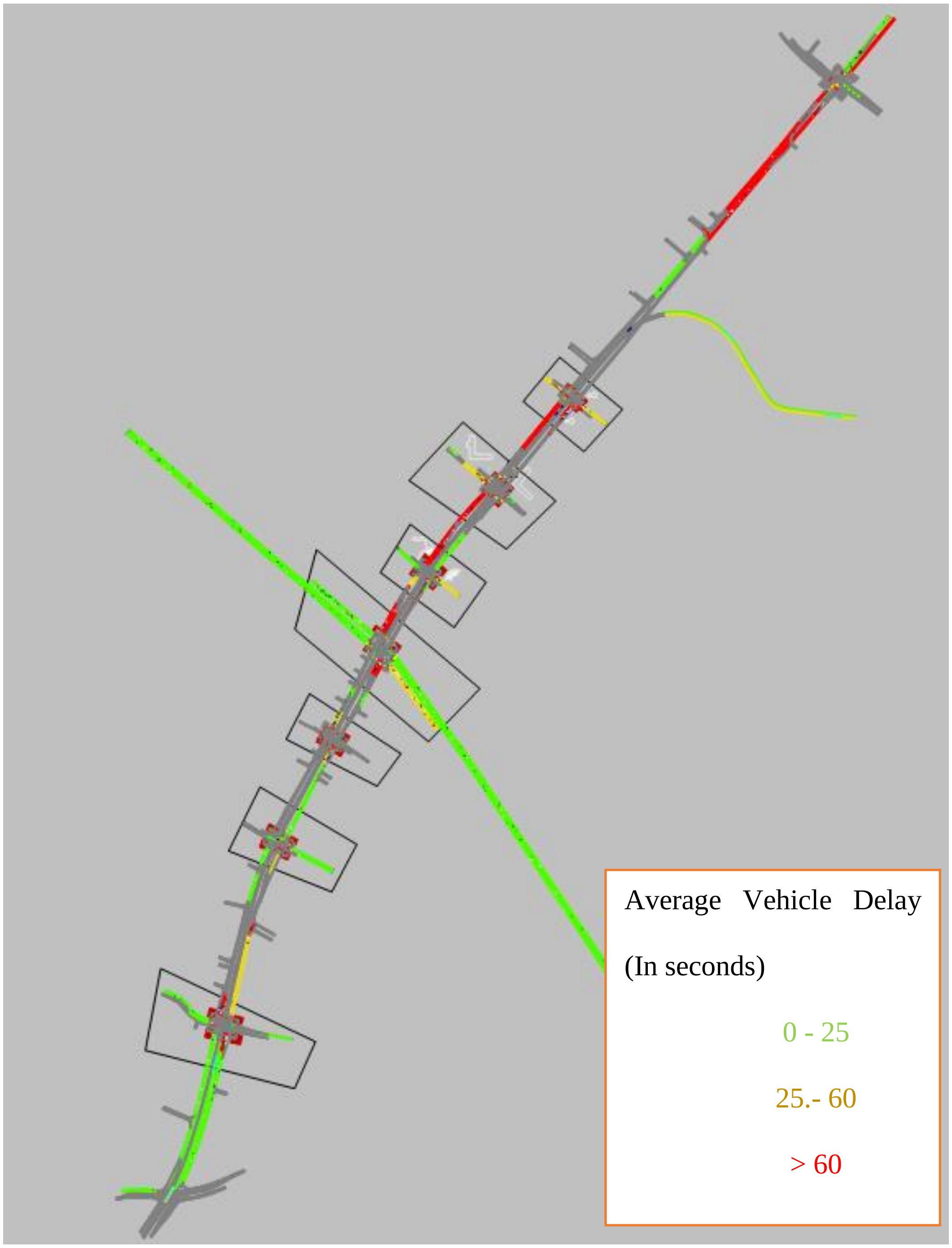



Figure 24 Vehicle Delay at a Corridor level - Vehicles + LRT (Frequency 8)

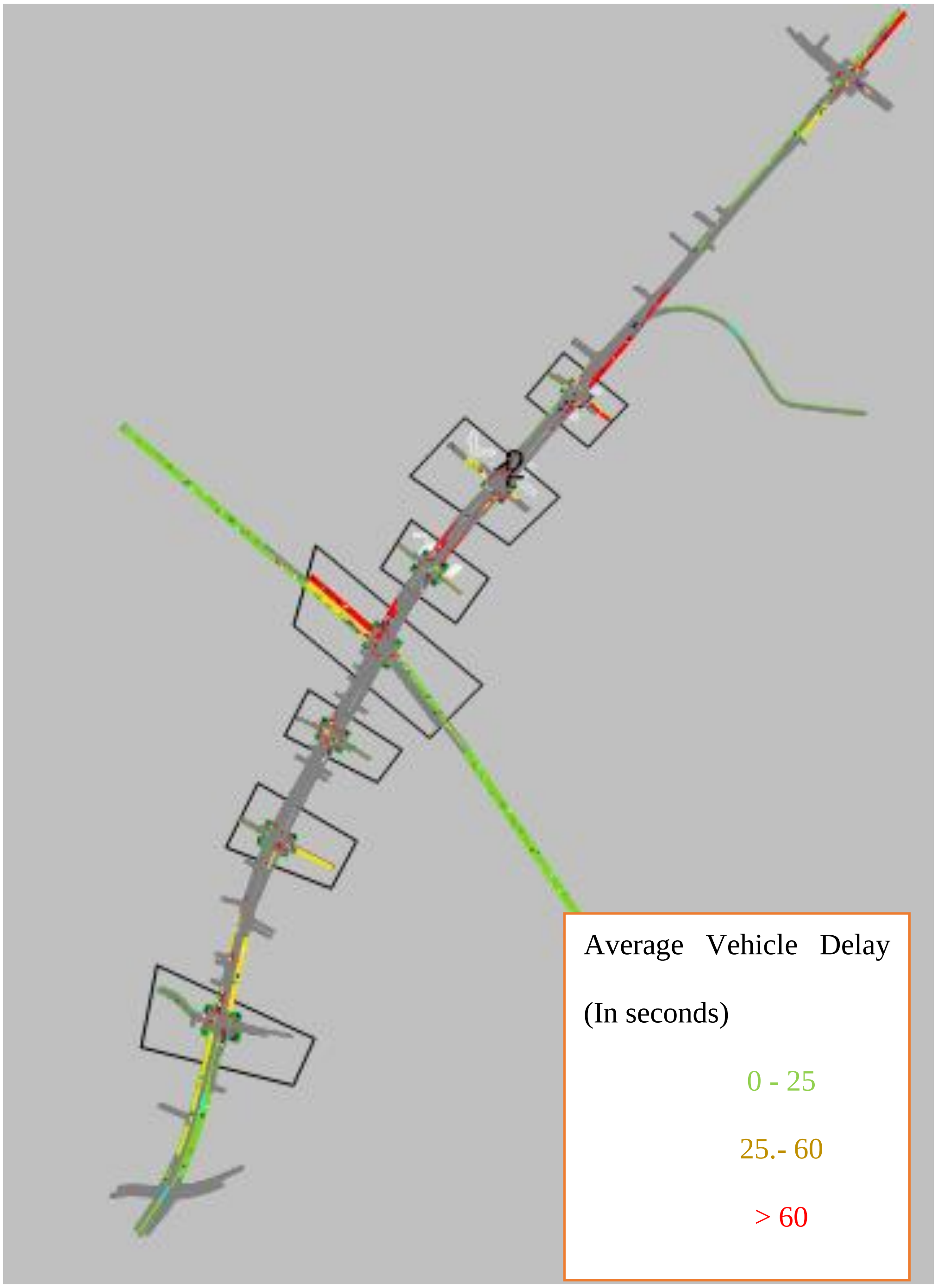



Figure 25 Vehicle Delay at a Corridor level: Vehicles + Pedestrians and Bicycles

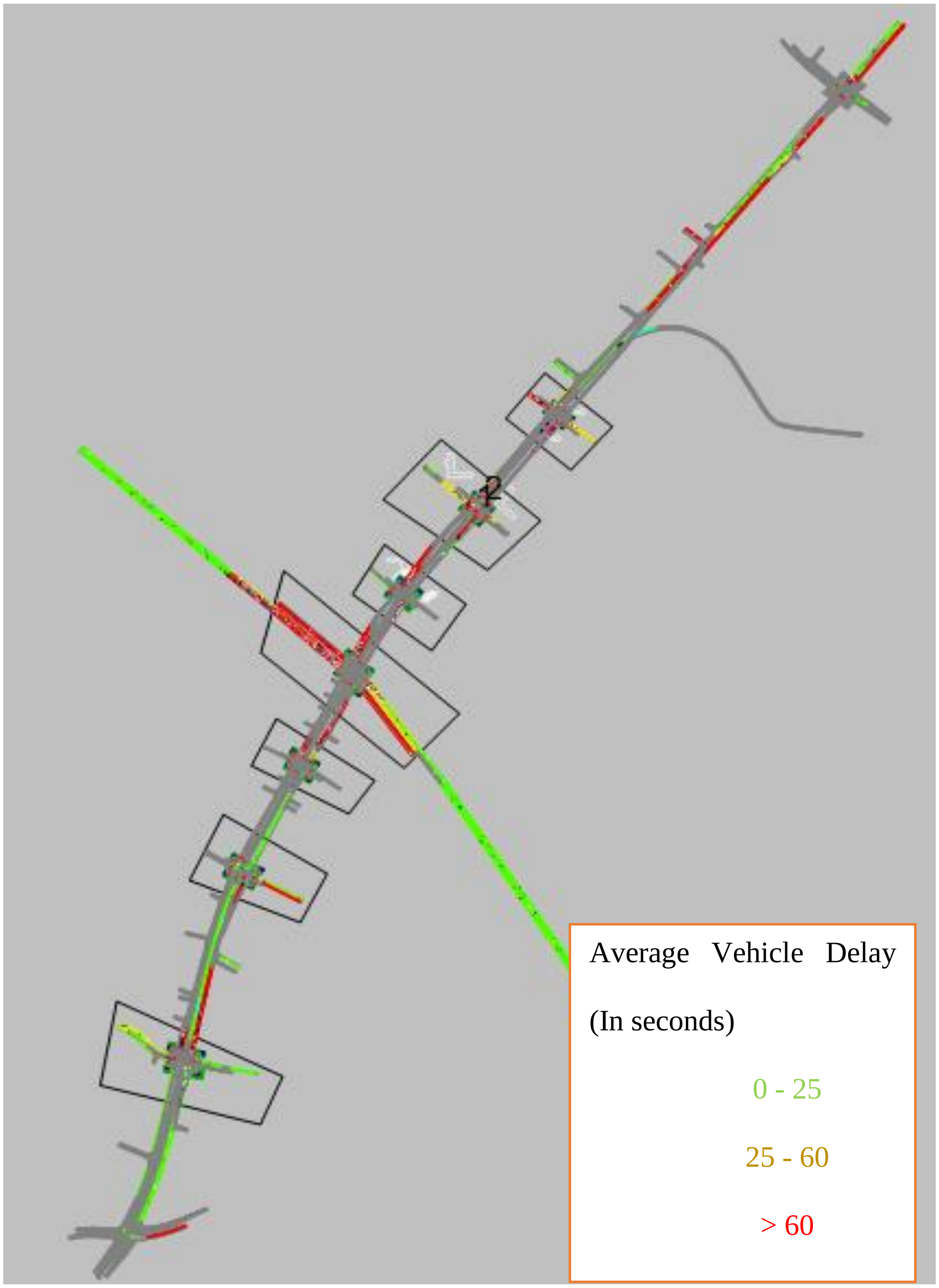



Figure 26 Vehicle Delay at a Corridor level: (Vehicles +15%) + Pedestrians and Bicycles


Figure 27 Vehicle Delay at a Corridor level: (Vehicles -15%) + Pedestrians and Bicycles

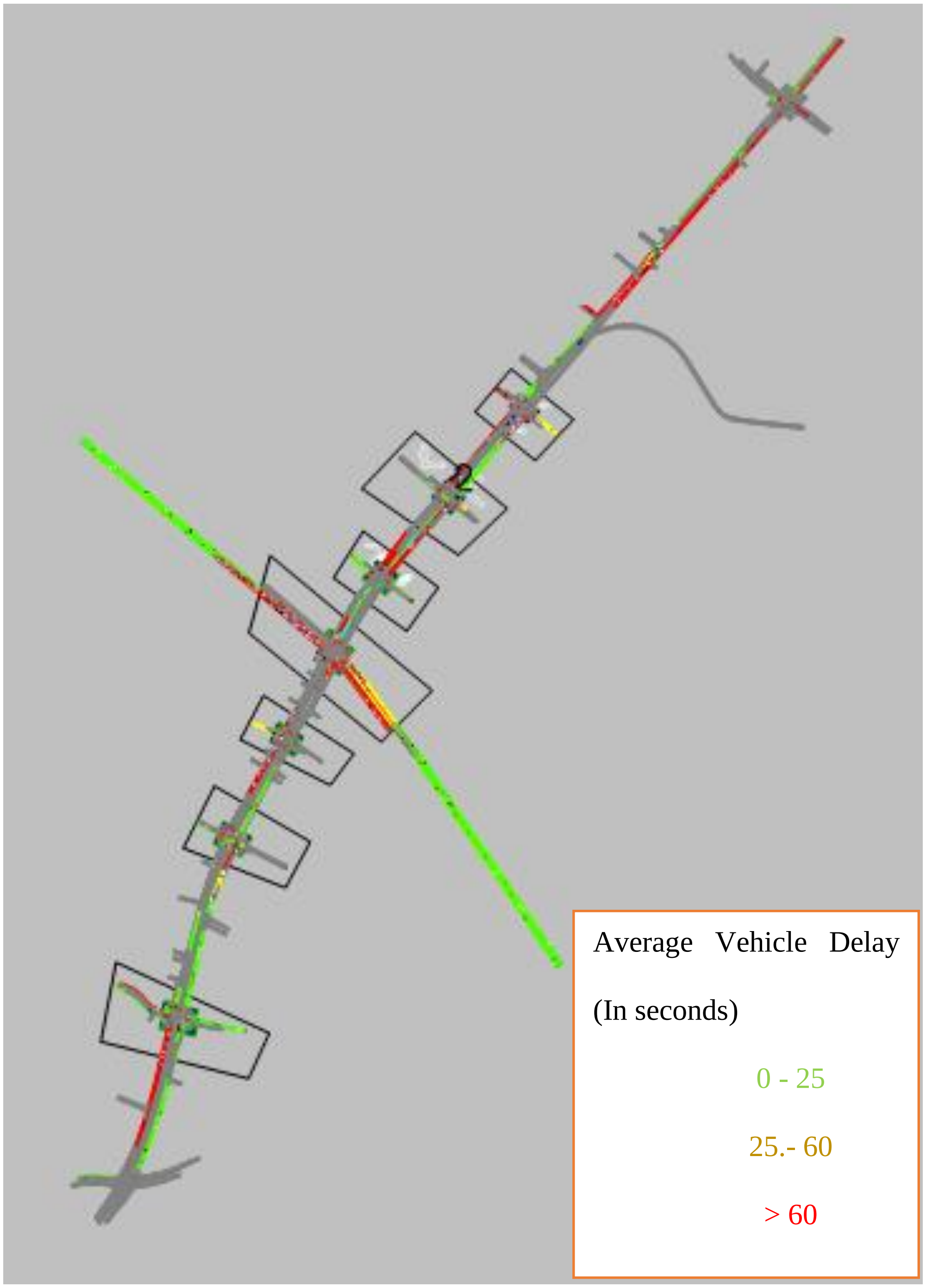



Figure 28 Vehicle Delay at a Corridor level: Vehicles + Pedestrians and Bicycles (Increase)

