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Modeling Operational Performance of Urban Roads with Heterogeneous Traffic Conditions

Swapneel R. Kodupuganti
Sonu Mathew
Srinivas S. Pulugurtha

Mineta Transportation Institute

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16. Abstract

The rapid growth in population and related demand for travel during the past few decades has had a catalytic effect on traffic congestion, air quality, and safety in many urban areas. Transportation managers and planners 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. However, there are no widely accepted methods, nor there is enough evidence to justify whether such plans are instrumental in improving mobility of the transportation system. Therefore, this project researches the operational performance of urban roads with heterogeneous traffic conditions to improve the mobility and reliability of people and goods. A 4-mile stretch of the Blue Line light rail transit (LRT) extension, which connects Old Concord Rd and the University of North Carolina at Charlotte's main campus on N Tryon St in Charlotte, North Carolina, was considered for travel time reliability analysis. The influence of crosswalks, sidewalks, trails, greenways, on-street bicycle lanes, bus/LRT routes and stops/stations, and street network characteristics on travel time reliability were comprehensively considered from a multimodal perspective. Likewise, a 2.5-mile-long section of the Blue Line LRT extension, which connects University City Blvd and Mallard Creek Church Rd on N Tryon St in Charlotte, North Carolina, was considered for simulation-based operational analysis. Vissim traffic simulation software was used to compute and compare delay, queue length, and maximum queue length at nine intersections to evaluate the influence of vehicles, LRT, pedestrians, and bicyclists, individually and/or combined. The statistical significance of variations in travel time reliability were particularly less in the case of links on N Tryon St with the Blue Line LRT extension. However, a decrease in travel time reliability on some links was observed on the parallel route (I-85) and cross-streets. While a decrease in vehicle delay on northbound and southbound approaches of N Tryon St was observed in most cases after the LRT is in operation, the cross-streets of N Tryon St incurred a relatively higher increase in delay after the LRT is in operation. The current pedestrian and bicycling activity levels seemed insignificant to have an influence on vehicle delay at intersections. The methodological approaches from this research can be used to assess the performance of a transportation facility and identify remedial solutions from a multimodal perspective.

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Mineta Transportation Institute

College of Business
San José State University
San José, CA 95192-0219

Tel: (408) 924-7560
Email: mineta-institute@sjsu.edu

transweb.sjsu.edu/research/1802

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Executive Summary

Several urban areas in the United States have planned for new facilities to cater to the needs of users of alternative modes of transportation (for example, public transportation, walking, and bicycling) over the next decade. As an example, the city of Charlotte has recently extended its 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 (for example, 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 the safety of the transportation system from a multimodal perspective. Further, there are no widely accepted methods to assess the influence of such facilities or transportation projects in terms of improved mobility and enhanced user safety. Therefore, the goal of this project is to research and model the operational performance of urban roads with heterogeneous traffic conditions to improve the mobility, reliability, and safety of people and goods. The objectives are:

- To collect data and comprehensively evaluate the influence 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, and
- 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.

First, a TTR-based approach was used to assess the influence of the LRT system on the road network within its vicinity. This approach included the influence of crosswalks, sidewalks, trails, greenways, on-street bicycle lanes, bus/LRT routes and stops/stations, and street network characteristics on travel time and TTR from a multimodal perspective. A four-mile stretch of the Blue Line LRT extension, which connects Old Concord Rd 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 the Regional Integrated Transportation Information System (RITIS) website 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 selected link by day of the week and time of the day. Further, the TTR of the selected links on the LRT study corridor and adjacent corridors (both the parallel route and the cross-streets) were computed and compared for different scenarios: network without LRT, the sixth month of LRT operation, the twelfth month of LRT operation, and the 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. The research further revealed increased green times as vehicles along N Tryon St obtained more green time due to frequent lane closures on cross-streets.

Such lane closures were put in place in order to prioritize LRT movement and a better coordination on the LRT corridor. The benefits associated with the alternative mode/route choice for commuters may be because of the steadiness in travel time performance measured in the LRT corridor.

The simulation-based analysis was conducted using data for a 2.5-mile-long corridor along the recently extended LRT route. This approach evaluated the influence of vehicles, LRT, pedestrians, and bicyclists, individually and/or combined, on transportation system performance from a multimodal perspective. The traffic and signal data were obtained from the city of Charlotte Department of Transportation (CDoT). It is important to note that there are no midblock or unsignalized crosswalks along the study corridor. The facilities and signal timings provided for pedestrians and bicyclists at intersections seem to be adequate based on current or projected activity levels. Models were built in Vissim for the following scenarios: no LRT build, build but LRT is not in operation, build and LRT is in operation, build and LRT is in operation with pedestrian activity, and build and LRT is in operation with pedestrian & bicyclist activity. Background maps were used in Vissim to import the network characteristics for each scenario. Vehicle delay, queue length, maximum queue length, and level of service (LOS) were used as the performance measures to evaluate the influence of an LRT and related activity on the transportation system's performance. There was a decrease in vehicle delay due to the change in geometric characteristics and signal phasings/timings at some selected intersections with LRT in operation. An increase in vehicle delay was observed on the cross-street approaches, whereas only a small change in vehicle delay was observed on N Tryon St for the LRT in operation scenario. Pedestrian and bicyclist activity at some intersections was found to have nominal influence on vehicle delay.

I. Introduction

Many urban areas in the United States have seen rapid population growth during the past few decades. The growth in population has had a catalytic effect on traffic congestion, air quality, and safety in these 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).[1] Congestion, in particular, is considered a "negative phenomenon" (Sierpiński 2011)[2] resulting from the increasing traffic volumes during peak hours, and it is one of the challenges almost every urban area faces today. Considering the pace at which the present population and travel demand growth rates are increasing, the annual delay and the forecasted nation-wide congestion costs are expected to be around 8.3 billion hours and $192 billion in 2020 (Urban Utility Score Card 2015).[3]

The construction of new roads, widening of existing roads, and improved connectivity help to mitigate and address the aforementioned 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 constraints (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 (for example, 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).[4] These modes help to move a larger number of people at lower operational costs and with a higher degree of reliability compared to commuter rail transit systems (Knowles 1996).[5] 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 LRT or similar travel modes could be six times safer than automobile travel (Linda 2003).[6]

1.1 Need for This Research

LRT is considered the best-suited option for serving travel demand in "medium-sized North American cities" since the nineties (Black 1993).[7] 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, 2017, around 543 million transit trips were reported across the United States (APTA 2019).[8] LRT ridership was reported to have surpassed commuter rail ridership from 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).[9]

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 make the LRT system more lucrative and safer for 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 on the major street. Giving signal priority to the LRT system on the major street could have a negative influence on operational performances along the cross-streets. Assessing the influence 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 effects of such changes on traffic operations are uncertain and ought to be researched.

Typical travel demand models capture the influence of large-scale transportation projects like the LRT system in a socio-economic-spatial aspect. However, it is difficult to fully understand the LRT system's influence on the region's traffic using only travel demand models. In that context, providing short-term evidence of LRT systems' influence 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 influence of such facilities or transportation projects on improving mobility and enhancing user safety. Questions such as those listed below have been lingering in the minds of researchers and practitioners.

- How effective are plans proposed by practitioners to enhance connectivity and improve mobility?
- What is the influence of an LRT line, and how far could the influence of an LRT line extend (spatially) and affect the operational performance of urban roads within its vicinity?
- What is the operational performance of urban roads from a multimodal perspective?

Therefore, the first objective of this research is to 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. In this case, the influence of crosswalks, sidewalks, trails, greenways, on-street bicycle lanes, bus/LRT routes and stops/stations, and street network characteristics on travel time and TTR are evaluated from a multimodal perspective. Processing and analyzing travel time data and accomplishing this objective does not, however, help reveal the influence of the LRT system, pedestrian activity, and bicyclist activity at an intersection or corridor level. This is because travel time data used and aggregated at a link-level for analysis does not help assess the interaction between various modes of travel.

This said, some unforeseen influence of the LRT system with associated pedestrian and bicycling facilities may not be captured from the travel time-based assessment. A few effects might be intricate and understanding the influence of heterogeneous traffic conditions is the key to better optimizing the LRT system. Moreover, modeling and understanding the influence of public transportation systems, walking, and bicycling allows researchers to address any shortcomings beforehand. Microscopic simulation software like Vissim serves as a platform for facilitating a detailed probing into the influence of LRT, pedestrians, and bicyclists (PTV Group 2019).[9] The findings will aid in understanding what to expect in the future and will help public agencies to accommodate modal shift and other traffic congestion related issues, leading to desirable geometric changes like the addition of a dedicated turn-lane associated with the LRT operation. Therefore, the second objective of this research is to evaluate the influence of the LRT system, pedestrian activity, and bicycling activity on transportation system performance along the study corridor using traffic simulation software.

Overall, this research aims at developing a methodological framework to assess the performance of a multimodal corridor using both data-driven and simulation-based approaches. 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 evaluation helps practitioners in understanding the influence from a practical standpoint, comprehensively considering all modes. It also sets up a platform to further probe into the analysis at more microscopic levels. The simulation-based evaluation helps practitioners in understanding the influence of vehicles, LRT, pedestrian activity, and bicycling activity, individually and/or combined, on operational performances at intersections.

1.2 Research Objectives

The goal of this project is to research and model the operational performance of urban roads with heterogeneous traffic conditions to improve the safety, reliability, and mobility of people and goods. The objectives of the proposed project are:

- To collect data and comprehensively evaluate the influence of crosswalks, sidewalks, trails, greenways, on-street bicycle lanes, bus/LRT routes and stops/stations, and street network characteristics on travel time and TTR from a multimodal perspective, and
- 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.

1.3 Organization of the Report

The remainder of the report comprises four chapters. Chapter II presents a review of past research. Chapter III summarizes the features of the study corridor and selected intersection characteristics. The travel time data collection and processing; computation of selected travel time performance measures; analysis of the LRT system in terms of improving the TTR on the LRT route, parallel route, and cross-streets are discussed in Chapter IV. Chapter V presents the methodology adopted for traffic simulation analysis and summarizes and compares results for various analytical scenarios. The conclusions from this research and the scope of future work are discussed in Chapter VI.

II. Literature Review

This chapter presents a review of the literature on LRT and transportation systems' performance, as well as the use of traffic simulation software to investigate the effect of vehicular traffic, LRT, pedestrians, and bicyclists on transportation system performance.

2.1 LRT and Transportation System Performance

The Transportation Research Board (TRB)'s Committee on LRT defines an LRT 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).[10] The capability of the LRT system to alleviate congestion has been analyzed by many researchers in the past (Clark 1984, Knowles 1992, Garrett 2004).[11,12,13] The capability of the LRT system to stimulate transit-oriented development initiatives has also been studied in the past (Arrington and Cervero 2008).[14]

Good quality service attracts personal vehicle users to the LRT system, thus reducing traffic congestion (Knowles 1996).[15] On the contrary, LRT systems' capability to reduce congestion has also been questioned in some studies. Mackett and Edwards (1998)[15] state that the positive effect of many rail-based transit systems throughout the world on traffic congestion is less than earlier projections by prior researchers and practitioners.

Regional travel demand models have long been used as part of large-scale transit planning processes to examine transportation projects/improvements, such as an LRT system on network travel times (Ewing et al. 2014).[16] 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 LRT's effect on road traffic within its vicinity requires a comprehensive understanding of traffic and LRT signalization. Venglar et al. (1994)[17] 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 the influence of the LRT is the length of the automobile queue accumulated during the passage of an LRT (Bates and Lee 1982).[18] Islam et al. (2016)[19] 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).[20-22] As the dedicated transit lanes significantly disrupt the general traffic, Eichler and Daganzo (2006)[20] observed that bus lanes with intermittent priority reduce the general traffic interference. Similarly, Chiabaut and Barcet (2019)[22] proposed the use of intermittent transit lanes with transit signal priority as a better alternative to the dedicated bus transit line. Chiabaut et al. (2018)[21] 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)[23] 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.