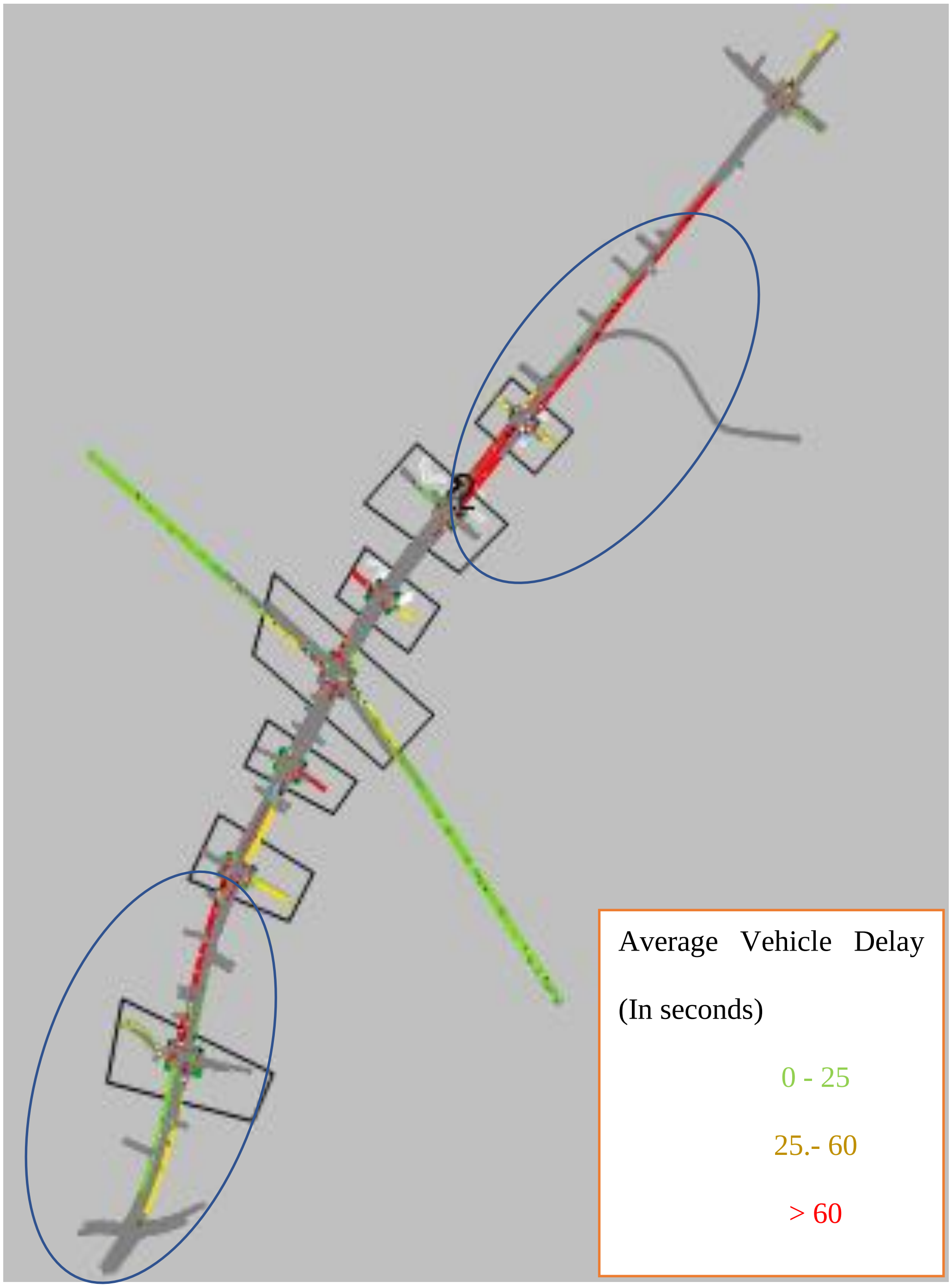



Figure 29 Vehicle Delay at a Corridor level: 6 LRT Frequency

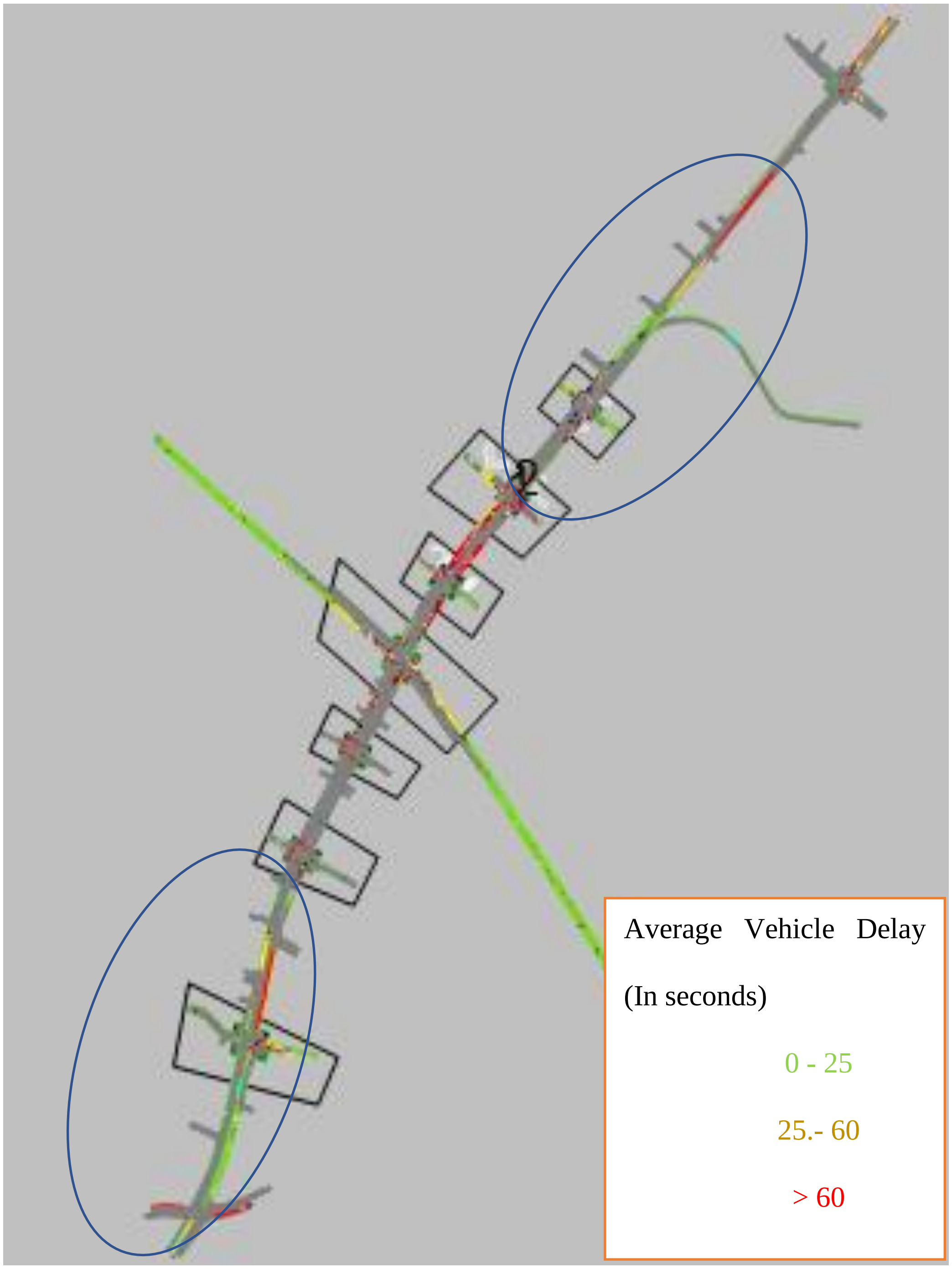
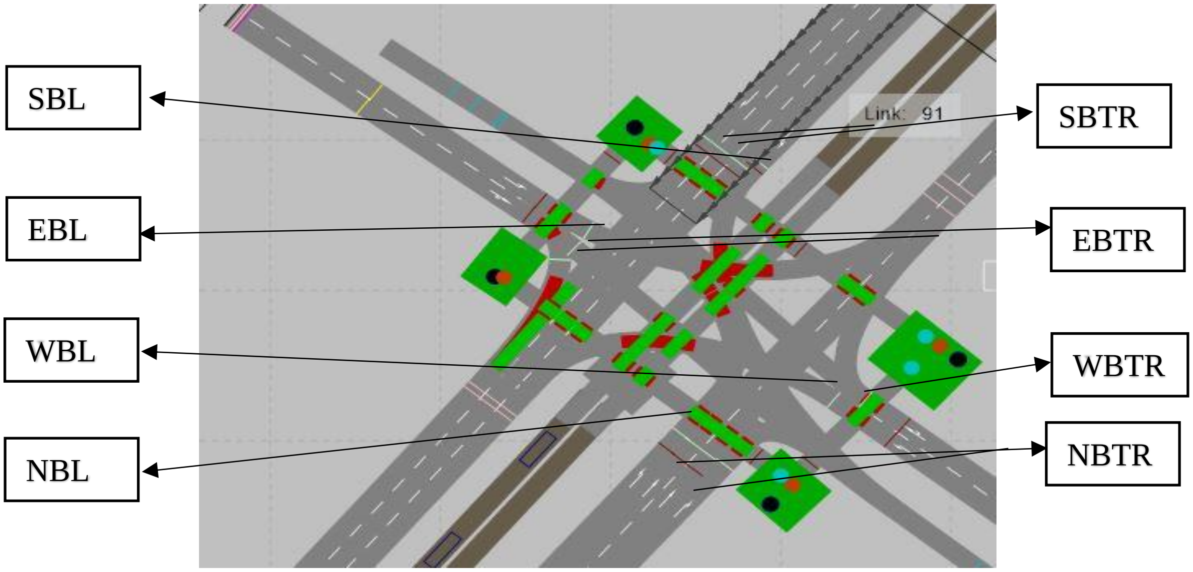



Figure 30 Vehicle Delay at a Corridor level: 10 LRT Frequency

The observations at a corridor level indicate that as heterogeneous conditions increase, there has been an increase in vehicle delay at few intersections. It can be observed that the delay on cross-streets could not be observed due to the absence of vehicles when the network performance is evaluated. But, on the other hand, the vehicle delay decreased with an increase in LRT frequency on the study corridor (as shown in Figure 26 and Figure 27). A comparison between Figure 24 and Figure 26 shows that the links within the nodes have a deteriorated performance (green to yellow (or) yellow to red) with pedestrian and bicycle activity. A comparison between Figure 25 and Figure 28 shows similar tends (increase in the vehicle delay) with an increase in vehicles within the nodes. A comparison of Figure 29 and Figure 30 shows the operational performance of vehicles with the change in LRT frequency. The marked locations in Figure 29 and Figure 30 show that the operational performance along the study corridor improved with an increase in LRT frequency. Also, it can be seen that no significant change in operational performance of vehicles is observed at at-grade intersections (E WT Harris Blvd and University City Blvd on N Tryon St).

The feature of link evaluation based on delay for vehicles show that the delay is varying at the corridor level. But it is important to address a few questions that will arise from the visual depiction, like 1) the data for a scenario provided is consistent, 2) increase/decrease in vehicle delay at a different intersection due to the added congestion at an upstream link/intersection, and 3) delay by the turning movement (parallel to LRT and against LRT movement), along the study corridor and cross-streets. To address these concerns, each scenario is run with five random seeds providing different outputs for operational performance. The average delay for all the five runs is used in the analysis. The delay is captured by the turning movement of the vehicles at the intersection as shown in Figure 31. Table 10 to Table 16 summarize the delay by turning movement counts for all the scenarios.




**Notes:** NBT-Northbound Through Right, SBTR-Southbound Through Right, EBTR-Eastbound Through Right, WBTR-Westbound Through Right, NBL- Northbound Left, SBL-Southbound Left, EBL-Eastbound Left, WBL-Westbound Left

Figure 31 Vehicle Delay by Turning Movement at an Intersection

Table 10. Delay by Turning Movement - Vehicular Traffic with LRT
(In seconds)

| Study Corridor (N Tryon St) Approaches | | | | | |
|---|---|---|---|---|---|
| Intersection 1 | Intersection 2 | NBTR | NBL | SBTR | SBL |
| Mallard Creek Ch Road | Institute Cir | | | 37.17 | 36.98 |
| Institute Cir | JW Clay Blvd | 50.98 | 85.57 | 47.95 | 47.14 |
| JW Clay Blvd | J M Keynes Blvd | 35.79 | 18.69 | 27.15 | 69.59 |
| J M Keynes Blvd | E WT Harris Blvd | 32.94 | 32.94 | 27.22 | 27.22 |
| E WT Harris Blvd | Ken Hoffmann Dr | 19.12 | N/A | 27.43 | 34.98 |
| Ken Hoffmann Dr | McCullough Dr | 29.3 | 59.77 | 1.67 | 0.25 |
| McCullough Dr | University Pointe Blvd | 26.55 | 30.62 | 23.36 | 38.91 |
| University Pointe Blvd | University City Blvd | 31.95 | 52.97 | | |
| Cross-street Approaches | | | | | |
| Intersection | | EBTR | EBL | WBTR | WBL |
| Institute Cir | | 66.5 | 84.14 | 79.27 | 68.98 |
| JW Clay Blvd | | 26.2 | 42.06 | 28.8 | 8.91 |
| J M Keynes Blvd | | 59.01 | 58.11 | 47.87 | 51.5 |
| E WT Harris Blvd | | 45.81 | N/A | 36.22 | N/A |
| Ken Hoffmann Dr | | 40.85 | N/A | 3.58 | N/A |
| McCullough Dr | | 10.07 | N/A | 18.54 | N/A |
| University Pointe Blvd | | 12.25 | 13.08 | 29.14 | 19.75 |

**Notes:** NBT-Northbound Through Right, SBTR-Southbound Through Right, EBTR-Eastbound Through Right, WBTR-Westbound Through Right, NBL- Northbound Left, SBL-Southbound Left, EBL-Eastbound Left, WBL-Westbound Left, N/A-Not Available

Table 10 summarizes the delay at the intersections by the turning movement for Scenario 1. The turning movements highlighted in green run parallel to LRT and share additional green time due to transit signal priority for LRT. The turning movements highlighted in yellow are the movements which oppose the LRT movement and have reduced green time during LRT presence. Northbound through and southbound through directions run parallel to the LRT and, hence, they have more green time due to transit signal priority. Majority of the left-turning movements (northbound left and southbound left) on the study corridor have higher delays than through movements at the intersections. The northbound left-turning movement between JW Clay Blvd and J M Keynes Blvd intersections has low vehicular volumes and, hence, has lower vehicle delay than northbound through movement. Some fields are marked “N/A” as number of vehicles in that route and resulting vehicle delay is zero (in the case of southbound left-turning movement between Ken Hoffmann Dr and McCullough Dr intersections) or due to the presence of shared through and left-turning lanes (in the case of all the observations in eastbound left and westbound left directions on cross-streets). The simulation results indicate that low number of left-turning movements had about 35% more delay than the through moving vehicles. The cumulative left-turning movement volumes were found to be 568 compared to 11808 through moving vehicles. But it can be noted that the same vehicle can be recorded multiple times because of the vehicle route for through movement.

While comparing the delays incurred by vehicles on the cross-streets with the study corridor, it can be observed that the vehicles on the cross-streets have incurred more delay compared to vehicles on the study corridor. The through and right-turning movements on the cross-streets at the intersection have been classified into the eastbound through or westbound through movements. The left-turning movements have been classified as eastbound left-turning or westbound left-turning movements. The delay incurred by the vehicles of the left-turning movements along the cross-streets are higher compared to the through and right-turning vehicles except in some cases (like JW Clay Blvd with relatively fewer left-turning vehicles as opposed to through and right-turning vehicles).

Table 11. Delay by Turning Movement - Vehicular Traffic with LRT and Pedestrians
(In seconds)

| Study Corridor (N Tryon St) Approaches | | | | | |
|---|---|---|---|---|---|
| Intersection 1 | Intersection 2 | NBTR | NBL | SBTR | SBL |
| Mallard Creek Ch Road | Institute Cir | | | 40.61 | 54.73 |
| Institute Cir | JW Clay Blvd | 50.77 | 93.36 | 44.65 | 68.14 |
| JW Clay Blvd | J M Keynes Blvd | 34.26 | 20.47 | 26.65 | 65.04 |
| J M Keynes Blvd | E WT Harris Blvd | 32.21 | 32.21 | 25.87 | 25.87 |
| E WT Harris Blvd | Ken Hoffmann Dr | 20.36 | N/A | 27.23 | 37.28 |
| Ken Hoffmann Dr | McCullough Dr | 29.01 | 60.71 | 1.81 | 0.45 |
| McCullough Dr | University Pointe Blvd | 27.01 | 29.14 | 22.19 | 39.2 |
| University Pointe Blvd | University City Blvd | 31.9 | 52.6 | | |
| Cross-street Approaches | | | | | |
| Intersection | | EBTR | EBL | WBTR | WBL |
| Institute Cir | | 82.29 | 99.16 | 61.97 | 63.12 |
| JW Clay Blvd | | 21.15 | 40.71 | 23.83 | 7.26 |
| J M Keynes Blvd | | 60.56 | 51.61 | 46.56 | 45.99 |
| E WT Harris Blvd | | 43.66 | N/A | 39.34 | N/A |
| Ken Hoffmann Dr | | 16.83 | N/A | 6.42 | N/A |
| McCullough Dr | | 10.43 | N/A | 27.5 | N/A |
| University Pointe Blvd | | 18.67 | 12.72 | 27.25 | 21.32 |

**Notes:** NBT-Northbound Through Right, SBTR-Southbound Through Right, EBTR-Eastbound Through Right, WBTR-Westbound Through Right, NBL- Northbound Left, SBL-Southbound Left, EBL-Eastbound Left, WBL-Westbound Left, N/A-Not Available

Table 12. Delay by Turning Movement - Vehicular Traffic with LRT, Pedestrians and Bicycles (In seconds)

| Study Corridor (N Tryon St) Approaches | | | | | |
|---|---|---|---|---|---|
| Intersection 1 | Intersection 2 | NBTR | NBL | SBTR | SBL |
| Mallard Creek Ch Road | Institute Cir | | | 45.77 | 54.72 |
| Institute Cir | JW Clay Blvd | 55.27 | 90.75 | 49.68 | 67.28 |
| JW Clay Blvd | J M Keynes Blvd | 34.82 | 20.74 | 26.74 | 64.6 |
| J M Keynes Blvd | E WT Harris Blvd | 32.18 | 32.18 | 26.53 | 26.53 |
| E WT Harris Blvd | Ken Hoffmann Dr | 20.08 | N/A | 27.25 | 35.71 |
| Ken Hoffmann Dr | McCullough Dr | 29.07 | 60.76 | 1.84 | 0.17 |
| McCullough Dr | University Pointe Blvd | 27.03 | 28.72 | 22.42 | 36.72 |
| University Pointe Blvd | University City Blvd | 32.34 | 52.86 | | |
| Cross-street Approaches | | | | | |
| Intersection | | EBTR | EBL | WBTR | WBL |
| Institute Cir | | 92.34 | 108.81 | 61.97 | 63.2 |
| JW Clay Blvd | | 21.74 | 40.8 | 24.44 | 7.06 |
| J M Keynes Blvd | | 60.62 | 51.96 | 46.56 | 46.38 |
| E WT Harris Blvd | | 43.86 | N/A | 39.63 | N/A |
| Ken Hoffmann Dr | | 16.82 | N/A | 6.45 | N/A |
| McCullough Dr | | 10.58 | N/A | 21.34 | N/A |
| University Pointe Blvd | | 18.71 | 12.77 | 27.75 | 21.34 |

**Notes:** NBT-Northbound Through Right, SBTR-Southbound Through Right, EBTR-Eastbound Through Right, WBTR-Westbound Through Right, NBL- Northbound Left, SBL-Southbound Left, EBL-Eastbound Left, WBL-Westbound Left, N/A-Not Available

Table 12 summarizes the delay for the vehicular traffic with LRT, pedestrians, and bicycles. Table 10 and Table 12 help assess the difference between the delay when pedestrians and bicycles are added to the network. The delay for all the movements were aggregated for the major approaches (northbound and Southbound) and cross-street approaches (eastbound and westbound) for scenario with LRT and scenario with LRT, pedestrians, and bicycles. It was found that the major approaches have seen an increase in vehicle delay by 5%, whereas the cross-street approaches had seen a decrease in vehicle delay by 0.6%.

Table 13 summarizes the change in vehicle delay percentage incurred at the intersection between scenario 1 and scenario 3.

Table 13. Change in Percentage of Delay Between Scenario 1 and Scenario 3

| Study Corridor (N Tryon St) Approaches | | | | | |
|---|---|---|---|---|---|
| Intersection 1 | Intersection 2 | NBTR | NBL | SBTR | SBL |
| Mallard Creek Ch Road | Institute Cir | | | 23.14 | 47.97 |
| Institute Cir | JW Clay Blvd | 8.42 | 6.05 | 3.61 | 42.72 |
| JW Clay Blvd | J M Keynes Blvd | -2.71 | 10.97 | -1.51 | -7.17 |
| J M Keynes Blvd | E WT Harris Blvd | -2.31 | -2.31 | -2.53 | -2.53 |
| E WT Harris Blvd | Ken Hoffmann Dr | 5.02 | N/A | -0.66 | 2.09 |
| Ken Hoffmann Dr | McCullough Dr | -0.78 | 1.66 | 10.18 | -32.00 |
| McCullough Dr | University Pointe Blvd | 1.81 | -6.21 | -4.02 | -5.63 |
| University Pointe Blvd | University City Blvd | 1.22 | -0.21 | | |
| Cross-street Approaches | | | | | |
| Intersection | | EBTR | EBL | WBTR | WBL |
| Institute Cir | | 38.86 | 29.32 | -21.82 | -8.38 |
| JW Clay Blvd | | -17.02 | -3.00 | -15.14 | -20.76 |
| J M Keynes Blvd | | 2.73 | -10.58 | -2.74 | -9.94 |
| E WT Harris Blvd | | -4.26 | N/A | 9.41 | N/A |
| Ken Hoffmann Dr | | -58.82 | N/A | 80.17 | N/A |
| McCullough Dr | | 5.06 | N/A | 15.1 | N/A |
| University Pointe Blvd | | 52.73 | -2.37 | -4.77 | 8.05 |

**Notes:** NBT-Northbound Through Right, SBTR-Southbound Through Right, EBTR-Eastbound Through Right, WBTR-Westbound Through Right, NBL- Northbound Left, SBL-Southbound Left, EBL-Eastbound Left, WBL-Westbound Left. Scenario 1- Vehicle with LRT, Scenario 3-Vehicles with LRT, Pedestrians and Bicycles., N/A-Not Available

Table 14 through Table 16 summarize the delay for the scenarios where there is increase/decrease in vehicular volumes and increase in pedestrian and bicycle activity. Three different scenarios of increasing vehicles with the same number of pedestrians and bicycles, increase in pedestrians and bicycles with same number of vehicles, decrease in vehicles with same number of pedestrians and bicycles are compared with Scenario 3 (including vehicles, LRT, pedestrians, and bicycles in the network). A decrease in vehicular traffic by 15% resulted in a decrease in the vehicle delay by about 6% along the study corridor and by about 15% along cross-streets.

Table 14. Delay by Turning Movement – Decrease in Vehicular Traffic with Pedestrians and Bicycles (In seconds)

| Study Corridor (N Tryon St) Approaches | | | | | |
|---|---|---|---|---|---|
| Intersection 1 | Intersection 2 | NBTR | NBL | SBTR | SBL |
| Mallard Creek Ch Road | Institute Cir | | | 42.89 | 25.18 |
| Institute Cir | JW Clay Blvd | 51.19 | 82.6 | 43.03 | 63.71 |
| JW Clay Blvd | J M Keynes Blvd | 33.73 | 18.74 | 24.98 | 67.51 |
| J M Keynes Blvd | E WT Harris Blvd | 30.9 | 30.9 | 24.68 | 24.68 |
| E WT Harris Blvd | Ken Hoffmann Dr | 17.75 | N/A | 26.01 | 35.78 |
| Ken Hoffmann Dr | McCullough Dr | 28.06 | 58.73 | 1.28 | 0.73 |
| McCullough Dr | University Pointe Blvd | 26.41 | 40.64 | 20.26 | 36.85 |
| University Pointe Blvd | University City Blvd | 31.63 | 55.62 | | |
| Cross-street Approaches | | | | | |
| Intersection | | EBTR | EBL | WBTR | WBL |
| Institute Cir | | 59.56 | 54.77 | 61.38 | 66.57 |
| JW Clay Blvd | | 18.89 | 40.96 | 22.92 | 6.45 |
| J M Keynes Blvd | | 56.12 | 54.77 | 47.97 | 47.09 |
| E WT Harris Blvd | | 36.9 | N/A | 35.73 | N/A |
| Ken Hoffmann Dr | | 11.1 | N/A | 5.98 | N/A |
| McCullough Dr | | 8.89 | N/A | 25.79 | N/A |
| University Pointe Blvd | | 17.36 | 10.97 | 26.97 | 18.52 |

**Notes:** NBT-Northbound Through Right, SBTR-Southbound Through Right, EBTR-Eastbound Through Right, WBTR-Westbound Through Right, NBL- Northbound Left, SBL-Southbound Left, EBL-Eastbound Left, WBL-Westbound Left, N/A-Not Available

Table 15. Delay by Turning Movement – Increase in Vehicular Traffic with Pedestrians and Bicycles (In seconds)

| Study Corridor (N Tryon St) Approaches | | | | | |
|---|---|---|---|---|---|
| Intersection 1 | Intersection 2 | NBTR | NBL | SBTR | SBL |
| Mallard Creek Church Rd | Institute Cir | | | 50.77 | 66.02 |
| Institute Cir | JW Clay Blvd | 73.19 | 102.99 | 52.53 | 70.58 |
| JW Clay Blvd | J M Keynes Blvd | 36.99 | 23.2 | 28.3 | 71.44 |
| J M Keynes Blvd | E WT Harris Blvd | 31.32 | 31.32 | 28.15 | 28.15 |
| E WT Harris Blvd | Ken Hoffmann Dr | 21.44 | N/A | 27.96 | 36.17 |
| Ken Hoffmann Dr | McCullough Dr | 32.13 | 61.98 | 1.94 | 3.24 |
| McCullough Dr | University Pointe Blvd | 26.82 | 45.96 | 22.57 | 45.37 |
| University Pointe Blvd | University City Blvd | 34.4 | 52.56 | | |

| Cross-street Approaches | | | | |
|---|---|---|---|---|
| Intersection | EBTR | EBL | WBTR | WBL |
| Institute Cir | 124.33 | 143.53 | 68.17 | 67.93 |
| JW Clay Blvd | 21.78 | 41.16 | 27.6 | 10.09 |
| J M Keynes Blvd | 60.89 | 52.61 | 49.09 | 50.01 |
| E WT Harris Blvd | 137.92 | N/A | 76.13 | N/A |
| Ken Hoffmann Dr | 18.74 | N/A | 5.08 | N/A |
| McCullough Dr | 12.36 | N/A | 28.31 | N/A |
| University Pointe Blvd | 19.76 | 12.06 | 33.08 | 21.38 |

**Notes:** NBT-Northbound Through Right, SBTR-Southbound Through Right, EBTR-Eastbound Through Right, WBTR-Westbound Through Right, NBL- Northbound Left, SBL-Southbound Left, EBL-Eastbound Left, WBL-Westbound Left, N/A-Not Available

Table 16. Delay by Turning Movement – Vehicular Traffic with Increase in Pedestrians and Bicycles (In seconds)

| Study Corridor (N Tryon St) Approaches | | | | | |
|---|---|---|---|---|---|
| Intersection 1 | Intersection 2 | NBTR | NBL | SBTR | SBL |
| Mallard Creek Church Rd | Institute Cir | | | 56.14 | 44.85 |
| Institute Cir | JW Clay Blvd | 154.13 | 192.76 | 58.08 | 40.69 |
| JW Clay Blvd | J M Keynes Blvd | 55.81 | 25.79 | 28.39 | 71.12 |
| J M Keynes Blvd | E WT Harris Blvd | 29.9 | 29.9 | 28.16 | 28.16 |
| E WT Harris Blvd | Ken Hoffmann Dr | 21.99 | N/A | 28.1 | 36.05 |
| Ken Hoffmann Dr | McCullough Dr | 31.27 | 63.65 | 2.18 | 0.06 |
| McCullough Dr | University Pointe Blvd | 27.74 | 25.67 | 23.15 | 41.85 |
| University Pointe Blvd | University City Blvd | 35.01 | 53.89 | | |
| Cross-street Approaches | | | | | |
| Intersection | | EBTR | EBL | WBTR | WBL |
| Institute Cir | | 118.18 | 132.27 | 69.09 | 65.07 |
| JW Clay Blvd | | 29.22 | 49.23 | 28.34 | 9.99 |
| J M Keynes Blvd | | 62.21 | 51.85 | 48.71 | 48.99 |
| E WT Harris Blvd | | 161.87 | N/A | 64.71 | N/A |
| Ken Hoffmann Dr | | 17.59 | N/A | 4.63 | N/A |
| McCullough Dr | | 10.45 | N/A | 27.79 | N/A |
| University Pointe Blvd | | 21.16 | 11.69 | 32.19 | 20.74 |

**Notes:** NBT-Northbound Through Right, SBTR-Southbound Through Right, EBTR-Eastbound Through Right, WBTR-Westbound Through Right, NBL- Northbound Left, SBL-Southbound Left, EBL-Eastbound Left, WBL-Westbound Left, N/A-Not Available

With an increase in 15% of vehicular volumes, an increase in vehicle delay by about 26% is seen along cross-streets while an increase in vehicle delay by about 6.5% was seen along the study corridor. From the above two observations, it can be observed that cross-streets have a significant change in operational performance with an increase/ decrease in vehicular volumes. During the evening peak hour, the cross-streets of Institute Cir and E WT Harris Blvd along N Tryon St have had a significant effect on the total vehicle delay percentage change, highlighted in Table 15. Upon visual inspection, it was noticed that the delay incurred by the vehicles at eastbound and westbound approaches are due to the less green time at the intersection due to LRT related activity. But, the increase/decrease in vehicle delay at E WT Harris Blvd is due to the vehicles being backed up from the upstream/downstream intersections.

A comparison between the scenarios of vehicles plus pedestrians and bicycles with vehicles plus increase in pedestrian and bicycle activity by 100% indicate that there is an increase in vehicle delay for vehicles by about 23% along the study corridor and by about 27% on cross-streets. The at-grade intersection at E WT Harris Blvd had a major part in that change in percentage. With the increase in pedestrians and bicycles at other intersections, cross-street movement of eastbound and westbound through movements on E WT Harris Blvd had an increase in vehicle delay by 270% and 63%, which skewed the overall change in vehicle delay percentage. Similar to the cross-streets, the northbound and southbound through movements at Institute Cir on the study corridor have seen a major change in the total delay percentage. With an increase in pedestrians and bicycles, the turning movements which counter LRT movement had no significant change in vehicle delay, as shown in Table 16.

Table 17 summarizes the change in percentage of delay between Scenario 3 and Scenario 6. The highlighted turning movements are vulnerable to an increase in non-motorist traffic.

Table 18 and Table 19 summarize the vehicle delay observed with vehicles, pedestrians and bicycles in the network with an LRT frequency of 6 per hour and 10 per hour. The base model (Scenario 1) has 8 LRT movements. The effect on vehicle delay with the change in LRT frequency (6, 8 and 10) is checked by comparing Table 10 with Table 18 and Table 19.