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).[24, 3] Studies related to the measures of the effectiveness of LRT on arterial traffic, based on TTR measures, are found to be very limited.

The average travel time (ATT) indicates the nominal level of congestion in a road link. It is typically an indicator of the expected travel time. 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), and buffer time index (BTI). PT is the 95th 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 trips. PT and BT indicate the variability in travel times from a road user's perspective and represent the level of reliability for the transportation system over time.

According to the report published by FHWA (2005),[25] the PTI can be used as a measure of average congestion in 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)[26] studied commuters' attitudes toward the TTR while considering alternative modes of transportation. They further studied travelers' decision making in choosing their mode of transportation after a public transportation service closure and concluded the effect of travel time variations in the selection process. Pulugurtha et al. (2017)[27] surveyed transportation system users' perceptions of TTR measures and monetized the value of reliability to evaluate transportation projects and alternatives.

Limitations in Past Research

In summary, 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 studied in the past.

2.2 Traffic Simulation Software to Assess Transportation System Performance

Signal priority for public transportation affects the vehicular traffic and other modes of transportation. Yedlin and Lieberman (1981)[28] conducted simulation studies to identify ideal conditions that benefit transit operations. In that study, several factors that could influence public transportation were considered, and interrelations were examined between the factors.

Gomes et al. (2004)[29] constructed and calibrated a microsimulation model in Vissim using a 15-mile freeway stretch with a high occupancy lane in Pasadena, California as the study corridor. 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 Xuegang et al. (2007)[30] using the San Francisco Bay Area, California as the study area.

Stirzaker and Hussein (2007)[31] 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 high occupancy vehicle lane, and a general traffic lane. The 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 road infrastructure.

To fully understand the operational performance of urban roads with heterogeneous traffic conditions, many researchers have proposed the use of microscopic simulation-based analysis. Marwah and Singh (2000)[32] conducted a simulation study on Indian traffic conditions to evaluate the operational classification of urban traffic. A calibrated traffic simulation model was developed to analyze the study area. Based on the simulation results, operating characteristics were identified under different scenarios to evaluate the level of service (LOS). The operational characteristics for the four levels of service were identified as road occupancy, journey speed of cars (and two-wheelers), and vehicles per unit distance.

Cellular automation is an efficient microsimulation tool that uses a finite element model to mimic and evaluate physical systems over space and time, such as traffic (Wolf 1999, Deo 2007, Gundaliya et al. 2008, Tonguz et al. 2009, Yuan et al. 2008).[33–37] Deo (2007)[34] used two-component cellular automation to model the heterogeneous motorized traffic flow. The vehicles were classified into two types (short and long) and the research was conducted for various types of roads such as the single-lane, multi-lane controlled vs. uncontrolled intersections, and roundabouts. Gundaliya et al. (2008)[35] 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. The model was calibrated using the outputs from Vissim. The simulation runs were significantly faster in the case of the Nagel–Schreckenberg model (a theoretical model for the simulation of freeway traffic) compared to grid-based and Vissim models. However, the grid-based approach was proposed to be appropriate for heterogeneous conditions due to the ease of implementation.

Vanajakshi et al. (2009)[38] 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. Coppola and Rosati (2009)[39] also used the Kalman Filter technique to assess the effects of information provided in a public transportation network under different network conditions. They concluded that providing information on waiting time results in an increase of average waiting time.

Kinderyte_Poškiene and Sokolovskij (2008)[40] studied the effect of the presence of multimodal facilities along a traffic corridor. Traffic control elements such as yield signs, stop signs, speed limits, traffic signals, access control, parking control, etc. were considered in their study. The traffic control devices were classified into two categories to examine their effect on the safety and mobility of the traffic stream. The results indicated that traffic elements such as the signalized pedestrian crossings, road message signs, access points, traffic signs (speed limits and stop signs), transit lines and stops, and traffic calming devices contribute to reducing the frequency of the crashes. Similarly, traffic elements such as one-way streets, priority roads, reversible lanes, bus lines (and bus stop design), parking control, and traffic signal control at intersections were observed to improve the mobility of a traffic stream.

Wu et al. (2017)[41] evaluated pedestrian/vehicle conflicts at signalized intersections using Vissim traffic simulation software and the surrogate safety assessment model (SSAM). They observed that Vissim software underestimated the number of pedestrian/vehicle conflicts, as illegal pedestrian behavior could not be modeled with that software. Kim and Park (2019)[42] used Vissim traffic simulation software and SSAM to mimic pedestrian and vehicular interactions. They concluded that the effect of pedestrians on vehicular traffic at signalized intersections varies based on geometric features of the intersections.

Limitations in Past Research

Extant literature documents several efforts to assess transportation system performance using traffic simulation software. However, not many studies have evaluated the influence of the LRT system, pedestrian activity, and bicyclist activity on transportation system performance along corridors.

III. Study Corridor and Selected Intersections

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 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 2014 was reported for the city (TTI 2015).[3]

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).[43]

Plans are also being discussed to expand the bus transportation network and/or commuter rail, streetcar, or LRT service by 2030, in conjunction with improved access to various land uses across the city (CATS 2019).[44] 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),[45] bicyclist facilities (CDoT 2017b),[46] and shared mobility facilities (CDoT 2018).[47]

A four-mile stretch of the recent 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 the 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. The Blue Line LRT contains many at-grade crossings. To understand the influence 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

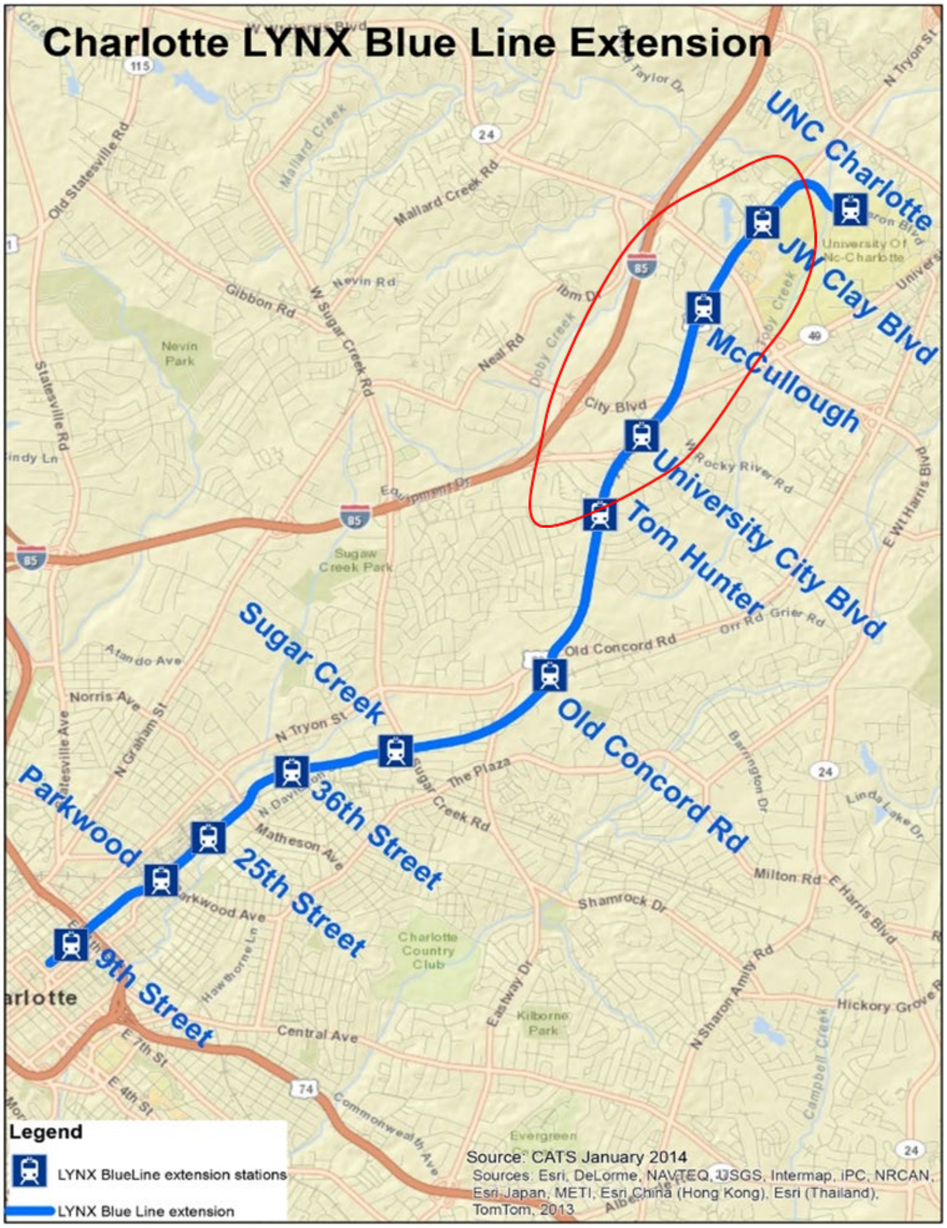
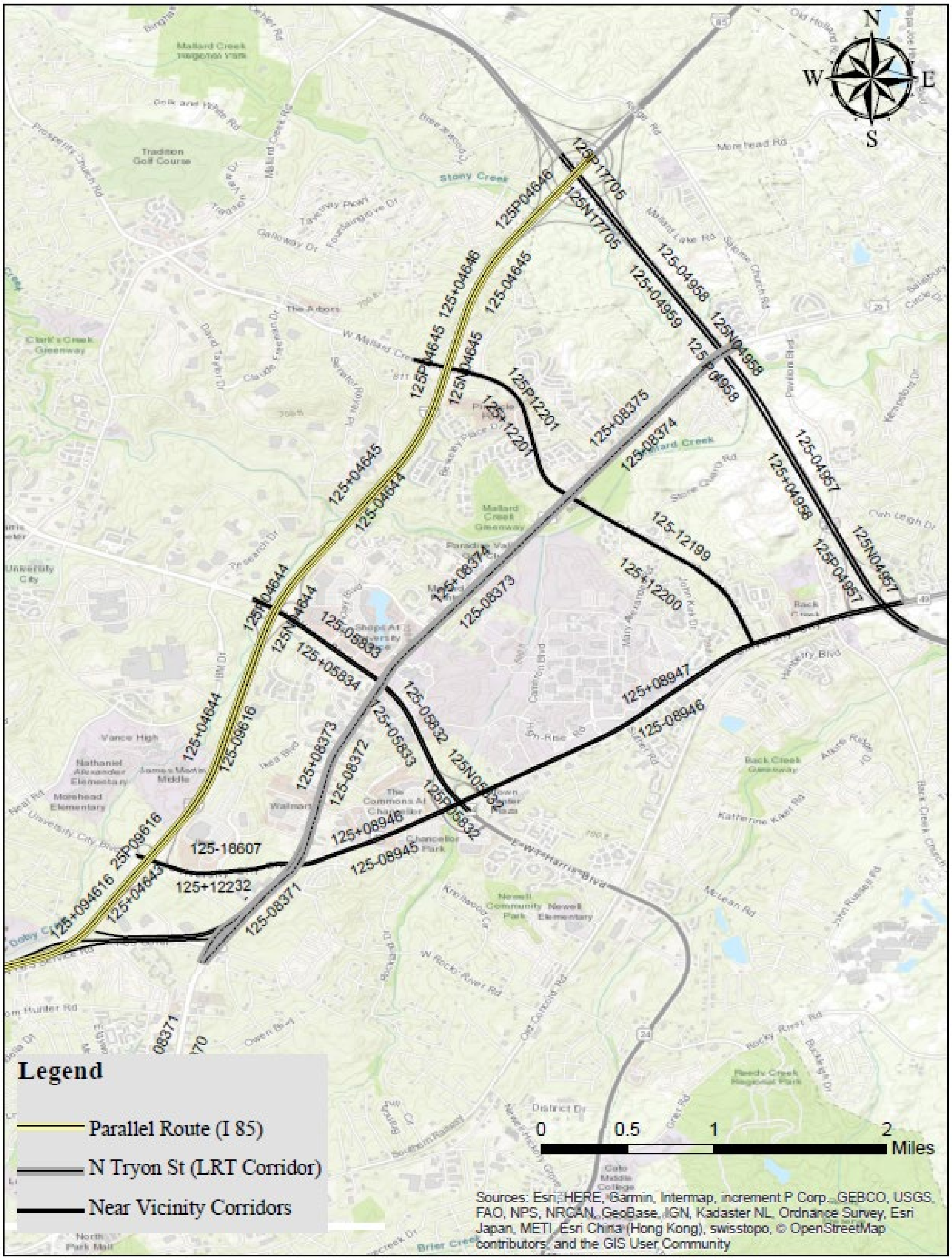