Table 17. Change in Percentage of Delay Between Scenario 3 and Scenario 6

| Study Corridor (N Tryon St) Approaches | | | | | |
|---|---|---|---|---|---|
| Intersection 1 | Intersection 2 | NBTR | NBL | SBTR | SBL |
| Mallard Creek Church Rd | Institute Cir | | | 22.66 | -18.04 |
| Institute Cir | JW Clay Blvd | 178.87 | 112.41 | 16.91 | -39.52 |
| JW Clay Blvd | J M Keynes Blvd | 60.28 | 24.35 | 6.17 | 10.09 |
| J M Keynes Blvd | E WT Harris Blvd | -7.09 | -7.09 | 6.14 | 6.14 |
| E WT Harris Blvd | Ken Hoffmann Dr | 9.51 | N/A | 3.12 | 0.95 |
| Ken Hoffmann Dr | McCullough Dr | 7.57 | 4.76 | 18.48 | -64.71 |
| McCullough Dr | University Pointe Blvd | 2.63 | -10.62 | 3.26 | 13.97 |
| University Pointe Blvd | University City Blvd | 8.26 | 1.95 | | |
| Cross-street Approaches | | | | | |
| Intersection | | EBTR | EBL | WBTR | WBL |
| Institute Cir | | 27.98 | 21.56 | 11.49 | 2.96 |
| JW Clay Blvd | | 34.41 | 20.66 | 15.96 | 41.50 |
| J M Keynes Blvd | | 2.62 | -0.21 | 4.62 | 5.63 |
| E WT Harris Blvd | | 269.06 | N/A | 63.29 | N/A |
| Ken Hoffmann Dr | | 4.58 | N/A | -28.22 | N/A |
| McCullough Dr | | -1.23 | N/A | 30.22 | N/A |
| University Pointe Blvd | | 13.09 | -8.46 | 16 | -2.81 |

**Notes:** NBT-Northbound Through Right, SBTR-Southbound Through Right, EBTR-Eastbound Through Right, WBTR-Westbound Through Right, NBL- Northbound Left, SBL-Southbound Left, EBL-Eastbound Left, WBL-Westbound Left. Scenario 3-Vehicles with LRT, Pedestrians and Bicycles, Scenario 6- Vehicles with LRT, Increase in Pedestrians and Bicycles., N/A-Not Available

Table 18. Delay by Turning Movement - Vehicular Traffic with LRT (frequency 6), Pedestrians and Bicycles (In seconds)

| Study Corridor (N Tryon St) Approaches | | | | | |
|---|---|---|---|---|---|
| Intersection 1 | Intersection 2 | NBTR | NBL | SBTR | SBL |
| Mallard Creek Church Rd | Institute Cir | | | 73.46 | 26.41 |
| Institute Cir | JW Clay Blvd | 52.92 | 50.94 | 111.83 | 61.38 |
| JW Clay Blvd | J M Keynes Blvd | 34.9 | 11.95 | 34.22 | 65.86 |
| J M Keynes Blvd | E WT Harris Blvd | 31.95 | 31.95 | 31.42 | 31.42 |
| E WT Harris Blvd | Ken Hoffmann Dr | 12.02 | N/A | 29.59 | 31.65 |
| Ken Hoffmann Dr | McCullough Dr | 28.44 | 60.42 | 1.86 | 0.45 |
| McCullough Dr | University Pointe Blvd | 28.06 | 30.86 | 28.83 | 35.9 |
| University Pointe Blvd | University City Blvd | 30.96 | 52.44 | | |
| Cross-street Approaches | | | | | |
| Intersection | | EBTR | EBL | WBTR | WBL |
| Institute Cir | | 48.51 | 60.81 | 44.08 | 45.41 |
| JW Clay Blvd | | 21.3 | 40.17 | 25.33 | 7.91 |
| J M Keynes Blvd | | 61.09 | 52.65 | 46.85 | 47.28 |
| E WT Harris Blvd | | 75.39 | N/A | 47.52 | N/A |
| Ken Hoffmann Dr | | 20.34 | N/A | 6.54 | N/A |
| McCullough Dr | | 12.78 | N/A | 17.69 | N/A |
| University Pointe Blvd | | 13.01 | 13.09 | 28.42 | 18.92 |

**Notes:** NBT-Northbound Through Right, SBTR-Southbound Through Right, EBTR-Eastbound Through Right, WBTR-Westbound Through Right, NBL- Northbound Left, SBL-Southbound Left, EBL-Eastbound Left, WBL-Westbound Left, N/A-Not Available

Table 19. Delay by Turning Movement - Vehicular Traffic with LRT (frequency 10), Pedestrians and Bicycles (In seconds)

| Study Corridor (N Tryon St) Approaches | | | | | |
|---|---|---|---|---|---|
| Intersection 1 | Intersection 2 | NBTR | NBL | SBTR | SBL |
| Mallard Creek Church Rd | Institute Cir | | | 28.04 | 54.72 |
| Institute Cir | JW Clay Blvd | 44.88 | 90.75 | 38.22 | 67.28 |
| JW Clay Blvd | J M Keynes Blvd | 29.3 | 20.74 | 25.24 | 64.6 |
| J M Keynes Blvd | E WT Harris Blvd | 27.16 | 32.18 | 22.28 | 26.53 |
| E WT Harris Blvd | Ken Hoffmann Dr | 9.36 | N/A | 23.21 | 35.71 |
| Ken Hoffmann Dr | McCullough Dr | 22.68 | 60.76 | 0.22 | 0.17 |
| McCullough Dr | University Pointe Blvd | 20.55 | 28.72 | 20.59 | 36.72 |
| University Pointe Blvd | University City Blvd | 24.86 | 52.86 | | |
| Cross-street Approaches | | | | | |
| Intersection | | EBTR | EBL | WBTR | WBL |
| Institute Cir | | 90.18 | 119.15 | 62.83 | 63.26 |
| JW Clay Blvd | | 16.57 | 32.74 | 13.17 | 8.25 |
| J M Keynes Blvd | | 53.89 | 47.23 | 35.66 | 42.47 |
| E WT Harris Blvd | | 94.5 | N/A | 43.59 | N/A |
| Ken Hoffmann Dr | | 41.08 | N/A | 17.83 | N/A |
| McCullough Dr | | 15.33 | N/A | 19.95 | N/A |
| University Pointe Blvd | | 16.02 | 16.05 | 32.22 | 26.22 |

**Notes:** NBT-Northbound Through Right, SBTR-Southbound Through Right, EBTR-Eastbound Through Right, WBTR-Westbound Through Right, NBL- Northbound Left, SBL-Southbound Left, EBL-Eastbound Left, WBL-Westbound Left, N/A-Not Available

Comparing Table 10 with Table 18 and Table 19 shows the effect of LRT frequency on the delay of vehicles. With the change in LRT frequency from 8 per hour to 6 per hour, the delay decreased for many turning movements along cross-streets. Whereas, the vehicle delay along the northbound through direction with an LRT frequency of 6 per hour remains similar to vehicle delay along the northbound direction with an LRT frequency of 8 per hour. However, the vehicle delay along the southbound through direction has increased with an LRT frequency of 6 per hour compared to 8 per hour. A decrease in vehicle delay was observed for an LRT frequency of 6 per hour for the northbound left-turning and southbound left-turning movements.

An increase in the LRT frequency did show a decrease in vehicle delay along the LRT parallel movements and an increase in the vehicle delay along the movements which run against the LRT movement, as shown in Table 19.

### 6.4.2 Queue Length (maximum) and Level of Service (LOS)

Delay as an evaluation parameter was used to analyze individual approaches at each intersection as the focus of the research is to compare the effect of one mode of transport on vehicular traffic. However, queue, maximum queue length and LOS were used to assess the overall performance at the intersection. The queue length and LOS are captured by creating nodes around the intersections.

Table 20 and Table 21 summarize the maximum queue length of all the intersections in the network for Scenario1, Scenario 2 and Scenario 3. The intersection of E Mallard Creek Church Rd at N Tryon S is not considered in the analysis as the LRT is not present at the intersection but the vehicle inputs are provided starting from the N Tryon St & E Mallard Creek Church Rd intersection.

Table 20. Maximum Queue Length at the Intersections in the Study Corridor

| Maximum Queue Length (In feet) | | | |
|---|---|---|---|
| Intersection | 1 | 2 | 3 |
| N Tryon St & Institute Cir | 587.15 | 609.44 | 662.39 |
| N Tryon St & JW Clay Blvd | 329.50 | 361.15 | 355.50 |
| N Tryon St & J M Keynes Blvd | 304.06 | 308.75 | 377.17 |
| N Tryon St & E WT Harris Blvd | 615.40 | 623.63 | 692.09 |
| N Tryon St & Ken Hoffmann Dr | 370.15 | 376.28 | 365.03 |
| N Tryon St & McCullough Dr | 341.31 | 343.65 | 335.28 |
| N Tryon St & University Pointe Blvd | 360.16 | 365.10 | 356.17 |

Notes: 1-Scenario 1 (Vehicle with LRT). 2-Scenario 2 (Vehicles with LRT and pedestrians). 3-Scenario 3 (Vehicles with LRT, Pedestrians and Bicycles).

Table 21. Maximum Queue Length at the Intersections in the Study Corridor with change in Heterogeneous Traffic Conditions

| Maximum Queue Length (In feet) | | | | |
|---|---|---|---|---|
| Intersection | 3 | 4 | 5 | 6 |
| N Tryon St & Institute Cir | 662.39 | 536.36 | 748.09 | 646.93 |
| N Tryon St & JW Clay Blvd | 355.5 | 313.62 | 388.04 | 374.23 |
| N Tryon St & J M Keynes Blvd | 377.17 | 252.63 | 339.9 | 292.54 |
| N Tryon St & EWT Harris Blvd | 692.09 | 471.04 | 1428.44 | 1461.05 |
| N Tryon St & Ken Hoffmann Dr | 365.03 | 314.02 | 384.33 | 392.55 |
| N Tryon St & McCullough Dr | 335.28 | 297.28 | 366.32 | 356.88 |
| N Tryon St & University Pointe Blvd | 356.17 | 289.04 | 423.91 | 368.26 |

Notes: 3-Scenario 3 (Vehicles with LRT, Pedestrians and Bicycles). 4-Scenario 4 (Decrease in Vehicles with LRT and pedestrians). 5-Scenario 5 (Increase in Vehicles with LRT and pedestrians). 6- Scenario 6 (Vehicles with LRT, increase in Pedestrians and Bicycles).

The maximum queue lengths for all the intersections were observed to increase with the addition of LRT. The intersection at E WT Harris Blvd has seen an increase in the maximum queue length by more than 100% with an increase in vehicles, pedestrians, and bicycles.

The LOS obtained for Scenario 1, Scenario 2, and Scenario 3 are summarized in Table 22. Changes in LOS at an intersection are indicated and are compared with the Scenario 1. The intersections at Institute Cir and J M Keynes Blvd have seen a decrease by a letter grade when pedestrians and bicycles are added to the simulations.

Table 22. Level of Service (LOS) at the Intersections in the Study Corridor

| Level of Service (LOS) | | | |
|---|---|---|---|
| Intersection | 1 | 2 | 3 |
| N Tryon St & Institute Cir | D | E | E |
| N Tryon St & JW Clay Blvd | D | D | D |
| N Tryon St & J M Keynes Blvd | C | C | D |
| N Tryon St & EWT Harris Blvd | D | D | D |
| N Tryon St & Ken Hoffmann Dr | C | C | C |
| N Tryon St & McCullough Dr | B | B | B |
| N Tryon St & University Pointe Blvd | D | D | D |

Notes: 1-Scenario 1 (Vehicle with LRT). 2-Scenario 2 (Vehicles with LRT and pedestrians). 3-Scenario 3(Vehicles with LRT, Pedestrians and Bicycles).

Table 23 summarizes the LOS for scenarios 3, 4, 5, and 6. The results for scenarios 4, 5 and 6 are compared with Scenario 3.

Table 23. Level of Service (LOS) at the Intersections in the Study Corridor with change in Heterogeneous Traffic Conditions

| Level of Service (LOS) | | | | |
|---|---|---|---|---|
| Intersection | 3 | 4 | 5 | 6 |
| N Tryon St & Institute Cir | E | E | E | E |
| N Tryon St & JW Clay Blvd | D | D | D | E |
| N Tryon St & J M Keynes Blvd | D | C | D | C |
| N Tryon St & EWT Harris Blvd | D | D | E | E |
| N Tryon St & Ken Hoffmann Dr | C | C | C | C |
| N Tryon St & McCullough Dr | B | B | B | B |
| N Tryon St & University Pointe Blvd | D | C | D | D |

Notes: 3-Scenario 3 (Vehicles with LRT, Pedestrians and Bicycles). 4-Scenario 4 (Decrease in Vehicles with LRT and pedestrians). 5-Scenario 5 (Increase in Vehicles with LRT and pedestrians). 6- Scenario 6 (Vehicles with LRT, increase in Pedestrians and Bicycles).

The intersection at E WT Harris Blvd has seen an increase in LOS by one letter grade with an increase in vehicular volumes as well as with an increase in pedestrians and bicycles. Some intersections have seen an improvement in performance with a decrease in vehicular volumes (scenario 4).

### 6.4.3 Pedestrian Performance Measures

Pedestrian performance measures are captured by evaluating the pedestrian areas. They can be pedestrian waiting areas or the links which pedestrian use to cross. The pedestrian areas are identified and are linked to the intersection for further analysis. The results are summarized in Table 24.

Table 24. Pedestrian Area Classification at the Intersections in the Study Corridor

| Pedestrian Areas | |
|---|---|
| Intersection | Areas |
| N Tryon St & Institute Cir | 1,2,5,6,9,10 |
| N Tryon St & JW Clay Blvd | 11,12,13,14,15,16 |
| N Tryon St & J M Keynes Blvd | 17,18,19,20,21,22 |
| N Tryon St & E WT Harris Blvd | 23,24,25,26,27,47 |
| N Tryon St & Ken Hoffmann Dr | 29,30, 31,32,33,34 |
| N Tryon St & McCullough Dr | 35,36,37,38,39,40 |
| N Tryon St & University Pointe Blvd | 41,42,43,44,45,46 |

The missing areas (for example, 4, 7, 8, etc.) are the pedestrian waiting areas at the LRT stations and are not used in the analysis. This is done as the pedestrians waiting for LRT be at stand still and will affect the overall pedestrian speeds. The selection of the areas for analysis is shown in Figure 32.

The performance measures captured for pedestrians are the average walking speed of pedestrians. The results are presented for Scenario 3 and Scenario 6. Scenario 1 does not have pedestrian inputs and, hence, there will be no values for pedestrian walking speeds. Scenario 2 is excluded as there is not much change in the pedestrian performances between Scenario 2 and Scenario 3 (same pedestrian and vehicle inputs for both the scenarios). Scenario 4 and Scenario 5 had same average walking speed as Scenario 3 even with an increase in vehicular volume. This is because the pedestrians are programmed to maneuver in accordance with the corresponding traffic signal phase and the vehicles yield to pedestrians (as defined in the priority rules), as shown in Figure 33.

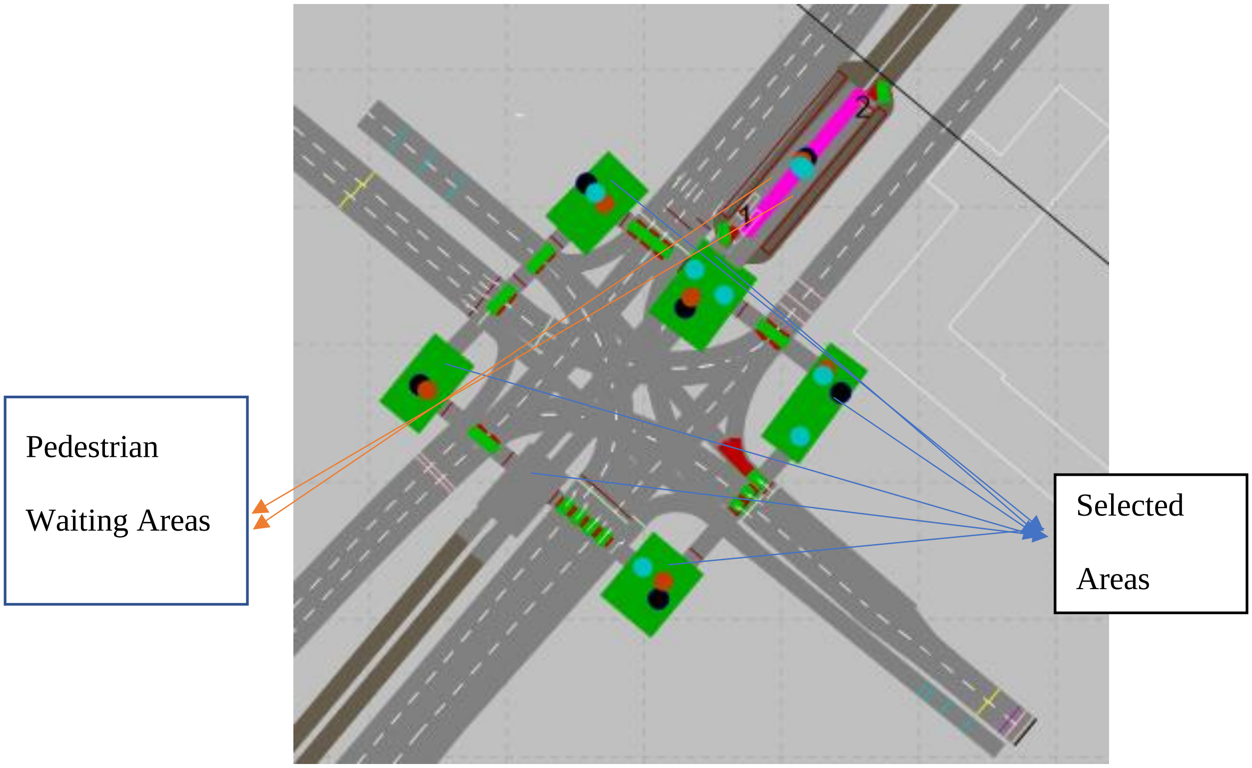



Figure 32 Pedestrian Area Selection

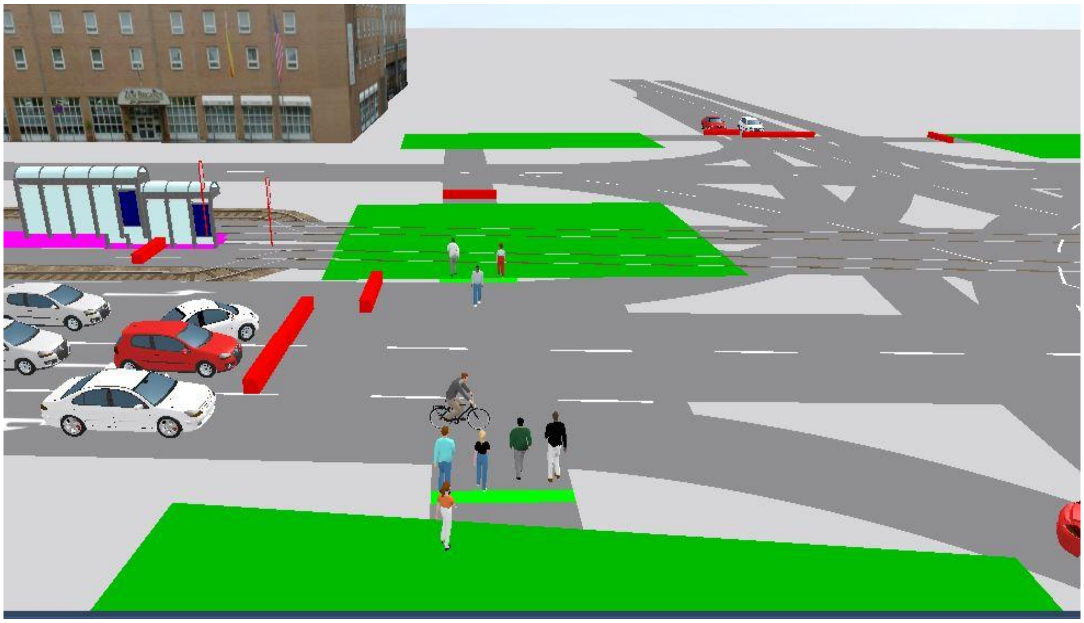


Figure 33 Pedestrian Signal Phasing at N Tryon St and JW Clay Blvd intersection

Also, all the pedestrian locations in the network are pre-programmed, and there are no pedestrian hybrid signals. Therefore, vehicular volume increase/ decrease did not have any effect on the pedestrian walking speed. Table 25 summarizes the average walking speed for scenarios with observed pedestrian volumes and an increase in pedestrian volumes by 100% in the network. The increase in pedestrian volume resulted in an increase in vehicle delay for the vehicles and other operational performances for vehicles. However, the increase in pedestrian volume did not show any notable effect/change on pedestrian speeds.

The ATT was also captured for all the scenarios. There was no significant change in the ATTs observed between all the scenarios. The summary for the travel time results for all the scenarios is provided in Tables A3 to A9 (appendix). In the scenario with an increase in vehicular volume and the scenario with an increase in pedestrians and bicycles, the travel times along the corridor increased by about 10%. Also, the travel times are only presented along the study corridor and no travel time data was captured for the cross-streets. (as the emphasis is to evaluate the operational performance on N Tryon St).

Table 25. Average Walking Speed for Pedestrians at Intersections (In mph)

| Average walking speed (mph) | | |
|---|---|---|
| Intersection | Scenario 3 | Scenario 6 |
| N Tryon St & Institute Cir | 1.99 | 2.01 |
| N Tryon St & JW Clay Blvd | 1.88 | 1.64 |
| N Tryon St & J M Keynes Blvd | 2.17 | 2.31 |
| N Tryon St & E WT Harris Blvd | 1.88 | 2.84 |
| N Tryon St & Ken Hoffmann Dr | 1.83 | 1.55 |
| N Tryon St & McCullough Dr | 2.29 | 2.67 |
| N Tryon St & University Pointe Blvd | 2.49 | 2.26 |

Notes: Scenario 3 (Vehicles with LRT, Pedestrians and Bicycles), Scenario 6 (Vehicles with LRT, increase in Pedestrians and Bicycles).

SSAM tool could only analyze the conflicts between vehicles and does not account for the conflict between vehicles and other modes of transportation. The intent is to assess the change in the number of conflicts due to other modes of transportation. Trajectory files for the base model were generated in Vissim. The trajectory files were run in SSAM to analyze the conflict points. The conflict points tend to change with the random seed numbers assigned to the simulation run. For Scenario 1, 30 simulation runs with random seeds are run and the average number of conflicts per hour are captured.

SSAM generates an output of conflict points, and the occurrence of conflicts on the links. The identification of links along with the IDs allow categorization of the conflicts for the specific intersection. As shown in Figure 34, the links heading towards the intersection (vehicles going towards the signalized intersection) are selected and conflict points on those links are identified and categorized at intersection (N Tryon St & McCullough Dr). The links which take the traffic to another intersection are also presented to show how the allocation is done in Figure 34.


Figure 34 Identification and Allocation of Links to an Intersection for Traffic Conflict Analysis

Table 26 summarizes the average number of conflict points per hour and the average number of crashes per year at the intersection in the study corridor.

Table 26. Conflicts/Hour and Crashes/Year at Intersections in the Study Corridor

| Intersection | Conflicts /hour | Crashes/year | Ratio |
|---|---|---|---|
| N Tryon St & University City Blvd | 300 | 39 | 7.69 |
| N Tryon St & University Pointe Blvd | 94 | 16 | 5.88 |
| N Tryon St & McCullough Dr | 89 | 13 | 6.85 |
| N Tryon St & Ken Hoffmann Dr | 40 | 9 | 4.44 |
| N Tryon St & E WT Harris Blvd | 349 | 39 | 8.95 |
| N Tryon St & JW Clay Blvd | 116 | 14 | 8.29 |
| N Tryon St & Institute Cir | 110 | 11 | 10.00 |
| N Tryon St & Mallard Creek Church Rd | 250 | 33 | 7.58 |
| Total | 1348 | 174 | 7.75 |

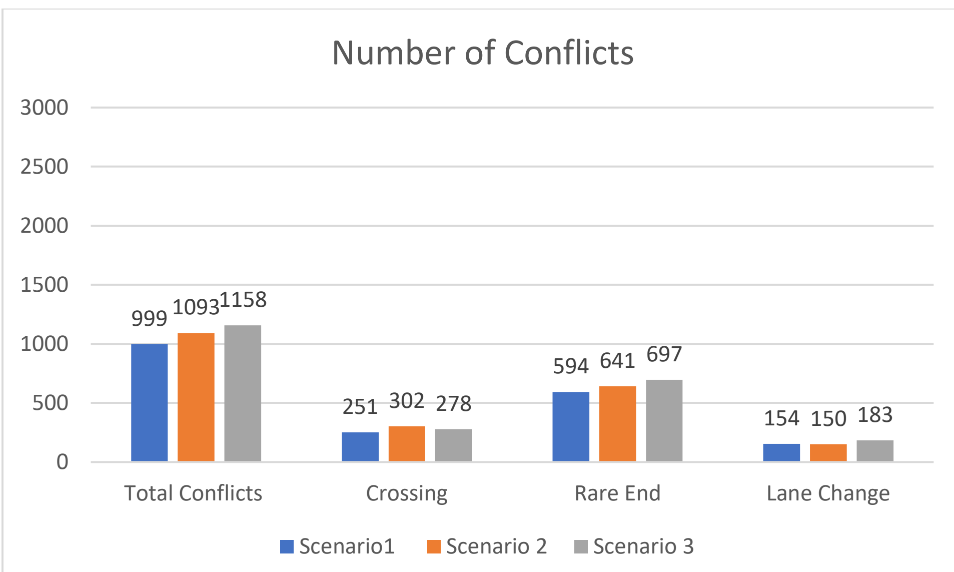
Notes: Ratio defined in the last column is the ratio between the conflicts/hour at the intersection to crashes/year at the intersection.

The number of crashes occurring on the road links is the field data that is usually assigned to the nearby intersection by the enforcement officers who generate the initial crash report. The technique used (assigning crashes to the intersection by the direction of travel) allows to keep the data consistent. Also, in the crash data the crashes were reported at the stop-controlled location of N Tryon St & Barton Creek Dr which falls in between Mallard Creek Church Rd and Institute Cir on N Tryon St. The crash data and the number of conflicts at the near vicinity links of Barton Creek Dr were assigned to the nearby intersection.

It can be inferred from Table 26 that the number of crashes is directly proportional to the number of conflicts per hour observed at the selected intersection. Therefore, the analysis of number of conflicts for all the other scenarios was done and compared with Scenario 1.

There are 3 types of conflicts possible as recorded in SSAM- 1) crossing, 2) rear-end, and 3) lane change collisions. The categorization of conflicts is defined by the angle of collision. An angle of 0 degrees to 30 degrees is considered as a rear-end type of collision. An angle of 30 degrees to 85 degrees is considered as a lane change type of collision. An angle of 85 degrees to 180 degrees is considered as a crossing type of collision. Rear-end type collisions occur when a vehicle crashes into the vehicle that is directly in front of them. Lane change type collisions occur when a vehicle crashes into another vehicle while trying to change the lane. Crossing collisions occur when a vehicle crashes into another vehicle at an intersection. Crossing collisions can also happen between other non-motorist road users and LRT, or vehicles with other non-motorist users or LRT.

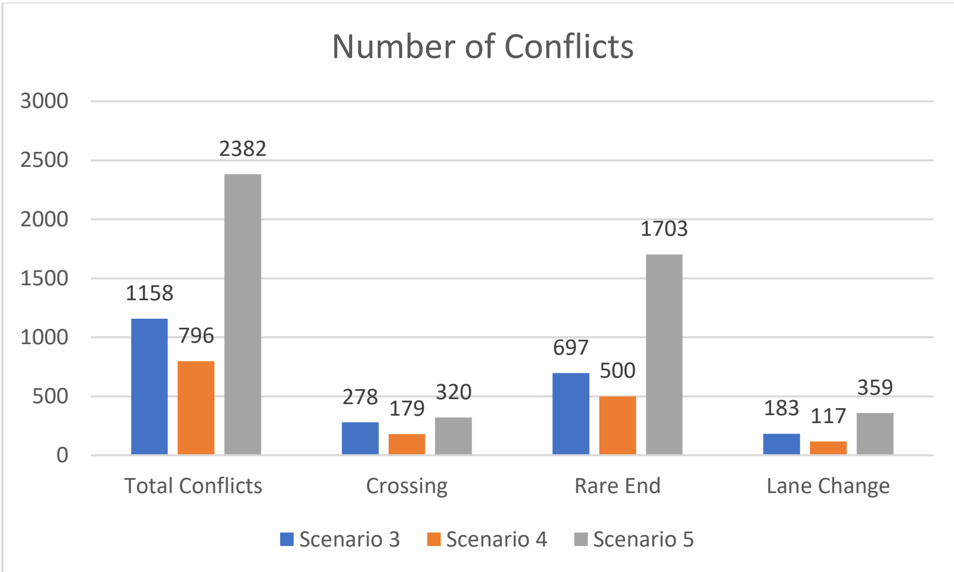
Figure 35 shows the average number of conflicts (of the five simulation runs) for Scenario 1, Scenario 2 and Scenario 3. As shown in the figure, there has been an increase in the number of conflicts with addition of pedestrians and bicycles to the existing network. For all the scenarios those values are presented in Figure 35.




Notes: 1-Scenario 1 (Vehicle with LRT). 2-Scenario 2 (Vehicles with LRT and pedestrians). 3-Scenario 3(Vehicles with LRT, Pedestrians and Bicycles).

Figure 35 Average Number of Conflicts for Scenario 1, Scenario 2, and Scenario 3

Figure 36 shows the average number of conflicts for scenario 3, scenario 4 and scenario 5. These three scenarios are compared to assess the change in the number of conflicts due to change in the vehicular volumes.

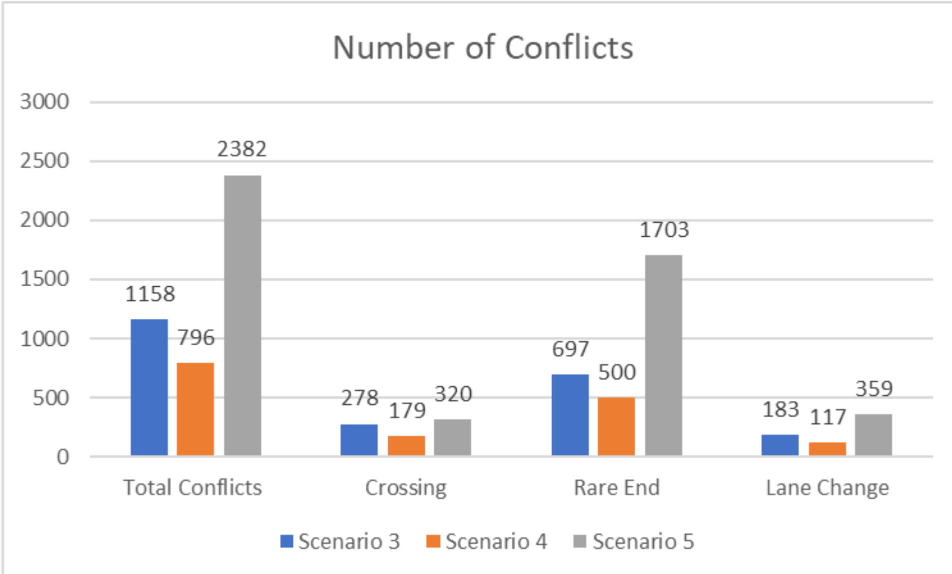



Notes: 3-Scenario 3 (Vehicles with LRT, Pedestrians and Bicycles). 4-Scenario 4 (Decrease in Vehicles with LRT and pedestrians). 5-Scenario 5 (Increase in Vehicles with LRT and pedestrians).

Figure 36 Average Number of Conflicts for Scenario 3, Scenario 4, and Scenario 5

The total number of conflicts reduced by 31% with the reduction in vehicular volumes by 15%. Whereas, the total number of conflicts increased by more than 100% with an increase in vehicular volumes by 15%. Further, it can be also noted that the proportion of increase of rear-end conflicts between Scenario 3 and Scenario 5 is greater than the other types of conflicts as observed in Figure 36. The increase in the number of conflicts can be mainly due to the increase in vehicle travel time and vehicle delay in Scenario 5.

Figure 37 shows the average number of conflicts for Scenario 3 and Scenario 6. With a 100% increase in pedestrians and bicycles on the network, there has been increase in the average number of conflicts by about 15%. But, the results indicate that the crossing and lane-change type of collisions did not change significantly between the two scenarios. The rear-end conflicts are the only type of conflicts that have increased, and are accounting for total increase in the conflict points.