Figure 2. Study Area with Selected Links



A part of the four-mile stretch was used to model the influence 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. The next section presents a brief description of the geometric conditions during the following situations: no build (2016: some construction activity ongoing), build but not in operation (2017: LRT constructed but not in service for the users), and build and in operation (2018 and 2019: LRT was constructed and serving the users) at selected intersections.

3.1 Geometric Conditions at Selected Intersections

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.

In Figures 3 through 11, the leftmost image represents geometric conditions during 2016. The center image represents geometric conditions during 2017 (when the LRT had been constructed but was not in operation for users), while the rightmost image represents geometric conditions during 2018 and 2019 (LRT was constructed and serving users). On-street bicycle lanes were added in some areas during 2017. They were then painted green in 2018, which can be noticed in some rightmost images. The addition of on-street bicycle lanes illustrates the emphasis on improving travel conditions for bicyclists at selected intersections of the study corridor.

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 can be observed in Figure 3 (2016) along with one left-turn lane and one right-turn lane in the southbound direction. Later in 2017, three through lanes, one left-turn lane, an on-street bicycle lane, and one right-turn lane can be observed. There were no changes in the northbound direction.

Figure 3. N Tryon St & University City Blvd Intersection: 2016, 2017, & 2018 (Left to Right)

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 2016 during the construction phase. Later, two left-turn lanes, two through lanes, an on-street bicycle lane, and one right-turn lane can be observed in 2017 (Figure 4). Similarly, one left-turn lane, one through lane, and one shared through/right-turn lane can be seen in the southbound direction in 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 4. N Tryon St & University Pointe Blvd Intersection: 2016, 2017, & 2018 (Left to Right)

N Tryon St & McCullough Dr. Intersection

There were no lane additions at the McCullough Dr. intersection (Figure 5). However, there is one left-turn lane, two through lanes, and one right-turn lane in 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 2017. No changes were made to the cross-streets.

Figure 5. N Tryon St & McCullough Dr. Intersection: 2016, 2017, & 2018 (Left to Right)

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 (Figure 6) during 2018.

Figure 6. N Tryon St & Ken Hoffman Dr. Intersection: 2016, 2017, & 2018 (Left to Right)

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 (Figure 7). 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 7. N Tryon St & E WT Harris Blvd Intersection: 2016, 2017, & 2018 (Left to Right)

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. It can also be observed in Figure 8 that the length of the left-turn lane increased from 2016 to 2017.

N Tryon St & JW Clay Blvd Intersection

The intersection at JW Clay Blvd had three lanes in the southbound direction in 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 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 cross-streets. However, an on-street bicycle lane was added in the northbound and southbound directions on N Tryon St in 2017 (Figure 9).

Figure 8. N Tryon St & J M Keynes Dr. Intersection: 2016, 2017, & 2018 (Left to Right)

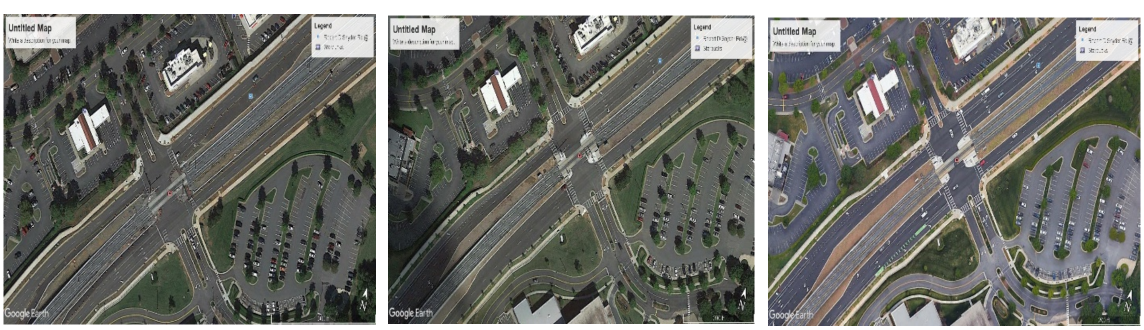
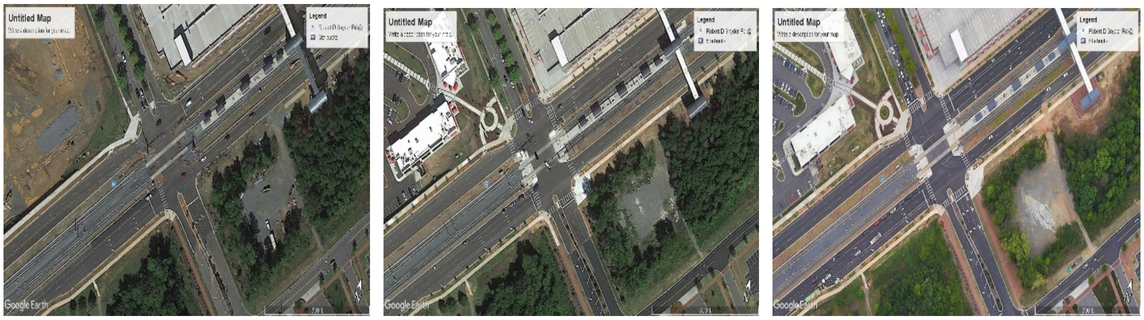


Figure 9. N Tryon St & JW Clay Blvd Intersection: 2016, 2017, & 2018 (Left to Right)



N Tryon St & Institute Cir Intersection

Institute Cir is the last intersection in the northern direction 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 (Figure 10). There were no lane changes in the northbound direction. However, there were three lanes in 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 2017, making it one left-turn lane, two through lanes, and one through/right-turn lane. It can be observed from the second and third pictures in Figure 10 that an on-street bicycle lane was added in the northbound direction from 2017 to 2018.

N Tryon St & E Mallard Creek Church Rd Intersection

Figure 11 shows the intersection at E Mallard Creek Church Rd. 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 10. N Tryon St & Institute Cir Intersection: 2016, 2017, & 2018 (Left to Right)

Figure 11. N Tryon St & E Mallard Creek Church Rd Intersection: 2016, 2017, & 2018 (Left to Right)

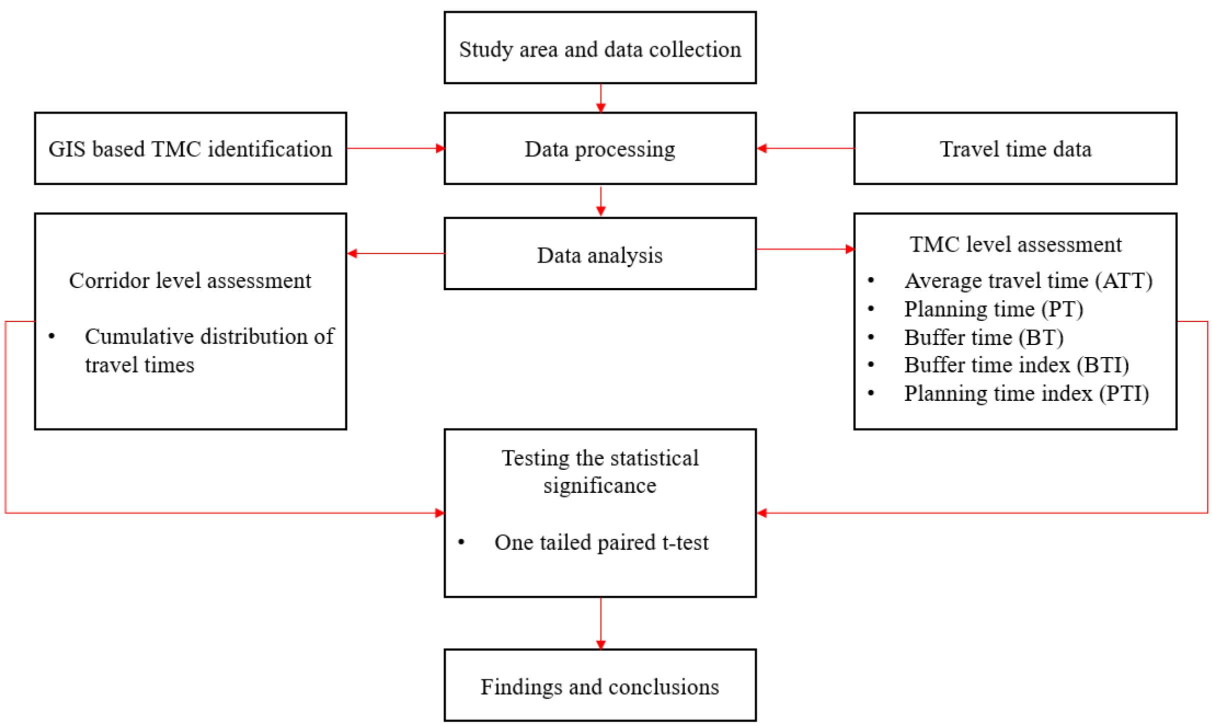
IV. Assessments Based on Travel Time and Travel Time Reliability (TTR)

This chapter presents 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 influence on travel time and TTR at the link and corridor levels.

4.1 Methodology

Figure 12 presents the methodological framework adopted for the TTR-based assessment of the transportation network (including the LRT system).

Figure 12. Methodological Framework for TTR-based Assessment



An elaborate discussion on each part of the methodology is presented in the subsequent sections.

Data Collection

Four different scenarios—network without 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 September 2017 are considered as representing the network without LRT in the operation. With the LRT infrastructure in place, several test runs were conducted in the fall of 2017. However, the LRT is not in operation for users.

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 is coded with a single identification code: namely, a Traffic Message Channel (TMC) ID. The data contain nine-digit TMC IDs, unique segment identification numbers (for example, 125+08373). The data processing is carried out at two levels: GIS-based link (TMC) identification and the computation of TTR indices.