Notes: 3-Scenario 3 (Vehicles with LRT, Pedestrians and Bicycles). 6-Scenario 6 (Vehicles with LRT, increase in Pedestrians and Bicycles)

Figure 37 Average Number of Conflicts for Scenario 3 and Scenario 6

Figures 38 to 44 show snapshots of the conflicts in SSAM. Rear-end conflicts are marked in red, crossing conflicts are marked in yellow, and the lane change conflicts are marked in blue. The snapshots of SSAM are shown only for one simulation run but the results presented are the average of five simulation runs. Appendix C summarizes the values that are used in figures 35 to 37.

Comparing Figure 38 and figure 39, it can be inferred that with increase in pedestrians, the northbound and southbound approaches at Institute Cir has seen an increase in rear-end conflicts.

Figure 39 and Figure 40 show similar trends in the number of conflicts. However, from observations, it was found that there has been a slight increase in the total number of conflicts between Scenario 2 and Scenario 3.

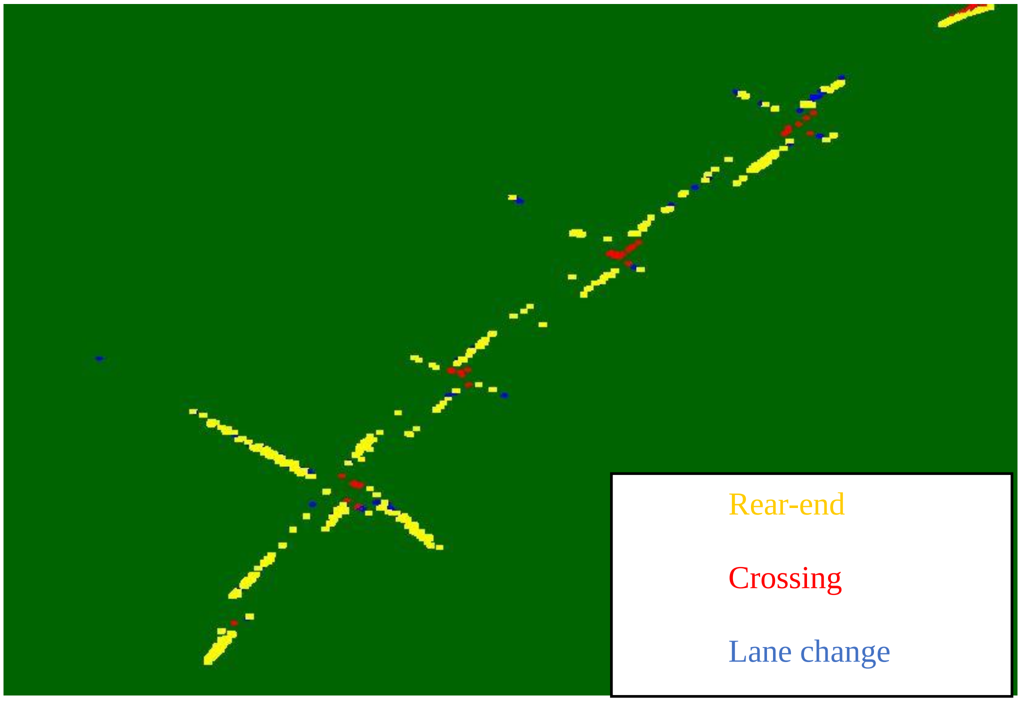



Figure 38 Conflict Visualization from E WT Harris Blvd to Institute Cir - Scenario 1 in SSAM

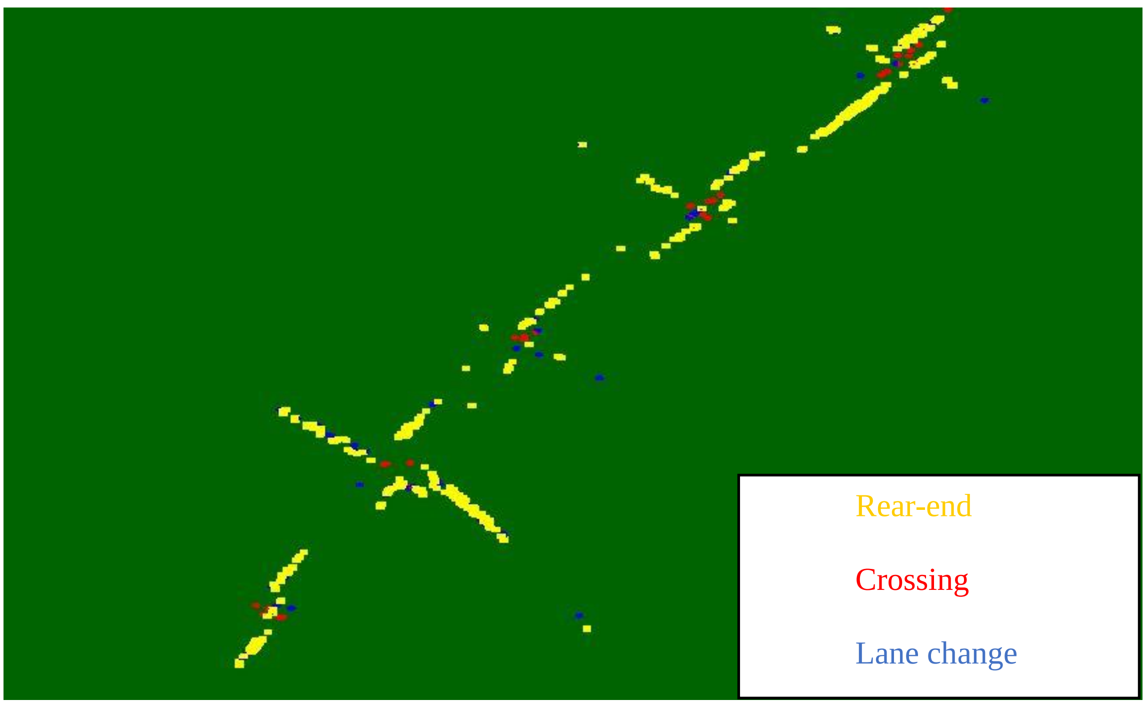



Figure 39 Conflict Visualization from E WT Harris Blvd to Institute Cir - Scenario 2 with Pedestrians in SSAM

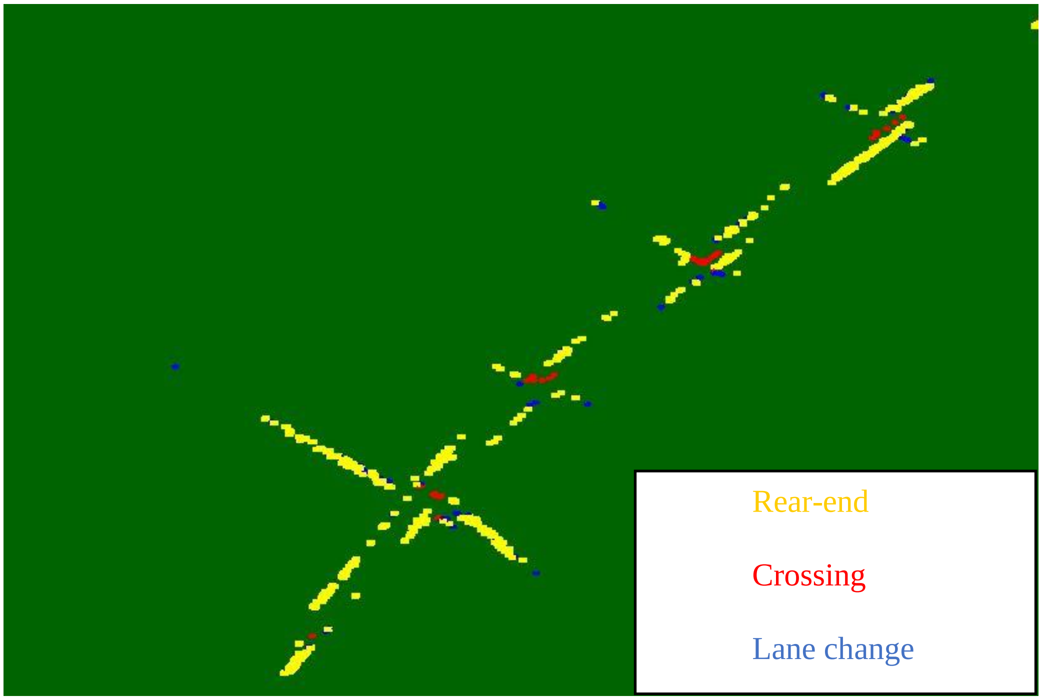



Figure 40 Conflict Visualization from E WT Harris Blvd to Institute Cir - Scenario 3 with Pedestrians and Bicycles in SSAM

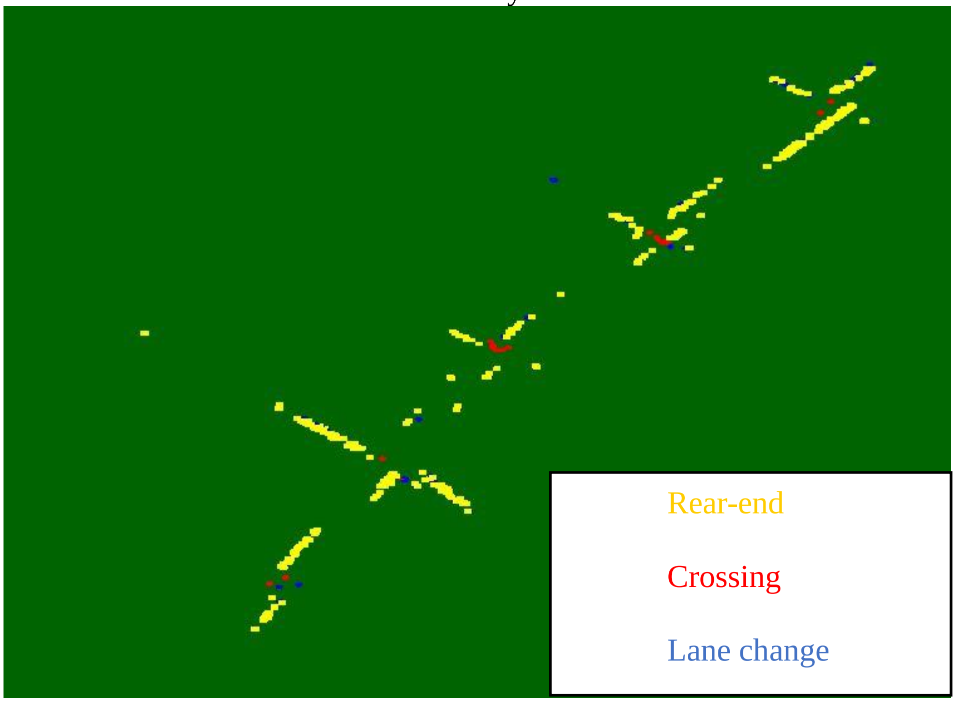



Figure 41 Conflict Visualization from E WT Harris Blvd to Institute Cir - Scenario 4 with Pedestrians and Bicycles, Decrease in Vehicular Volume in SSAM

Figure 41 indicates a clear decrease in the number of conflicts with a decrease in vehicular volumes. The number of conflicts at the intersections are found to be consistent with other scenarios. But, the links leading up to the intersections have seen a decrease in the number of conflicts, as shown in Figure 41.

Figure 42 indicates a clear increase in the number of conflicts with a decrease in vehicular volumes. The rear-end conflicts in the corridor have increased (more than doubled) when compared to other scenarios with a 15% increase in vehicular volumes.

Figure 43 shows increase in number of conflicts when bicycles and pedestrians are doubled, but not as much as in the case when compared to a 15% increase in vehicular volumes. From a safety perspective, and comparing all the scenarios, it can be said that the existing road network is more vulnerable to change in the vehicular volumes than other road users. A combination of increase in LRT frequency and bicycles with a decrease in vehicular volumes has a potential to reduce the existing number of conflicts in the network. Encouraging a shift in the mode choice of road users would help improve the safety at a corridor level.

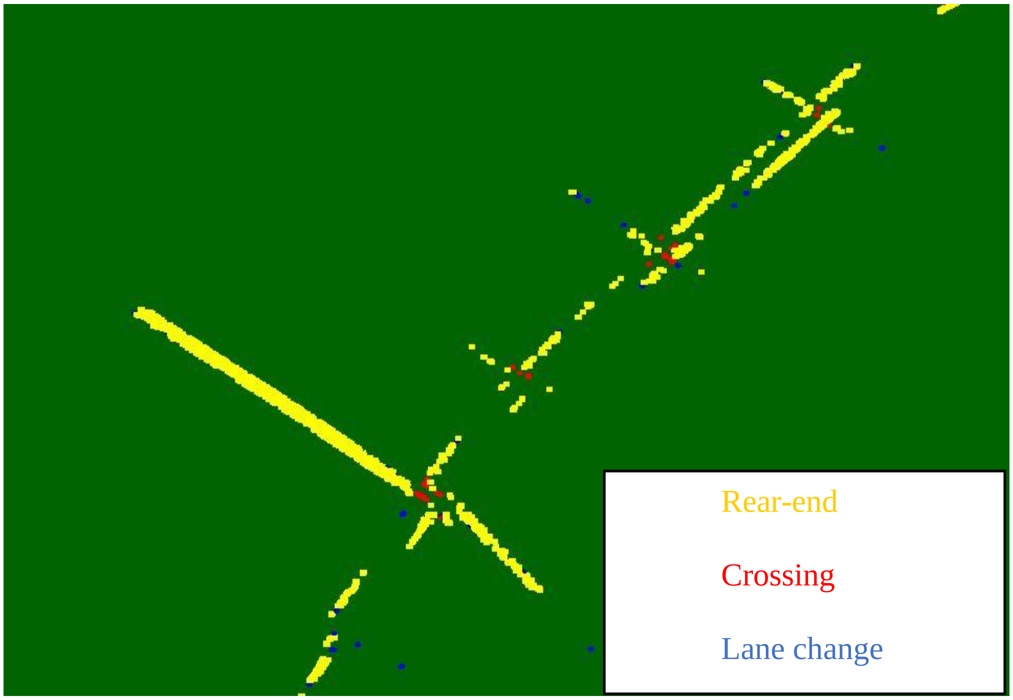



Figure 42 Conflict Visualization from E WT Harris Blvd to Institute Cir - Scenario 5 with Pedestrians and Bicycles, Increase in Vehicular Volume in SSAM

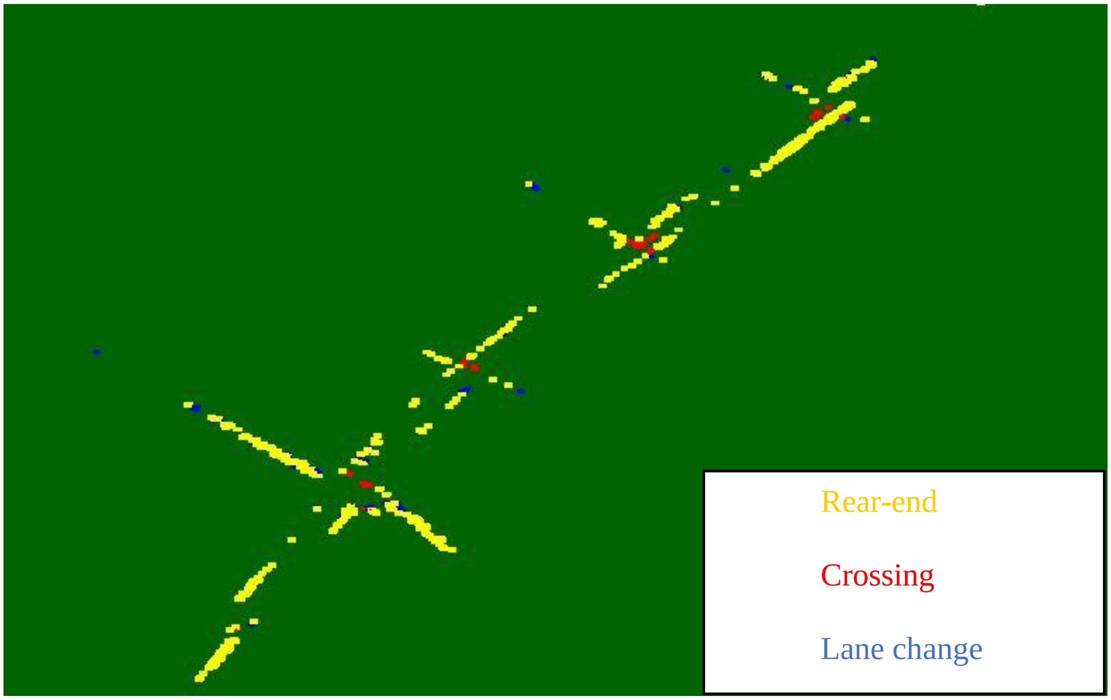



Figure 43 Conflict Visualization from E WT Harris Blvd to Institute Cir - Scenario 6 with Increase in Pedestrians and Bicycles with Constant Vehicles in SSAM

# CHAPTER 8: CONCLUSIONS

Growing cities (such as Charlotte) are focusing on "transit-oriented development" and implementation of programs like "complete streets" to ensure mobility options for various types of transportation system users. In addition, alternative modes of transportation are explored by practitioners to alleviate the growing traffic demand. While these developments focus on provision of alternate modes of transportation, the resulting heterogeneous traffic conditions (from various modes of transportation and their complex interactions) need to be assessed by considering the effect at a corridor-level. In addition, understanding the effect of increasing/decreasing number of users (motorized or non-motorized) over time help in efficient transportation planning strategies. Hence, this research focuses on understanding the effect of heterogeneous traffic conditions using a calibrated microsimulation approach. The research analysis was complimented by a travel time analysis to understand the travel time reliability patterns across traffic corridor.