Data Processing

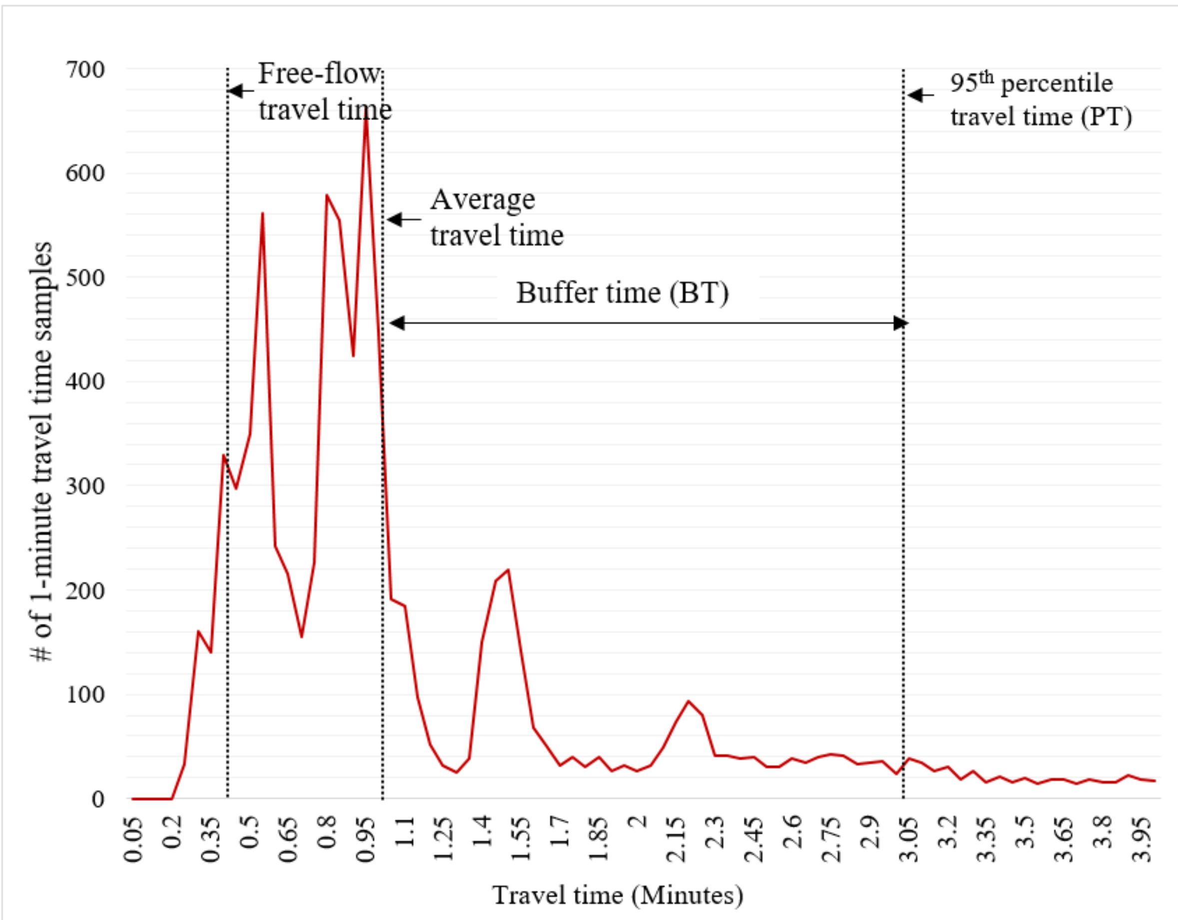
Geo-referencing of the links was done using four well-defined points (start latitude, start longitude, end latitude, and end longitude). The exact coordinates of these points were obtained from the RITIS database. These points were transferred to the street map of North Carolina. A buffer of one mile 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 during peak hours 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. The traffic signal cycles and green times need to be adjusted to give priority to the LRT. Due to this, the N Tryon St traffic may get more green time compared to the cross-streets. To understand the influence 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, E WT 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 travel time reliability 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 nighttime (8:00 PM – 9:00 PM) were considered.

Various percentile-based TTR measures were considered to assess the influence of the LRT system on transportation system performance. All these measures were derived from the travel time distributions (for example, as shown in Figure 13).

Figure 13. Travel Time Distribution: N Tryon St Study Corridor



The ATT, the free-flow travel time, and the 95th percentile travel time (PT) were computed for each link by aggregating data by day of the week and time of the day using Microsoft SQL. The 95th percentile travel time indicates that 95% of the time, the performance of the study link will not be worse than the values associated with the 95th percentile travel time. It is directly computed from the travel time data and also referred to as PT. BT is the difference between the 95th percentile travel time 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.

$$BT = 95th\ percentile\ travel\ time - ATT \quad (1)$$

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.

$$PTI = \frac{95th\ percentile\ travel\ time}{Free\text{−}flow\ travel\ time} \quad (2)$$

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

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

Data Analysis

An LRT system with dedicated right-of-way and signal priority influence the arterial street traffic. Figure 14 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 influence of the LRT system on the specific link of the road. Moreover, route-level aggregation may only provide the overall influence of TTR along the selected study corridor. As this research proposes a methodological framework for the assessment of the influence 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 of a link by the length of the corresponding link. The measures of TTR (i.e., ATT, PT, BT, BTI, and PTI) are derived from these distributions.

Figure 14. Interaction of the LRT System with the Moving Traffic, On-street Bicycle Lane, and Pedestrian Crosswalks

The statistical significance of the change in TTR measures (ATT, PT, BT, BTI, and PTI) over different phases of LRT operation was evaluated using one-tail paired t-tests. A one-tailed t-test helps assess if the mean TTR measure of a phase of LRT operation is significantly greater than or less than the mean TTR measure for the network without an LRT operation. This analysis was performed at a 95% confidence level. The null hypothesis assumes that the TTR measure for the network without an LRT operation is equal to the TTR measure for the selected phase of LRT operation. The alternate hypothesis assumes that the TTR measure for the network without LRT operation is greater than the TTR measure for the selected phase of an LRT operation.

4.2 Analysis of Travel Time Data

The analysis of travel time data at the link level and corridor level is discussed in this section.

Travel Time Reliability (TTR) at the 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 hours of the day. This section demonstrates the link-level TTR assessment of selected corridors during different phases of LRT operation.

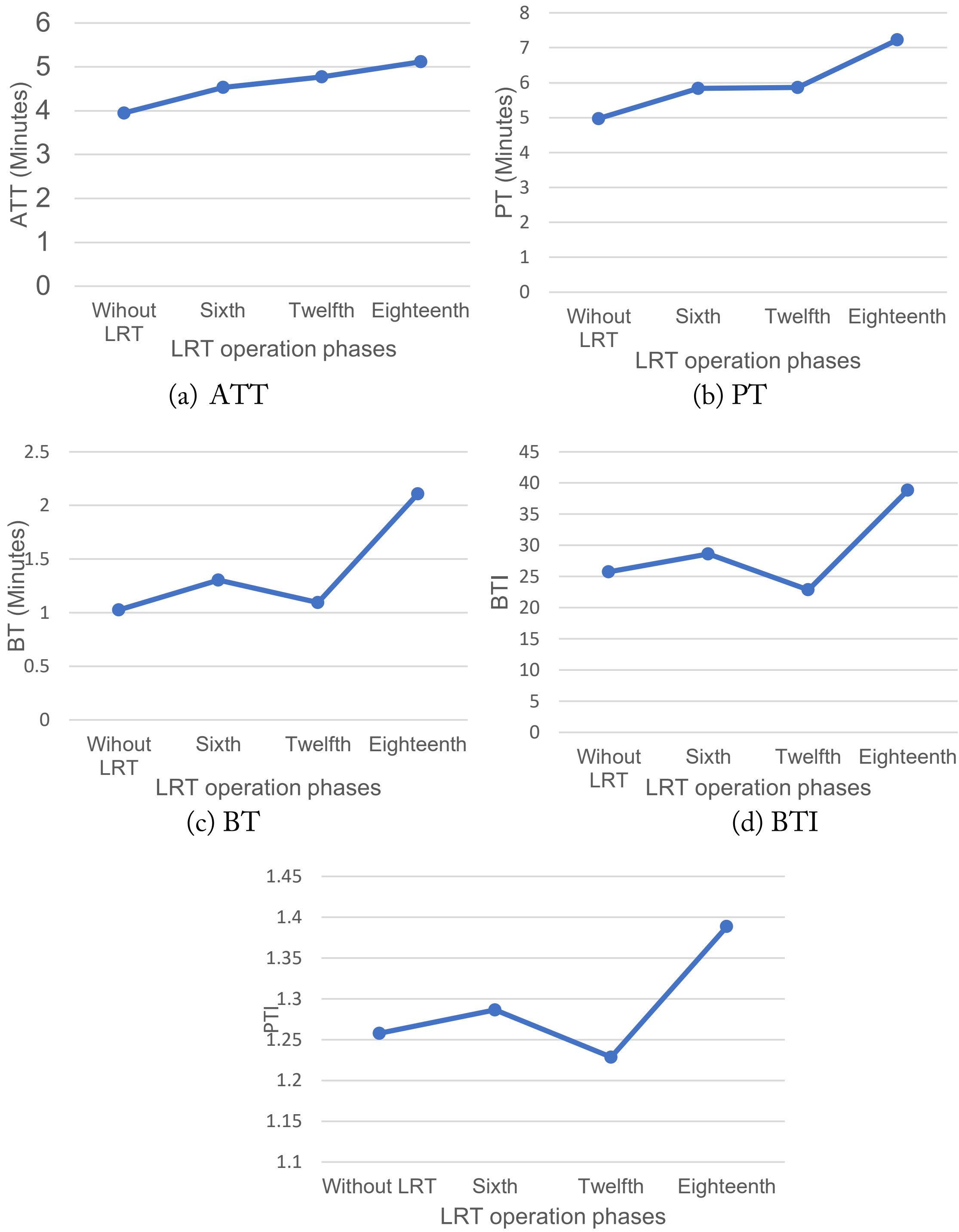
Influence on the Study Corridor (N Tryon St)

The TTR assessment was carried out on twelve different links on 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 15. From Figure 15, there is a trend of worsening TTR over different phases of LRT operation. The influence is at a maximum during the eighteenth month of LRT operation.

Further, for each selected link, the ratio between the travel time performance measure for (a) the analysis phase and (b) the network without the LRT phase was computed. A ratio value greater than one indicates a decrease in the TTR measures, 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 1. The column corresponding to the network without LRT shows the TTR measures, and the change in TTR during different phases is shown with ratios.

The green shaded cells indicate a ratio of less than one, which indicates an improvement in the performance measure after the operation of the Blue Line 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 1, is reported as 0.94 for link ID -125+08371. This implies a 6% decrease in the ATT during the sixth month of LRT operation when compared to the network without the LRT condition.

Figure 15. TTR of 125+08371 over Different Phases of LRT Operation



(a) ATT (b) PT (c) BT (d) BTI (e) PTI

In Table 1, 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 performance. While looking into the twelfth month of LRT operation, many links showed an improvement in reliability compared to the sixth month of an LRT operation. During the eighteenth month of an LRT 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 during the evening peak hour, as illustrated in Table 2. However, a trend of deterioration in performance is observed on some of the links during different phases of LRT operation. The vehicle 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 LRT operation. The vehicle delay associated with the left-turn movements to parking decks and significant trip attractions, or 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.

Influence on the Parallel Route (I-85)

The TTR assessment was carried out on sixteen different links on the parallel route for four different phases of LRT operation. The results for the I-85 parallel route for a typical morning peak hour are shown in Table 3. From the link-level TTR assessment of the parallel route, a substantial adverse influence 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 LRT operation, the buffer measure notably worsened in all the selected links.

Similar to the morning peak hour, TTR measures showed a consistent trend of worsening in the evening peak for all the phases of LRT operation (Table 4). Also, the degree of change is higher in the evening peak hour compared to the morning peak hour.

Influence on the Near Vicinity Cross-streets

A similar analysis was performed on 42 links on the selected near vicinity cross-streets, and the results are shown in Table 5 and Table 6. There is a trend of decreases 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 hours.

Overall, the link-level analysis indicates that many links in the study area 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 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. Overall, link-level TTR analysis is useful in identifying locations or links where system control, regulation, advisory input, and other strategies are needed to enhance route reliability.

Table 1. 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	1.7	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	1.1	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	0.8	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

Improvement Worsening

Table 2. 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	1.7	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	1.1	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	0.8	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

Improvement — Worsening

Table 3. 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

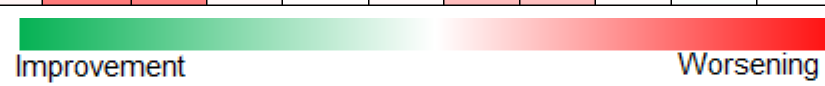


Table 4. TTR Measures: I-85 Parallel Route (Evening Peak)

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 5. 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	0.5	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	0.6	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

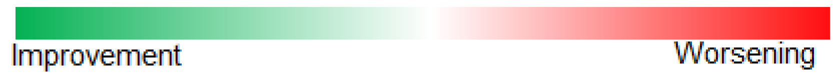
Link	Length (miles)	TTR for the network without LRT					Ratio of TTR values for network with and without LRT														
							Sixth month					Twelfth month					Eighteenth month				
		ATT	PT	BT	BTI	PTI	ATT	PT	BT	BTI	PTI	ATT	PT	BT	BTI	PTI	ATT	PT	BT	BTI	PTI
125N12232	0.19	0.31	0.41	0.10	30.84	1.31	0.98	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	0.5	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	0.2	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 6. 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	0.5	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	0.6	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

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
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	0.5	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	0.2	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



4.3 Corridor-Level Analysis

To compare the overall influence 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 of a link by the length of the corresponding link.

Influence 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 16. The cumulative distribution of travel times along N Tryon St demonstrated a similar pattern during the selected time periods, but the central tendency shifted across 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 time per mile can be seen in the evening peak hours after the LRT was opened for complete service. The median travel time varied from 1.5–2.5 minutes/mile in all the selected hours of analysis.

Influence on the Parallel Route (I-85)

A corridor-level analysis was also performed for the I-85 parallel route (Figure 17). The travel time distributions for morning peak hour substantiate the results 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 50^{th} percentile normalized travel time for morning and evening peak hours. The deterioration in the PT or the 95^{th} percentile travel time, as well as buffer measures (the difference between ATT and PT), can be observed from Figure 9, similar to observations in the link-level analysis. However, during the morning and evening peak hours, a shift in travel time distribution was observed beyond the 50^{th} percentile. The travel time per mile is observed to be at a minimum before the opening of the LRT for service. Overall, the results 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.

Influence on the Near Vicinity Cross-streets

The results for the cross-street analysis are shown in Figure 18. 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 hours, whereas the median travel time during the nighttime is ~one minute/mile. The high dispersion (or variability) in the TTR distribution can be observed in all selected scenarios.

One point that arises from the corridor-level analysis is the difference in morning and evening peak hour commutes in the study region. In general, there is a significant difference in travel time patterns between the morning peak and evening peak hours. 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 hour, rather than commuters favoring a single peak hour. Besides, the variations in normalized travel times were observed to be minimal from 12:00 PM – 1:00 PM and 8:00 PM – 9:00 PM for the selected categories of roads in the TTR assessment.

Figure 16. Cumulative Distribution of Travel Times: N Tryon St

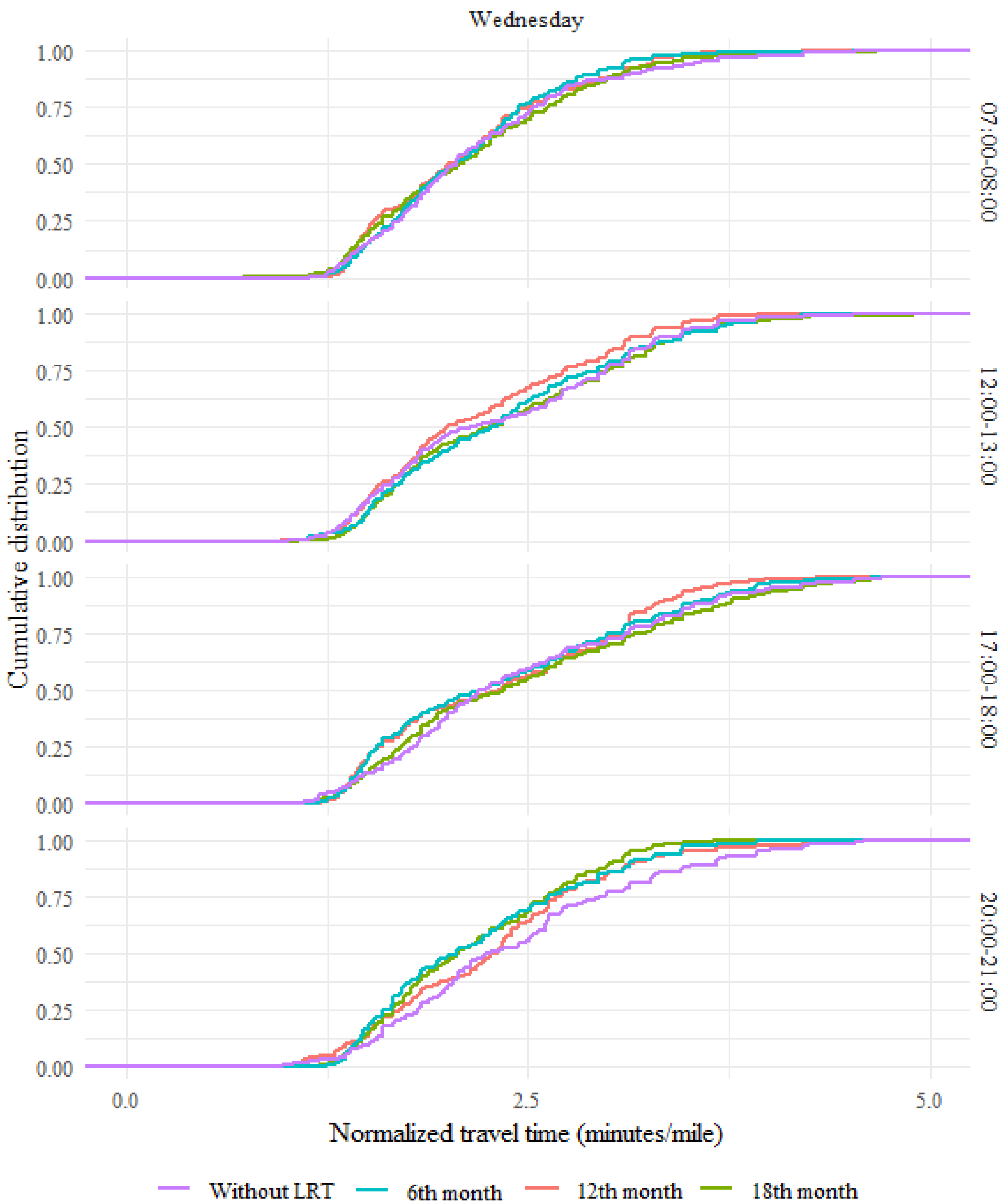


Figure 17. Cumulative Distribution of Travel Times: I-85 Parallel Route

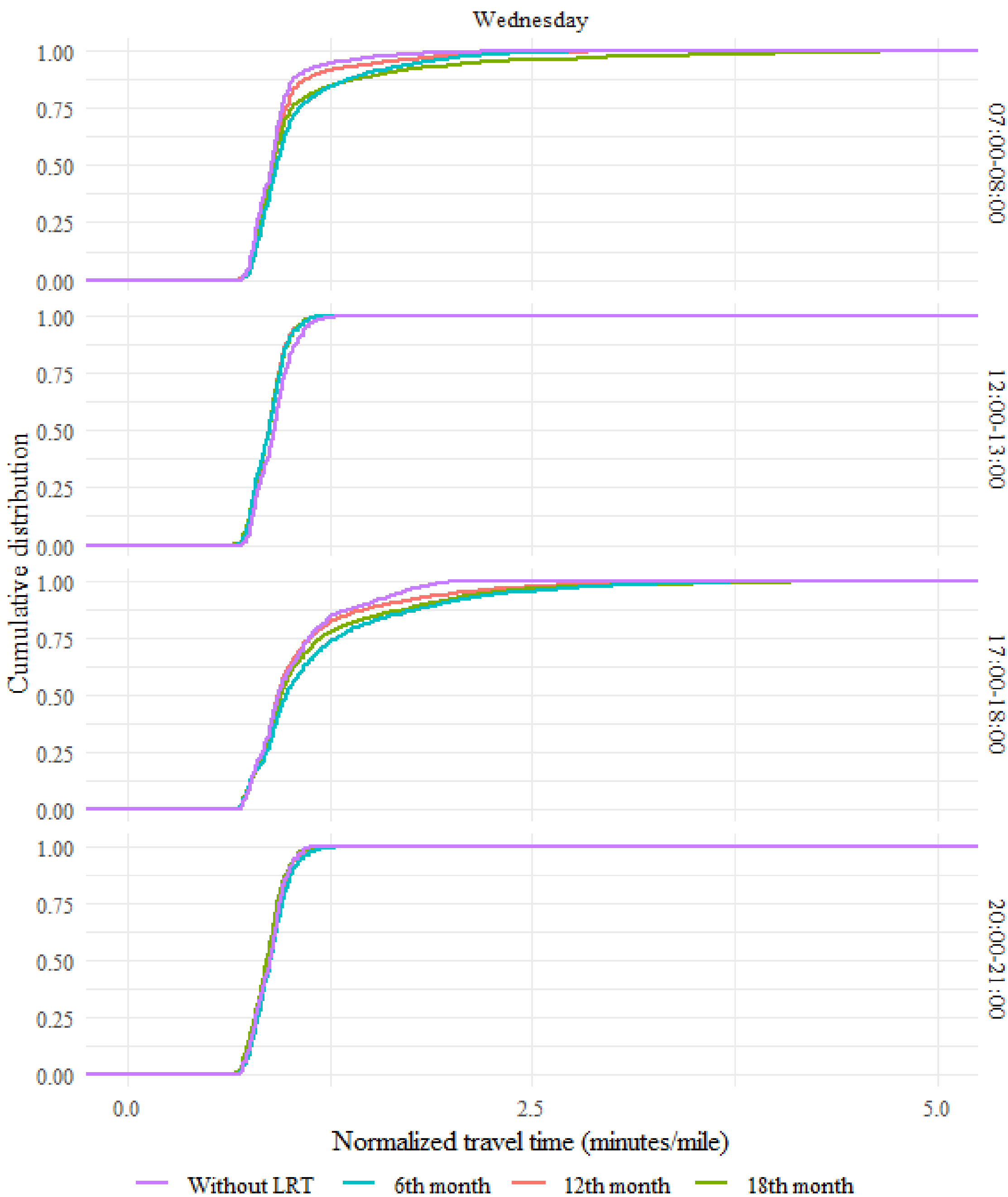
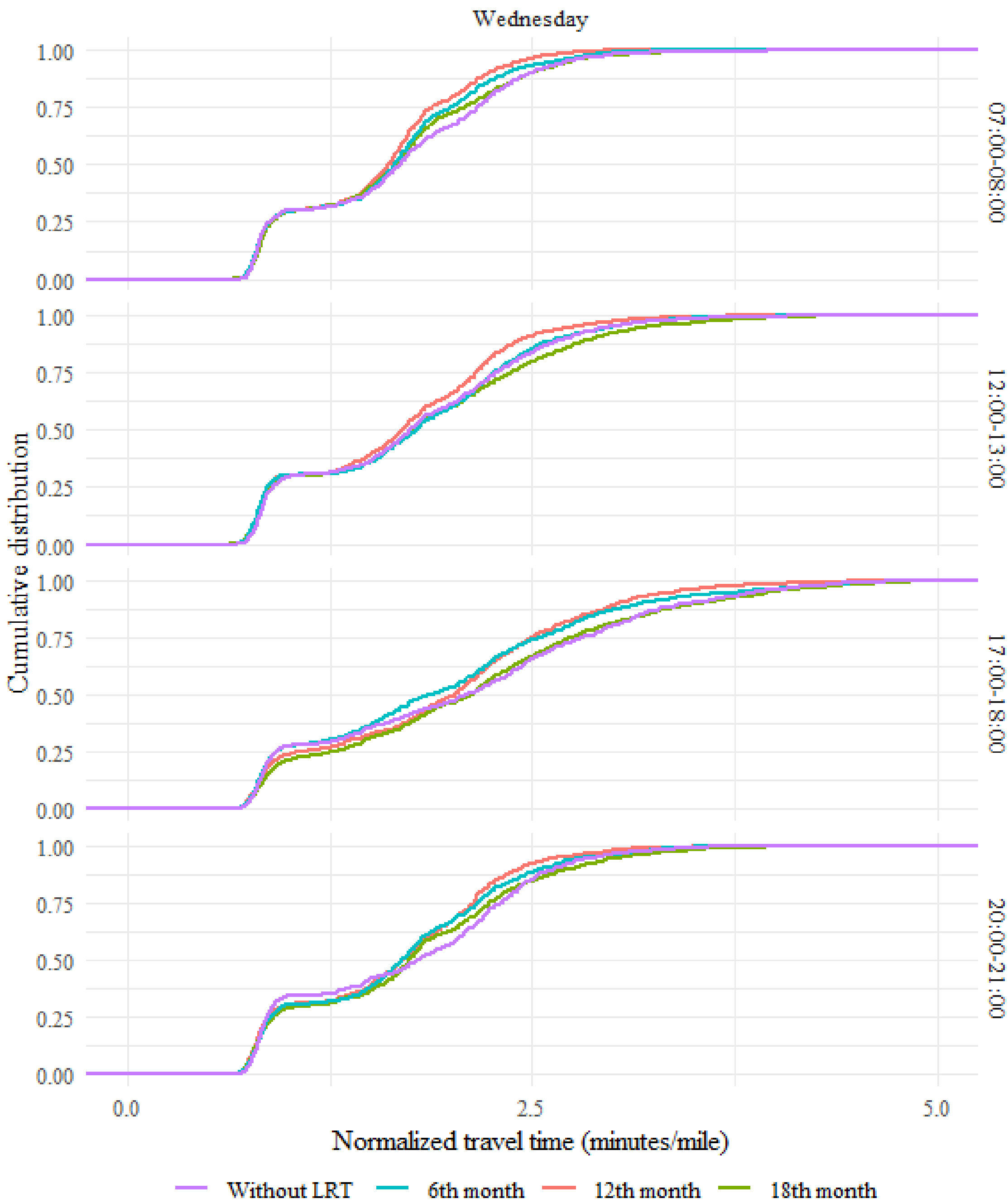