A four-mile stretch of the new extension of Blue Lynx Light Rail that connects Old Concord Rd and UNC Charlotte's main campus, running through the N Tryon St median, was considered for travel time and TTR analysis. A part of the urban arterial corridor (N Tryon St) from the University Pointe Blvd intersection to Mallard Creek Church Rd intersection was used for simulation analysis.

Vehicle travel time and TTR patterns for before and after the commencement of LRT is examined on the primary route (N Tryon St) and the parallel route (I-85). To understand the statistical significance of the results, a paired t-test was conducted at a 95% confidence level. Travel time and TTR measures with heterogeneous conditions and without heterogeneous conditions are examined, in addition to the simulation-based approach to understand the influence of alternative modes of transportation on vehicular traffic.

In the simulation analysis, all the network characteristics were mimicked for the year 2018 and a calibrated model is developed. To build and accommodate the LRT, some important geometric changes were made to the network to encourage all modes of transportation. The geometric changes made during these years were captured and are reported in the research. The traffic signal timings have also been changed after 2018 with LRT preemption allowing more green time to few signal phases. Vehicle delay at the intersection was the primary performance measure that was used to capture the effect of changes in geometric conditions, signal timings, and/or effect of other modes of transportation on vehicular traffic. Vehicle delay is captured by the direction of travel along the study corridor (N Tryon St) and the cross-streets at selected intersections. Maximum queue length and LOS at the intersection were also captured to understand the effect of alternative modes on vehicular traffic.

The conclusions from the TTR analysis are listed next.

- The average vehicle travel times during peak hours of travel on the study corridor has increased significantly after the LRT is in operation.
- Other TTR measures like BT and BTI have also increased when LRT is in operation on the study corridor.
- On the parallel route, as observed from the link-level and corridor-level analysis, there is a clear trend of a worsening in TTR measures.
- On the study corridor, the change in TTR measures is found to be less significant and can be associated with few scenarios.
- The balance between the travel time loss due to frequent lane closures and the benefits associated with the alternate route choice for commuters may be considered as the reason behind less significant change in TTR measures.

The conclusions from the simulation analysis are listed next.

- The cross-streets on the study corridor incurred more delay after the LRT is in operation.
- The reduction in total green time for cross-streets at at-grade intersections is the primary reason for these trends.
- The LRT frequency had an effect vehicle delay for traffic on the cross-streets and the left turning movements on to the study corridor.
- As some intersections along the study corridor have started allowing the vehicles to get on to the study corridor from cross-streets by providing dedicated right-turn lanes/ shared through and right-turn lanes (as a part of geometric improvement due to LRT), maximum queue length and LOS is evaluated at all the intersections.
- Scenario with pedestrians and bicycles in the network have seen a slight increase in vehicle delay (5% increase in vehicle delay on the study corridor and no significant change along cross-streets).
- As the vehicular volumes and pedestrian volumes increase, the operational performance decreased on the study corridor.
- With the increase in vehicular volume or pedestrian volume, two intersections saw a significant increase in vehicle delay (Institute Cir and E WT Harris Blvd on N Tryon St).
- The intersection of Institute Cir has seen an increase in vehicle delay due to the characteristics at the intersection. But, the intersection of E WT Harris Blvd has seen an increase in vehicle delay due to traffic backing up from preceding intersections (high vehicular volume in the eastbound and westbound approaches).

- The LOS also worsened at E WT Harris Blvd by a letter grade with an increase in vehicular volume/ pedestrians.
- The maximum queue length increased at all the intersections with an increase in vehicular volume/ pedestrian volume.
- Combining the results from TTR analysis and simulation analysis, the operational performance on the cross-streets has deteriorated at a corridor level effecting the overall performance in the study area.
- Increase in heterogeneity effects only few sections in the study corridor. But the overall performance at the corridor level did not see a significant change in the operational performance.
- A comparison between the scenarios of vehicular traffic plus pedestrians and bicycles with vehicular traffic plus increase in pedestrian and bicycle activity by 100% indicate that there is an increase in vehicle delay for vehicles by about 23% along the study corridor and by about 27% on cross-streets.
- With an increase in 15% of vehicular volumes, an increase in vehicle delay by about 26% is seen along the cross-streets while an increase in vehicle delay by about 6.5% was seen along the study corridor.
- The changes in geometric conditions (lane markings, shared lanes and addition of lanes), dedicated bicycle lanes and traffic signal phasing were accommodated by the planning organizations due to the commencement of LRT.
- While these changes showed improvement in operational performance of vehicles, there is still a need to focus on improving efficiency for non-motorist traffic.

The conclusions from the surrogate safety assessment are listed next.

- The existing road network is more vulnerable to change in the vehicular volumes than from alternative mode users.
- The increase in the number of traffic conflicts was more than 100% with a 15% increase in vehicular volume. A 15% increase in the number of traffic conflicts was observed when pedestrians and bicycles were increased by 100%.

Many cities are transitioning toward multimodal mobility patterns through the provision of infrastructure for transit users, pedestrians, and bicyclists. To plan and build infrastructure with such complex mobility patterns, the interactions between all mode users need to be considered, modeled, and evaluated. This research proposes the use of travel time analysis and simulation framework to evaluate and understand these complex mobility patterns. The methodological approach used in this research is cross-disciplinary, transferable, and can be applied to other areas of development.

## 8.1 Limitations and Future Scope Of Work

The primary focus of this research was to analyze the effect of an increase in one mode of transportation on the vehicular traffic and the overall system performance. TTR analysis was done by comparing before LRT to after, sixth-month, twelfth-month, eighteenth-month after LRT is in operation. Future research could include comparing after LRT is in operation for longer periods.

No connected and automated vehicles (CAVs) penetration was used in the hypothetical scenarios as they account for negligible portion of the vehicular traffic. Different scenarios can be defined with different market penetration rates of CAVs and explored in the future. Pedestrians are expected to comply at the traffic signals, but the pedestrians who do not follow the traffic signal are not accounted in this analysis. Pedestrian performance measures like pedestrian delay, waiting time, and number of stops can be captured to develop a pedestrian-based LOS.

Surrogate safety assessment was conducted at a corridor-level for different hypothetical scenarios. Future research could include developing equations to estimate the crashes based on conflicts per hour and characteristics like vehicular volume, number of lanes etc. at the intersection-level to analyze and identify vulnerable sections. Safety prediction models could also be developed using the number of conflicts as one of the independent variables.

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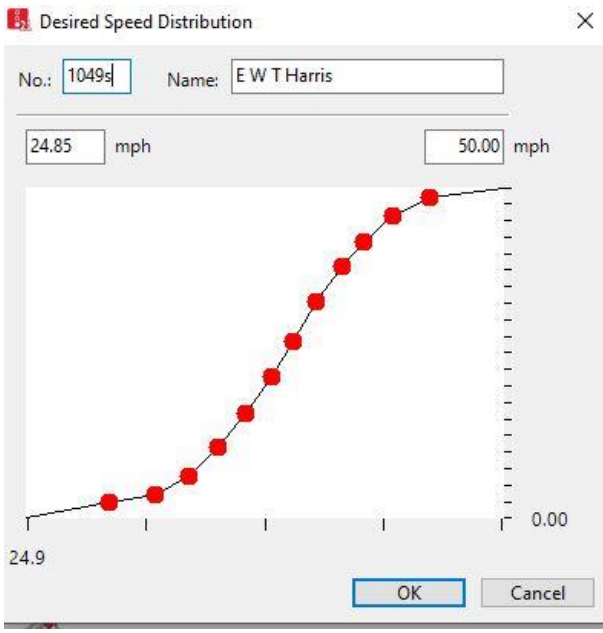
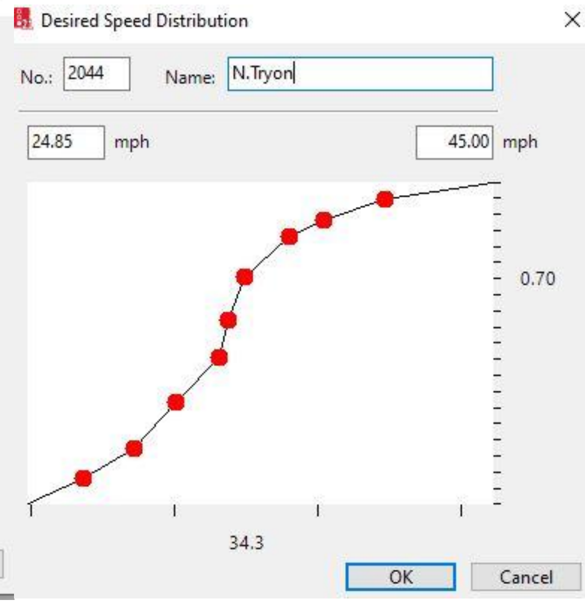
# APPENDIX A: SPEED DISTRIBUTION CURVES, OUTPUT VALIDATION AND TRAVEL TIME RESULTS FROM VISSIM

This appendix presents the speed distribution curves that are used in the model, vehicular volume outputs for Scenario 1 and travel times at corridor level for all the scenarios.

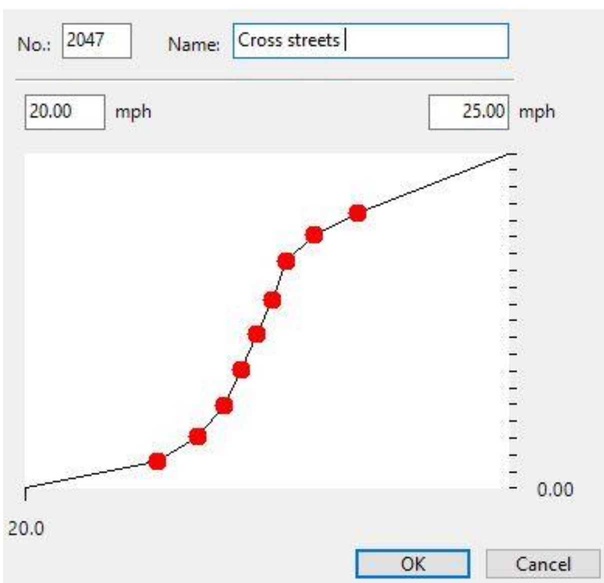
Figure A1 shows the desired speed distribution curves for the network. The speed distribution curves are developed for the study corridor and the cross-streets based on the speed data available from the RITIS website.




(a)




(b)

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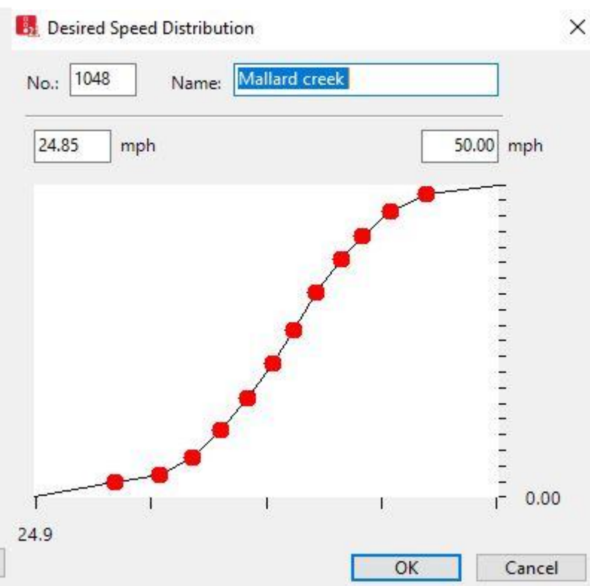


(d)

Figure A1 Speed Distribution Curves Used on the Links in the Network

Table A2 summarizes the vehicular volumes observed in the simulation runs against the desirable vehicular volumes at intersections on the study corridor. The data collection points are provided at the intersection before the vehicles diverge on their paths. The data collection was also done on cross-streets, but the simulation volumes and the observed volumes are the same for all approaches on the cross-streets.

Table A2. Vehicular Volumes from Simulation Runs vs. Desired Vehicular Volumes at Intersections on the Study Corridor

| Intersection | Simulation volumes | TMC Volumes |
|---|---|---|
| N Tryon St & Mallard Creek Church Rd | 1484 | 1722 |
| N Tryon St & Institute Cir | 1434 | 1374 |
| N Tryon St & JW Clay Blvd | 1314 | 1226 |
| N Tryon St & J M Keynes Blvd | 1326 | 1018 |
| N Tryon St & E WT Harris Blvd | 1245 | 928 |
| N Tryon St & Ken Hoffmann Dr | 1191 | 1230 |
| N Tryon St & McCullough Dr | 1501 | 1864 |
| N Tryon St & University Pointe Blvd | 1288 | 1330 |

Notes: TMC Volumes is the turning movement count volume provided by CDOT for the evening peak hour. Simulation volumes are the turning movement count volume at the respective intersection.

Tables A3 to A10 summarize the vehicle travel times between the intersections and total corridor level travel times observed from simulations. The intersection of University City Blvd is the first intersection. Hence the travel time calculation will start from that intersection. Therefore, University City Blvd is excluded, and the travel time measurements will be documented starting from University Pointe Blvd.