Figure 18. Cumulative Distribution of Travel Times: Near Vicinity Cross-streets



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 sixth month of LRT operation 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 sixth month of LRT operation is less than 0). The mathematical representations of the null and alternate hypotheses are shown as equations 4 and 5.

$$H_0: TTR_d = 0 \quad (4)$$

$$H_1: TTR_d < 0 \quad (5)$$

In these equations, TTR 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 7. The statistical significance of the variations in travel time performance measures was found to be particularly less in the case of N Tryon St (LRT extension corridor). The results are insignificant in the majority of cases in the morning and evening peak hours. Moreover, there exists a statistically significant improvement in TTR during the afternoon and evening peak hours in the study corridor in different phases of LRT operation. 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 7. 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–6:00 PM), N: nighttime (8:00 PM–9:00 PM).

V. Simulation-Based Assessment

This chapter presents the analytical scenarios, methodology, and results from the simulation-based assessment.

5.1 Analytical Scenarios

This section summarizes the analytical scenarios developed using Vissim traffic simulation software.

2016 No Build Scenario

The Blue Line LRT extension from uptown Charlotte to UNC Charlotte's main campus was under construction during 2016. Lane closures were common at most of the intersections. General practice was to close the left-turn lanes, convert the leftmost through lane into a left-turn lane, and decrease the number of through lanes by one. Road inventory data from Google Earth for the associated time period was used to build the network to precisely replicate the then-existing conditions. There were no on-street bicycle lanes at any of the selected intersections on the study corridor.

2017 Build but LRT not in Operation Scenario

The construction of the Blue Line LRT extension was completed in 2017. The number of lanes during the pre-construction scenario were added back on most of the links. All the closed left-turn lanes were restored, and the lane drops for through movement were added back. However, there were lateral shifts in the lane configurations with the center of the road being occupied by the LRT. The LRT was not yet in operation in 2017. Some test runs were conducted during the fall of 2017.

2018 Build and LRT in Operation Scenario

The Blue Line LRT started to operate along the route on March 16, 2018. The turning movement counts obtained from the city of Charlotte Department of Transportation (CDoT) were recorded at the end of April and the beginning of May. The data used in this scenario were collected 45 days after the LRT came into operation.

Only one park and ride facility is available along the study corridor; it was 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.

2018 Build and LRT is in Operation with Pedestrian Activity Scenario

After the Blue Line 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 simulation models were developed with the CDoT data, observed pedestrian data, and extrapolated pedestrian data at the selected intersections to evaluate the influence of pedestrian activity on transportation system performance.

2018 Build and LRT in Operation with Pedestrian & Bicyclist Activity Scenario

No data dedicated to bicycle counts were previously recorded. The only bicycle data available came through the observations made during pedestrian data collection. Though on-street bicycle lanes were constructed in 2018, bicycle counts along the network 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 simulation models were developed using the observed and extrapolated bicyclist count data at the selected intersections to evaluate the influence of bicyclist activity on transportation system performance.

5.2 Methodology

Turning movement counts, pedestrian counts, bicyclist counts, and signal timing details were collected for simulation modeling and analysis. Traffic simulation models were then developed for each analytical scenario. They are discussed next.

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 years 2016, 2017, and 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 in 2018.

Turning Movement Counts

The vehicle 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. However, there were some missing data for a few intersections during 2016 and 2017, which were estimated based on the available data from previous/preceding years and vehicle volumes at the nearby intersections. 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 vehicle 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). Vehicle volume balancing was performed to track inaccuracies in vehicle volumes throughout the study corridor.

Vehicle Volume Balancing

Balancing vehicle 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 vehicle volume imbalances as the numbers might be slightly different on the very next day. To obtain realistic numbers, the average vehicle volumes of a peak period (for example, 4:00 PM – 7:00 PM) were used as hourly vehicle volumes.

The Wisconsin Department of Transportation (WsDOT) has developed a tool to minimize the imbalances and adjust the corresponding vehicle volumes along the corridor (WsDOT 2019)[48]. The vehicle volumes for all the intersections (by approach and turning movement direction) are fed into a macro-enabled Excel sheet 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 vehicle volumes. These vehicle volumes are initially balanced using the vehicle volume balancing tool. The difference in the entering and exiting vehicle volumes at two successive intersections is distributed proportionally based on their corresponding vehicle volumes. The tool runs multiple iterations (maximum of 500) adjusting the vehicle volumes until the differences in vehicle volumes are minimal. In spite of the applying the process, vehicle 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).[48]

WsDOT has also provided acceptable values that serve as benchmarks to tally the final remaining errors. This error is defined as Equation 6.

$$Error = \sqrt{\frac{(Raw\ volume - Balanced\ volume)^2}{Raw\ Volume}} \qquad (6)$$

The vehicle 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 vehicle volumes at intersections along the study corridor were projected based on the available vehicle volumes from adjacent intersections. The relative vehicle volume ratios were calculated for the intersections that had data for years 2016 and 2017 against 2018 volumes. 2018 was considered a base scenario because of the availability of vehicle volume data for all the selected intersections. These ratios were then used to project any missing data for the two previous years.

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 parking services. Bicyclist counts were low as opposed to an expected increase in activity after the LRT is in operation.

Signal Timings

The traffic signal timings and phasing patterns 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.

Vissim Simulation Models

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 intersection. While this is advantageous to the through and right traffic 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 have to 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 provided by the WsDOT. There are 20 locations with vehicle inputs in the network. Table 8 shows vehicle inputs for all 20 locations for all years of the analysis. About a 5% increase in the vehicle volume per year was observed at the considered intersections.

Table 8. Vehicle Inputs: Evening Peak Period

Approach	Vehicle Inputs		
	2016	**2017**	**2018**
N Tryon St & University City Blvd (NB)	726	764	802
N Tryon St & University City Blvd (EB)	645	679	713
N Tryon St & University City Blvd (WB)	1009	1062	1115
N Tryon St & University Pointe Blvd (EB)	261	275	289
N Tryon St & University Pointe Blvd (WB)	201	212	223
N Tryon St & McCullough Dr (EB)	102	107	112
N Tryon St & McCullough Dr (WB)	402	423	444
N Tryon St & Ken Hoffmann Dr (EB)	217	228	239
N Tryon St & Ken Hoffmann Dr (WB)	180	189	198
N Tryon St & WWT Harris Blvd (EB)	1714	1804	1894
N Tryon St & WWT Harris Blvd (WB)	1590	1674	1758
N Tryon St & J M Keynes Dr (EB)	104	109	114
N Tryon St & J M Keynes Dr (WB)	36	38	40
N Tryon St & JW Clay Blvd (EB)	257	271	285
N Tryon St & JW Clay Blvd (WB)	200	210	221
N Tryon St & Institute Cir (EB)	393	414	435
N Tryon St & Institute Cir (WB)	229	241	253
N Tryon St & Mallard Creek Church Rd (SB)	779	820	861
N Tryon St & Mallard Creek Church Rd (EB)	1336	1406	1476
N Tryon St & Mallard Creek Church Rd (WB)	932	981	1030

EB, NB, SB, and WB are eastbound, northbound, southbound, and westbound, respectively.

Input parameters such as the vehicle volumes were allocated at each cross-street and the end of each major street (both ends). Based on the balanced vehicle volumes, the routes were allocated from each major route by analytical scenario (study year). 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.

Simulation models were generated using PTV Vissim 11 for each analytical scenario. Each model was calibrated by comparing the simulated number of vehicles and the vehicle 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. They were generated using three different random seed numbers. The average of the three random seed numbers was used for tabulations and interpretations.

5.3 Results Based on Simulation Analysis

Delays for vehicles in Vissim were computed using the extra time a vehicle takes in the simulation than the ideal allocated time. It was computed as the difference between the ideal travel time from the actual travel time (PTV Group 2019)[9]. Vehicle delay is quantified by approach (defined consistently along the study corridor as shown in Figure 19) rather than by intersection to observe the influence by the direction of travel due to the change in geometric conditions and the addition of LRT across the first three scenarios. Pedestrian and bicyclist activity were added sequentially to the 2018 build scenario and the LRT in operation scenario in the last two analytical scenarios. Queue length, maximum queue length, and LOS were quantified to identify the performance at the intersections instead of capturing performance by approach. Queue length is the average of all the intersection approaches. The maximum queue length is also the maximum value considering all the intersection approaches.

Figure 19. N Tryon St & Institute Cir Intersection with Approaches

2016 No Build Scenario

The cross-streets north of E WT Harris Blvd heading in the northbound direction bring in significant traffic, resulting in congested conditions. The geometric conditions in the direction of the traffic flow during the period of analysis did not change significantly during LRT system construction. The majority of the lane closures observed during LRT system construction were along the southbound approaches.

The results are divided into vehicle delays for the northbound approaches, vehicle delay for the southbound approaches, and vehicle delays on the cross-street approaches. Vehicle delay results for this scenario are presented in Tables 9, 10, and 11. Some approaches along the same direction of travel have different signal phase timings. Therefore, the vehicle delay results are reported by the phase of a given signal. The addition of vehicle delay results by signal phase allows for comparison with other scenarios (for example, during a 2018 LRT in operation scenario).

Table 9. Vehicle Delay between Successive Intersections: Northbound Approach (No Build)

Intersection 1	Intersection 2	D
University City Blvd	University Pointe Blvd	10.66
University Pointe Blvd	McCullough Dr	16.83
McCullough Dr	Ken Hoffman Dr	24.83
Ken Hoffman Dr	E WT Harris Blvd	32.79
E WT Harris Blvd	J M Keynes Dr	27.74
J M Keynes Dr	JW Clay Blvd	39.96
JW Clay Blvd	Institute Cir	53.41
Institute Cir	E Mallard Creek Church Rd	46.40

D is vehicle delay in seconds.

Table 10. Vehicle Delay between Successive Intersections: Southbound Approach (No Build)

Intersection 1	Intersection 2	D
E Mallard Creek Church Rd	Institute Cir	378.49
Institute Cir	JW Clay Blvd	429.20
JW Clay Blvd	J M Keynes Dr	36.69
J M Keynes Dr	E WT Harris Blvd	34.21
E WT Harris Blvd	Ken Hoffman Dr	22.04
Ken Hoffman Dr	McCullough Dr	23.15
McCullough Dr	University Pointe Blvd	23.93
University Pointe Blvd	University City Blvd	3.99

D is vehicle delay in seconds.

The northbound approach vehicle delay values are less than 1 minute. The vehicle delay is relatively higher for JW Clay Blvd and Institute Cir intersections in the northbound direction during the no build scenario. These vehicle delays can be attributed to the vehicle volumes generated at the cross-streets from the university area.

Table 11. Vehicle Delay along Eastbound and Westbound Approaches by Intersection (No Build)

Cross-street	D	
	Eastbound	Westbound
University City Blvd	55.66	480.23
University Pointe Blvd	20.93	31.19
McCullough Dr	154.85	8.70
Ken Hoffman Dr	14.88	0.28
E WT Harris Blvd	35.13	35.57
J M Keynes Dr	58.86	26.65
JW Clay Blvd	34.36	8.37
Institute Cir	43.42	33.00

D is vehicle delay in seconds.

The vehicle delay values are higher for the southbound approaches compared to the other approaches. The vehicle delay is very high at E Mallard Creek Church Rd and Institute Cir intersections of the southbound approaches during the no build scenario. Due to the LRT construction, one through lane along the southbound direction is closed to vehicular traffic starting at the intersection of N Tryon St & E Mallard Creek Church Rd until the intersection of N Tryon St & JW Clay Blvd. The traffic from the university is headed toward I-85 during this period, leading to an increased vehicle delay of up to seven minutes.

Vehicle delays for the eastbound approaches is the highest at McCullough Dr intersection, equal to 154.85 seconds. On the other hand, the vehicle delay for westbound approaches are the highest at University City Blvd intersection, equal to 480.23 seconds. These high vehicle delay values at the cross-streets are attributed to the traffic generated near the commercial and office areas.

2017 Build but LRT Not in Operation Scenario

In this scenario, all the proposed geometric road changes after the construction of the LRT are present. To incorporate heterogeneous traffic conditions and models from a multimodal perspective, on-street bicycle lanes and pedestrian waiting/crossing areas were built into the model. However, not much activity was observed at most of the intersections, as the LRT system was still not in operation. In other words, this scenario can be considered as the scenario for vehicles where no other mode of transportation (including the LRT system) would hinder vehicle operations (though geometric conditions are fairly similar to 2018 LRT in operation scenario).

The results are divided into vehicle delay for the northbound approaches, vehicle delay for the southbound approaches, and vehicle delay on the cross-street approaches. They are presented in

Tables 12, 13, and 14. The percent difference compared to the no build scenario is also presented in the Tables.

Table 12. Vehicle Delay between Successive Intersections: Northbound Approach (Build but LRT is Not in Operation)

Intersection 1	Intersection 2	D	P
University City Blvd	University Pointe Blvd	35.28	231.00
University Pointe Blvd	McCullough Dr	27.06	60.80
McCullough Dr	Ken Hoffman Dr	19.51	-21.40
Ken Hoffman Dr	E WT Harris Blvd	26.44	-19.40
E WT Harris Blvd	J M Keynes Dr	47.12	69.90
J M Keynes Dr	JW Clay Blvd	143.89	260.10
JW Clay Blvd	Institute Cir	207.44	288.40
Institute Cir	E Mallard Creek Church Rd	31.51	-32.10

D is vehicle delay in seconds; P is % diff. compared to no build scenario.

Table 13. Vehicle Delay between Successive Intersections: Southbound Approach (Build but LRT is Not in Operation)

Intersection 1	Intersection 2	D	P
E Mallard Creek Church Rd	Institute Cir	59.95	-84.20
Institute Cir	JW Clay Blvd	306.77	-28.50
JW Clay Blvd	J M Keynes Dr	35.25	-3.90
J M Keynes Dr	E WT Harris Blvd	29.83	-12.80
E WT Harris Blvd	Ken Hoffman Dr	29.99	36.10
Ken Hoffman Dr	McCullough Dr	18.03	-22.10
McCullough Dr	University Pointe Blvd	20.61	-13.90
University Pointe Blvd	University City Blvd	33.73	745.40

D is vehicle delay in seconds; P is % diff. compared to no build scenario.

As observed based on the travel patterns, there was an increase in the overall vehicle delay along all the northbound approaches. The intersections at JW Clay Blvd and J M Keynes Dr on N Tryon St have an increase in the vehicle delay.

When southbound approaches are considered, there was a significant decrease in vehicle delay at Institute Cir and a minor decrease in vehicle delay at JW Clay Blvd on N Tryon St. The addition of an exclusive right lane, heading toward I-85, helped to mitigate the vehicle delay at these intersections. It should be noted that both these intersections are closely spaced. There was a marginal increase in vehicle delay at all other southbound approaches. This could be due to an increase in the vehicle volume.

Table 14. Vehicle Delay along Eastbound and Westbound Approaches by Intersection (Build but LRT is Not in Operation)

Cross-street	Eastbound		Westbound	
	D	**P**	**D**	**P**
University City Blvd	183.17	229.09	20.07	-95.82
University Pointe Blvd	81.90	291.30	14.71	-52.84
McCullough Dr	70.46	-54.50	42.90	393.10
Ken Hoffman Dr	56.00	276.34	65.63	>500.00
E WT Harris Blvd	42.32	20.47	0.28	-99.21
J M Keynes Dr	16.36	-72.21	10.39	-61.01
JW Clay Blvd	2.26	-93.42	30.74	267.26
Institute Cir	9.51	-78.10	73.45	122.58

D is vehicle delay in seconds; P is % diff. compared to no build scenario.

Due to the addition of lanes along the corridor, an increase in traffic volume was observed from the data provided by the CDoT. The vehicle delays along the cross-street approaches did not increase significantly. However, a roughly 200% increase in vehicle delay was observed on the eastbound approach along University City Blvd. A decrease in vehicle delay was observed on the University City Blvd westbound approach when compared to the no build scenario. Even with the increase in vehicle volume, there was a decrease in the vehicle delay on this approach, as the travel patterns (static vehicle routes in Vissim) indicate that more vehicles were traveling along the major approach of N Tryon St.

2018 Build and LRT in Operation Scenario

All geometric changes associated with the LRT construction project were considered complete in this scenario. The LRT system was in operation. Eight trains per hour were observed operating during the evening peak period. While on-street bicycle lanes, crosswalks, and sidewalks were built into the model, pedestrian and bicyclist activity was ignored. In other words, only the influence of the LRT system in operation was examined in this scenario.

The results are divided into vehicle delay for the northbound approaches, vehicle delay for the southbound approaches, and vehicle delay on the cross-street approaches. Tables 15, 16, and 17 show the vehicle delay results obtained for this scenario. The percent differences compared to the scenario with build but no LRT operation are also presented in the tables.

Signal preemption is provided to the traffic in northbound and southbound directions to accommodate the LRT system. This would mean that the cross-streets at all the intersections, excluding the intersections at University City Blvd and E WT Harris Blvd, would receive relatively reduced green times in the signal cycle. In other words, eastbound and westbound traffic need to wait for longer durations with red light, as priority is given to LRT and N Tryon St.

Table 15. Vehicle Delay between Successive Intersections: Northbound Approach (Build and LRT is in Operation)

Intersection 1	Intersection 2	D	P
University City Blvd	University Pointe Blvd	34.03	-3.50
University Pointe Blvd	McCullough Dr	27.66	2.20
McCullough Dr	Ken Hoffman Dr	17.43	-10.70
Ken Hoffman Dr	E WT Harris Blvd	33.06	25.00
E WT Harris Blvd	J M Keynes Dr	78.63	66.90
J M Keynes Dr	JW Clay Blvd	188.25	30.80
JW Clay Blvd	Institute Cir	245.83	18.50
Institute Cir	E Mallard Creek Church Rd	28.54	-9.40

D is vehicle delay in seconds; P is % diff. compared to build but LRT is not in operation scenario.

Table 16. Vehicle Delay between Successive Intersections: Southbound Approach (Build and LRT is in Operation)

Intersection 1	Intersection 2	D	P
E Mallard Creek Church Rd	Institute Cir	87.06	45.20
Institute Cir	JW Clay Blvd	316.24	3.10
JW Clay Blvd	J M Keynes Dr	35.99	2.10
J M Keynes Dr	E WT Harris Blvd	28.82	-3.40
E WT Harris Blvd	Ken Hoffman Dr	30.33	1.10
Ken Hoffman Dr	McCullough Dr	17.23	-4.40
McCullough Dr	University Pointe Blvd	21.26	3.20
University Pointe Blvd	University City Blvd	43.66	29.40

D is vehicle delay in seconds; P is % diff. compared to build but LRT is not in operation scenario.

Table 17. Vehicle Delay along Eastbound and Westbound Approaches by the Intersection (Build and LRT is in Operation)

Cross-street	Eastbound		Westbound	
	D	**P**	**D**	**P**
University City Blvd	173.18	-5.50	21.01	4.70
University Pointe Blvd	134.66	64.40	16.68	13.40
McCullough Dr	76.57	8.70	64.15	49.50
Ken Hoffman Dr	65.84	17.60	102.81	56.70
E WT Harris Blvd	41.47	-2.00	2.60	828.60
J M Keynes Dr	15.78	-3.50	11.56	11.30
JW Clay Blvd	19.45	760.60	81.49	165.10
Institute Cir	29.46	209.80	65.15	-11.30

D is vehicle delay in seconds; P is % diff. compared to build but LRT is not in operation scenario.