Table A3. Vehicle Travel times from Simulation Runs at Link and Corridor Level - Scenario 1

| Scenario 1 - ATT (In seconds) | | |
|---|---|---|
| Intersection | NB | SB |
| N Tryon St & University Pointe Blvd | 68.00 | 24.76 |
| N Tryon St & McCullough Dr | 64.67 | 66.83 |
| N Tryon St & Ken Hoffmann Dr | 51.24 | 21.26 |
| N Tryon St & E WT Harris Blvd | 37.39 | 44.35 |
| N Tryon St & J M Keynes Blvd | 47.38 | 37.29 |
| N Tryon St & JW Clay Blvd | 57.01 | 41.87 |
| N Tryon St & Institute Cir | 73.35 | 62.49 |
| N Tryon St & Mallard Creek Church Rd | 76.41 | 101.03 |
| Corridor | 475.46 | 399.88 |

Notes: NB-Northbound, SB-Southbound

Table A4. Vehicle Travel times from Simulation Runs at Link and Corridor Level - Scenario 2

| Scenario 2 - ATT (In seconds) | | |
|---|---|---|
| Intersection | NB | SB |
| N Tryon St & University Pointe Blvd | 68.48 | 24.71 |
| N Tryon St & McCullough Dr | 64.70 | 67.05 |
| N Tryon St & Ken Hoffmann Dr | 51.40 | 21.33 |
| N Tryon St & E WT Harris Blvd | 37.12 | 44.41 |
| N Tryon St & J M Keynes Blvd | 47.36 | 37.98 |
| N Tryon St & JW Clay Blvd | 57.43 | 42.03 |
| N Tryon St & Institute Cir | 78.05 | 67.42 |
| N Tryon St & Mallard Creek Church Rd | 75.94 | 106.19 |
| Corridor | 480.48 | 411.12 |

Notes: NB-Northbound, SB-Southbound

Table A5. Vehicle Travel times from Simulation Runs at Link and Corridor Level - Scenario 3

| Scenario 3 - ATT (In seconds) | | |
|---|---|---|
| Intersection | NB | SB |
| N Tryon St & University Pointe Blvd | 67.37 | 24.63 |
| N Tryon St & McCullough Dr | 63.59 | 67.61 |
| N Tryon St & Ken Hoffmann Dr | 51.47 | 21.00 |
| N Tryon St & E WT Harris Blvd | 28.90 | 44.44 |
| N Tryon St & J M Keynes Blvd | 47.83 | 38.54 |
| N Tryon St & JW Clay Blvd | 58.30 | 42.22 |
| N Tryon St & Institute Cir | 73.52 | 64.09 |
| N Tryon St & Mallard Creek Rd | 76.11 | 97.55 |
| Corridor | 467.09 | 400.08 |

Notes: NB-Northbound, SB-Southbound

Table A6. Vehicle Travel times from Simulation Runs at Link and Corridor Level - Scenario 4

| Scenario 4 - ATT (In seconds) | | |
|---|---|---|
| Intersection | NB | SB |
| N Tryon St & University Pointe Blvd | 67.71 | 24.55 |
| N Tryon St & McCullough Dr | 64.00 | 64.21 |
| N Tryon St & Ken Hoffmann Dr | 50.26 | 20.73 |
| N Tryon St & E WT Harris Blvd | 34.79 | 43.15 |
| N Tryon St & J M Keynes Blvd | 46.06 | 36.00 |
| N Tryon St & JW Clay Blvd | 56.27 | 40.04 |
| N Tryon St & Institute Cir | 73.82 | 59.32 |
| N Tryon St & Mallard Creek Church Rd | 75.43 | 103.29 |
| Corridor | 468.34 | 391.29 |

Notes: NB-Northbound, SB-Southbound

Table A7. Vehicle Travel times from Simulation Runs at Link and Corridor Level - Scenario 5

| Scenario 5 - ATT (In seconds) | | |
|---|---|---|
| Intersection | NB | SB |
| N Tryon St & University Pointe Blvd | 70.48 | 24.97 |
| N Tryon St & McCullough Dr | 64.50 | 67.25 |
| N Tryon St & Ken Hoffmann Dr | 54.43 | 21.41 |
| N Tryon St & E WT Harris Blvd | 38.48 | 45.09 |
| N Tryon St & J M Keynes Blvd | 46.50 | 39.53 |
| N Tryon St & JW Clay Blvd | 59.75 | 43.46 |
| N Tryon St & Institute Cir | 85.71 | 69.94 |
| N Tryon St & Mallard Creek Church Rd | 76.04 | 111.24 |
| Corridor | 495.89 | 422.89 |

Notes: NB-Northbound, SB-Southbound

Table A8. Vehicle Travel times from Simulation Runs at Link and Corridor Level - Scenario 6

| Scenario 6 - ATT (In seconds) | | |
|---|---|---|
| Intersection | NB | SB |
| N Tryon St & University Pointe Blvd | 73.44 | 25.12 |
| N Tryon St & McCullough Dr | 65.55 | 67.98 |
| N Tryon St & Ken Hoffmann Dr | 53.33 | 21.08 |
| N Tryon St & E WT Harris Blvd | 39.74 | 45.85 |
| N Tryon St & J M Keynes Blvd | 44.72 | 39.05 |
| N Tryon St & JW Clay Blvd | 59.80 | 42.70 |
| N Tryon St & Institute Cir | 90.02 | 77.63 |
| N Tryon St & Mallard Creek Church Rd | 75.59 | 116.24 |
| Corridor | 502.18 | 435.65 |

Notes: NB-Northbound, SB-Southbound

Table A9. Vehicle Travel times from Simulation Runs at Link and Corridor Level - (LRT Frequency is 6)

| LRT 6 Frequency - ATT (In seconds) | | |
|---|---|---|
| Intersection | NB | SB |
| N Tryon St & University Pointe Blvd | 67.99 | 24.79 |
| N Tryon St & McCullough Dr | 65.08 | 66.14 |
| N Tryon St & Ken Hoffmann Dr | 51.14 | 21.59 |
| N Tryon St & E WT Harris Blvd | 30.87 | 44.34 |
| N Tryon St & J M Keynes Blvd | 48.74 | 38.29 |
| N Tryon St & JW Clay Blvd | 57.83 | 43.52 |
| N Tryon St & Institute Cir | 75.00 | 63.47 |
| N Tryon St & Mallard Creek Church Rd | 76.13 | 100.86 |
| Corridor | 472.78 | 403.00 |

Notes: NB-Northbound, SB-Southbound

Table A10. Vehicle Travel times from Simulation Runs at Link and Corridor Level - (LRT Frequency is 10)

| LRT 10 Frequency- ATT (In seconds) | | |
|---|---|---|
| Intersection | NB | SB |
| N Tryon St & University Pointe Blvd | 66.77 | 24.53 |
| N Tryon St & McCullough Dr | 62.88 | 70.03 |
| N Tryon St & Ken Hoffmann Dr | 51.68 | 20.51 |
| N Tryon St & E WT Harris Blvd | 27.69 | 42.60 |
| N Tryon St & J M Keynes Blvd | 45.94 | 39.69 |
| N Tryon St & JW Clay Blvd | 58.32 | 41.43 |
| N Tryon St & Institute Cir | 73.35 | 64.84 |
| N Tryon St & Mallard Creek Church Rd | 76.25 | 97.20 |
| Corridor | 462.88 | 400.84 |

Notes: NB-Northbound, SB-Southbound

# APPENDIX B: OTHER OPERATIONAL PERFORMANCE MEASURES FROM SIMULATION ANALYSIS

This appendix presents the other operational performance measures that are captured for all the hypothetical scenarios.

Tables B1, B2 and B3 summarize the average queue length (in feet) at the intersections in the study corridor. Tables B4 and B5 presents the Maximum queue length and LOS for change in the LRT frequency. Table B6 presents the average walking speed of pedestrians in scenario 4 and scenario 5.

Table B1. Average Queue Length for Scenario 1, Scenario 2, and Scenario 3

| Average Queue Length (In feet) | | | |
|---|---|---|---|
| Intersection | 1 | 2 | 3 |
| N Tryon St & Institute Cir | 54.60 | 59.57 | 55.13 |
| N Tryon St & JW Clay Blvd | 46.37 | 48.62 | 56.28 |
| N Tryon St & J M Keynes Blvd | 26.95 | 27.27 | 28.86 |
| N Tryon St & E WT Harris Blvd | 75.59 | 76.28 | 82.05 |
| N Tryon St & Ken Hoffmann Dr | 29.74 | 29.85 | 30.69 |
| N Tryon St & McCullough Dr | 12.20 | 12.28 | 11.79 |
| N Tryon St & University Pointe Blvd | 33.33 | 33.89 | 35.42 |

Notes: 1-Scenario 1 (Vehicle with LRT). 2-Scenario 2 (Vehicles with LRT and pedestrians). 3-Scenario 3 (Vehicles with LRT, Pedestrians and Bicycles).

Table B2. Average Queue Length for Scenario 3, Scenario 4, Scenario 5, and Scenario 6

| Average Queue Length (In feet) | | | | |
|---|---|---|---|---|
| Intersection | 3 | 4 | 5 | 6 |
| N Tryon St & Institute Cir | 55.13 | 46.95 | 77.77 | 73.45 |
| N Tryon St & JW Clay Blvd | 56.28 | 41.00 | 55.64 | 59.02 |
| N Tryon St & J M Keynes Blvd | 28.86 | 22.53 | 30.84 | 34.13 |
| N Tryon St & E WT Harris Blvd | 82.05 | 58.19 | 214.81 | 72.69 |
| N Tryon St & Ken Hoffmann Dr | 30.69 | 24.17 | 35.20 | 29.07 |
| N Tryon St & McCullough Dr | 11.79 | 10.05 | 14.36 | 14.92 |
| N Tryon St & University Pointe Blvd | 35.42 | 27.40 | 40.03 | 36.21 |

Notes: 3-Scenario 3 (Vehicles with LRT, Pedestrians and Bicycles). 4-Scenario 4 (Decrease in Vehicles with LRT and pedestrians). 5-Scenario 5 (Increase in Vehicles with LRT and pedestrians). 6- Scenario 6 (Vehicles with LRT, increase in Pedestrians and Bicycles).

Table B3. Average Queue Length for Scenario 3, Scenario 7, and Scenario 8

| Average Queue Length (In feet) | | | |
|---|---|---|---|
| Intersection | 3 | 7 | 8 |
| N Tryon St & Institute Cir | 55.13 | 53.14 | 57.82 |
| N Tryon St & JW Clay Blvd | 56.28 | 54.46 | 56.12 |
| N Tryon St & J M Keynes Blvd | 28.86 | 27.68 | 29.76 |
| N Tryon St & E WT Harris Blvd | 82.05 | 91.01 | 80.83 |
| N Tryon St & Ken Hoffmann Dr | 30.69 | 30.16 | 30.18 |
| N Tryon St & McCullough Dr | 11.79 | 11.26 | 12.31 |
| N Tryon St & University Pointe Blvd | 35.42 | 35.71 | 34.79 |

Notes: 3-Scenario 3 (Vehicles with LRT, Pedestrians and Bicycles). 7-Scenario 7 Decrease in the LRT frequency with vehicles and pedestrians). and pedestrians). 8-Scenario 8 (Increase in the LRT frequency with vehicles and pedestrians).

Table B4. Maximum Queue Length for Scenario 3, Scenario 7, and Scenario 8

| Maximum Queue Length (In feet) | | | |
|---|---|---|---|
| Intersection | 3 | 7 | 8 |
| N Tryon St & Institute Cir | 662.39 | 621.15 | 707.97 |
| N Tryon St & JW Clay Blvd | 355.50 | 308.51 | 388.00 |
| N Tryon St & J M Keynes Blvd | 377.17 | 441.49 | 412.29 |
| N Tryon St & E WT Harris Blvd | 692.09 | 950.54 | 710.40 |
| N Tryon St & Ken Hoffmann Dr | 365.03 | 338.59 | 396.12 |
| N Tryon St & McCullough Dr | 335.28 | 287.90 | 353.26 |
| N Tryon St & University Pointe Blvd | 356.17 | 334.60 | 285.50 |

Notes: 3-Scenario 3 (Vehicles with LRT, Pedestrians and Bicycles). 7-Scenario 7 Decrease in the LRT frequency with vehicles and pedestrians). and pedestrians). 8-Scenario 8 (Increase in the LRT frequency with vehicles and pedestrians).

Table B5. Level of Service (LOS) for Scenario 3, Scenario 7, and Scenario 8

| Level of Service (LOS) | | | |
|---|---|---|---|
| Intersection | 3 | 7 | 8 |
| N Tryon St & Institute Cir | E | E | E |
| N Tryon St & JW Clay Blvd | D | D | D |
| N Tryon St & J M Keynes Blvd | D | D | D |
| N Tryon St & E WT Harris Blvd | D | D | D |
| N Tryon St & Ken Hoffmann Dr | C | C | C |
| N Tryon St & McCullough Dr | B | B | B |
| N Tryon St & University Pointe Blvd | D | D | D |

Notes: 3-Scenario 3 (Vehicles with LRT, Pedestrians and Bicycles). 7-Scenario 7 Decrease in the LRT frequency with vehicles and pedestrians). and pedestrians). 8-Scenario 8 (Increase in the LRT frequency with vehicles and pedestrians).

Table B6. Average walking speed for Scenario 4 and Scenario 5

| Average walking speed (mph) | | |
|---|---|---|
| Intersection | Scenario 4 | Scenario 5 |
| N Tryon St & Institute Cir | 1.99 | 1.99 |
| N Tryon St & JW Clay Blvd | 1.88 | 1.88 |
| N Tryon St & J M Keynes Blvd | 2.17 | 2.17 |
| N Tryon St & E WT Harris Blvd | 1.88 | 1.88 |
| N Tryon St & Ken Hoffmann Dr | 1.83 | 1.83 |
| N Tryon St & McCullough Dr | 2.29 | 2.29 |
| N Tryon St & University Pointe Blvd | 2.49 | 2.49 |

Notes: Scenario 4- (Decrease in Vehicles with LRT, pedestrians, and bicycles). Scenario 5- (Increase in Vehicles with LRT and pedestrians).

APPENDIX C: SURROGATE SAFETY ASSESMENT MODEL OUTPUTS

This appendix presents the surrogate safety assessment model conflict results for all scenarios. Table C1 to C6 show the conflict results for individual simulation runs and the average of these simulation runs are used in figures 34 to 36.

Table C1. Traffic Conflicts / Hour for Scenario 1

| Scenario 1 | | | | |
|---|---|---|---|---|
| Simulation Run | Total | Crossing | Rear end | Lane change |
| 1 | 1010 | 273 | 595 | 142 |
| 2 | 1009 | 240 | 613 | 156 |
| 3 | 1005 | 261 | 590 | 154 |
| 4 | 996 | 264 | 579 | 153 |
| 5 | 976 | 218 | 594 | 164 |
| Average | 999 | 251 | 594 | 154 |

Notes : Scenario 1- Vehicles with LRT

Table C2. Traffic Conflicts / Hour for Scenario 2

| Scenario 2 | | | | |
|---|---|---|---|---|
| Simulation Run | Total | Crossing | Rear end | Lane change |
| 1 | 1048 | 282 | 631 | 135 |
| 2 | 1062 | 254 | 629 | 179 |
| 3 | 1172 | 283 | 713 | 176 |
| 4 | 1129 | 270 | 676 | 183 |
| 5 | 1055 | 236 | 652 | 167 |
| Average | 1093 | 265 | 660 | 168 |

Notes : Scenario 2- Vehicles with LRT and pedestrians

Table C3. Traffic Conflicts / Hour for Scenario 3

| Scenario 3 | | | | |
|---|---|---|---|---|
| Simulation Run | Total | Crossing | Rear end | Lane change |
| 1 | 1213 | 287 | 746 | 180 |
| 2 | 1256 | 241 | 821 | 194 |
| 3 | 1084 | 246 | 689 | 149 |
| 4 | 1102 | 262 | 677 | 163 |
| 5 | 1136 | 217 | 750 | 169 |
| Average | 1158 | 250 | 737 | 171 |

Notes : Scenario 3- Vehicles with LRT, pedestrians and bicycles

Table C4. Traffic Conflicts / Hour for Scenario 4

| Scenario 4 | | | | |
|---|---|---|---|---|
| Simulation Run | Total | Crossing | Rear end | Lane change |
| 1 | 791 | 189 | 481 | 121 |
| 2 | 828 | 197 | 513 | 118 |
| 3 | 748 | 148 | 496 | 104 |
| 4 | 828 | 179 | 535 | 114 |
| 5 | 783 | 183 | 475 | 125 |
| Average | 796 | 180 | 500 | 116 |

Notes : Scenario 4- Decrease in Vehicles with LRT, pedestrians and bicycles

Table C5. Traffic Conflicts / Hour for Scenario 5

| Scenario 5 | | | | |
|---|---|---|---|---|
| Simulation Run | Total | Crossing | Rear end | Lane change |
| 1 | 2977 | 332 | 2176 | 469 |
| 2 | 1954 | 318 | 1318 | 318 |
| 3 | 3293 | 318 | 2517 | 458 |
| 4 | 2027 | 331 | 1409 | 287 |
| 5 | 1661 | 302 | 1094 | 265 |
| Average | 2382 | 320 | 1703 | 359 |

Notes : Scenario 5- Increase in Vehicles with LRT, pedestrians and bicycles

Table C6. Traffic Conflicts / Hour for Scenario 6

| Scenario 6 | | | | |
|---|---|---|---|---|
| Simulation Run | Total | Crossing | Rear end | Lane change |
| 1 | 1256 | 278 | 814 | 164 |
| 2 | 1389 | 266 | 930 | 193 |
| 3 | 1343 | 238 | 899 | 206 |
| 4 | 1369 | 245 | 932 | 192 |
| 5 | 1288 | 238 | 865 | 185 |
| Average | 1329 | 253 | 888 | 188 |

Notes : Scenario 6- Vehicles with LRT, pedestrians and bicycles (increase)