The percentage difference between the vehicle delay values from the LRT in operation to not in operation scenario remains consistently low for the northbound approaches. However, exceptions apply to E WT Harris Blvd intersection with a difference of 67%. The vehicle delay results for the southbound approaches also indicate significantly low percentage difference values in comparison to the northbound approaches with E Mallard Creek Church Rd and University Pointe Blvd being exceptions.

The lane configurations at JW Clay Blvd and Institute Cir were changed by CDoT on the westbound approaches for the traffic heading out of the university, which is considered in the analysis. These lanes were changed to provide exclusive right-turn lanes as opposed to a shared through/right-turn lane at both the intersections to reduce vehicle delay for right-turning vehicles.

When results for the eastbound approaches are observed, JW Clay Blvd and Institute Cir have seen a significant increase in the vehicle delay values compared to the LRT not in operation scenario. On the other hand, when results for the westbound approaches are observed, JW Clay Blvd and E WT Harris Blvd have seen a significant increase in the vehicle delay values compared to the LRT not in operation scenario.

2018 Build and LRT in Operation Based on LRT Frequency

The frequency of LRT in operation during the evening peak period was observed as eight trains per hour. The frequency is lower during off-peak hours. To assess the influence during off-peak hours, an analysis was also conducted using four and six trains per hour. Vehicle delay along all the approaches at the intersections in the study corridor are summarized in Tables 18, 19, and 20.

In Table 18, no specific trend was observed though marginal decrease in vehicle delay was observed along a few northbound approaches with the increase in LRT frequency. Contrarily, a decrease in vehicle delay was observed along most of the southbound approaches with the increase in LRT frequency (Table 19). The trends indicate an increase in vehicle delay along the eastbound and westbound approaches with an increase in LRT frequency (Table 20). Decreases in vehicle delays in northbound and southbound approaches as well as increases in vehicle delay for eastbound and westbound approaches could be attributed to the increase in green times for traffic on northbound and southbound directions with the increase in LRT frequency. The counterintuitive trends are due to higher vehicle delays for the left-turning traffic at some intersections.

Table 18. Vehicle Delay between Successive Intersections Based on LRT Frequency: Northbound Approach

Intersection 1	**Intersection 2**	**LRT Trains / Hour**		
		4	**6**	**8**
University City Blvd	University Pointe Blvd	29.10	31.25	34.03
University Pointe Blvd	McCullough Dr	29.84	32.45	27.66
McCullough Dr	Ken Hoffman Dr	14.64	19.23	17.43
Ken Hoffman Dr	E WT Harris Blvd	48.54	50.04	33.06
E WT Harris Blvd	J M Keynes Dr	25.64	32.25	78.63
J M Keynes Dr	JW Clay Blvd	231.45	202.58	188.25
JW Clay Blvd	Institute Cir	234.60	240.23	245.83
Institute Cir	E Mallard Creek Church Rd	22.55	28.65	28.54

Note: 2018 LRT in operation scenario was considered.

Table 19. Vehicle Delay between Successive Intersections Based on LRT Frequency: Southbound Approach

Intersection 1	Intersection 2	LRT Trains / Hour		
		4	6	8
University City Blvd	University Pointe Blvd	92.54	88.87	87.06
University Pointe Blvd	McCullough Dr	172.56	169.36	316.24
McCullough Dr	Ken Hoffman Dr	113.46	103.42	35.99
Ken Hoffman Dr	E WT Harris Blvd	85.46	96.50	28.82
E WT Harris Blvd	J M Keynes Dr	35.65	33.08	30.33
J M Keynes Dr	JW Clay Blvd	10.45	12.17	17.23
JW Clay Blvd	Institute Cir	62.54	54.46	21.26
Institute Cir	E Mallard Creek Church Rd	81.54	62.45	43.66

Note: 2018 LRT in operation scenario was considered.

Table 20. Vehicle Delay along Eastbound and Westbound Approaches by Intersection Based on LRT Frequency

Cross-street	Eastbound			Westbound		
LRT Trains / Hour	4	6	8	4	6	8
University City Blvd	128.65	148.43	173.18	14.54	18.54	21.01
University Pointe Blvd	82.54	112.55	134.66	12.54	14.22	16.68
McCullough Dr	48.21	68.21	76.57	42.47	50.35	64.15
Ken Hoffman Dr	18.25	54.15	65.84	60.22	81.26	102.81
E WT Harris Blvd	32.54	34.23	41.47	2.44	2.45	2.60
J M Keynes Dr	14.56	14.00	15.78	12.10	10.22	11.56
JW Clay Blvd	17.86	17.54	19.45	51.21	65.42	81.49
Institute Cir	26.51	24.51	29.46	22.14	34.32	65.15

Note: 2018 LRT in operation scenario was considered.

2018 Build and LRT in Operation with Pedestrian Activity Scenario

To make conditions more heterogeneous, pedestrian activity was added to the 2018 build and LRT in operation scenario with eight trains per hour. The results are divided into vehicle delays for northbound and southbound approaches in addition to cross-street approaches. Tables 21, 22, and 23 show vehicle delay results for this scenario with pedestrian activity. The percent differences compared to the "LRT is in operation" scenario is also presented in the tables.

Table 21. Vehicle Delay Results between Successive Intersections due to Pedestrian Activity: Northbound Approach (Build and LRT is in Operation)

Intersection 1	Intersection 2	D	P
University City Blvd	University Pointe Blvd	42.22	24.1
University Pointe Blvd	McCullough Dr	22.45	-18.8
McCullough Dr	Ken Hoffman Dr	15.22	-12.7
Ken Hoffman Dr	E WT Harris Blvd	48.06	45.4
E WT Harris Blvd	J M Keynes Dr	85.43	8.6
J M Keynes Dr	JW Clay Blvd	144.22	-23.4
JW Clay Blvd	Institute Cir	220.22	-10.4
Institute Cir	E Mallard Creek Church Rd	36.22	26.9

D is vehicle delay in seconds; P is % diff. compared to build and LRT is in operation scenario.

The pedestrian activity was found to be greatest during peak hours at the intersections of JW Clay Blvd (149 pedestrians) and Institute Cir (109 pedestrians). The pedestrian signals are activated using the pushbuttons; pedestrians are provided a walk phase when the vehicular traffic in the same direction of travel has a green phase.

The influence of an increase in pedestrian activity at the intersections was also studied. However, no change in vehicle delay was observed. The minimal influence of pedestrian activity on vehicle traffic could be due to a lack of signal preemption for pedestrians or higher vehicular green times compared to the time allocated for pedestrians to cross the street.

Table 22. Vehicle Delay between Successive Intersections due to Pedestrian Activity: Southbound Approach (Build and LRT is in Operation)

Intersection 1	Intersection 2	D	P
E Mallard Creek Church Rd	Institute Cir	69.06	-20.70
Institute Cir	JW Clay Blvd	285.06	-9.90
JW Clay Blvd	J M Keynes Dr	41.87	16.30
J M Keynes Dr	E WT Harris Blvd	26.43	-8.30
E WT Harris Blvd	Ken Hoffman Dr	25.98	-14.30
Ken Hoffman Dr	McCullough Dr	15.22	-11.70
McCullough Dr	University Pointe Blvd	17.26	-18.80
University Pointe Blvd	University City Blvd	38.65	-11.50

D is vehicle delay in seconds; P is % diff. compared to build and LRT is in operation scenario.

Table 23. Vehicle Delay along Eastbound and Westbound Approaches by Intersection due to Pedestrian Activity (Build and LRT is in Operation)

Cross-street	Eastbound		Westbound	
	D	**P**	**D**	**P**
University City Blvd	158.39	-8.5	19.22	-8.5
University Pointe Blvd	132.55	-1.6	15.48	-7.2
McCullough Dr	72.43	-5.4	58.26	-9.2
Ken Hoffman Dr	67.22	2.1	121.82	18.5
E WT Harris Blvd	39.04	-5.9	4.54	74.6
J M Keynes Dr	14.54	-7.9	12.65	9.4
JW Clay Blvd	21.22	9.1	78.22	-4.0
Institute Cir	24.56	-16.6	62.32	-4.3

D is vehicle delay in seconds; P is % diff. compared to build and LRT is in operation scenario.

When compared across 2016 and 2018, vehicle delays are higher for southbound approaches on N Tryon St during 2016. The southbound approach between E Mallard Creek Church Rd and Institute Cir saw a greater decrease in vehicle delay from 2016 to 2017 and also 2018. There was a decrease in vehicle delay on the southbound approach between Institute Cir and JW Clay Blvd from 2016 to 2017. However, there was not much of a change in vehicle delay from 2017 to 2018 between Institute Cir and JW Clay Blvd. The decrease in vehicle delay can be attributed to geometric improvements between these intersections.

The influence on eastbound and westbound approaches is different when compared to northbound and southbound approaches. This difference could be attributed to changes in geometric conditions and signal phasings/timings along the LRT study corridor. The westbound approach of University City Blvd saw a decrease in vehicle delays from 2016 to 2017 and 2018. However, the vehicle delays along the eastbound approach increased from 2016 to 2017 and 2018. There were several changes in geometric conditions at the JW Clay Blvd and Institute Cir intersections on N Tryon St. The vehicle delays along eastbound approaches decreased, whereas the vehicle delays along westbound approaches increased from 2016 to 2017 and 2018. This could be attributed to proportionally higher green times for key turning movements as well as allowing right turns at red lights.

2018 Build and LRT in Operation with Pedestrian & Bicycle Activity Scenario

In addition to vehicle volumes, LRT, and pedestrian activity, bicycle activity was added at selected intersections to evaluate transportation system performance from a multimodal perspective. The results are divided into vehicle delay for the northbound approaches, vehicle delay for the southbound approaches, and vehicle delay on the cross-street approaches. Tables 24, 25, and 26 show the vehicle delay results on the corridor with bicycle activity. The percent differences compared to the “LRT is in operation with pedestrian activity” scenario is also presented.

Table 24. Vehicle Delay between Successive Intersections due to Bicyclist Activity: Northbound Approach (Build and LRT is in Operation)

Intersection 1	Intersection 2	D	P
University City Blvd	University Pointe Blvd	34.03	-19.40
University Pointe Blvd	McCullough Dr	27.66	23.20
McCullough Dr	Ken Hoffman Dr	17.43	14.50
Ken Hoffman Dr	E WT Harris Blvd	33.06	-31.20
E WT Harris Blvd	J M Keynes Dr	78.63	-8.00
J M Keynes Dr	JW Clay Blvd	188.25	30.50
JW Clay Blvd	Institute Cir	245.83	11.60
Institute Cir	E Mallard Creek Church Rd	28.54	-21.20

D is vehicle delay in seconds; P is % diff. compared to LRT is in operation with pedestrian activity scenario.

Table 25. Vehicle Delay between Successive Intersections due to Bicyclist Activity: Southbound Approach (Build and LRT is in Operation)

Intersection 1	Intersection 2	D	P
E Mallard Creek Church Rd	Institute Cir	87.06	26.10
Institute Cir	JW Clay Blvd	316.24	10.90
JW Clay Blvd	J M Keynes Dr	35.99	-14.00
J M Keynes Dr	E WT Harris Blvd	28.82	9.00
E WT Harris Blvd	Ken Hoffman Dr	30.33	16.70
Ken Hoffman Dr	McCullough Dr	17.23	13.20
McCullough Dr	University Pointe Blvd	21.26	23.20
University Pointe Blvd	University City Blvd	43.66	13.00

D is vehicle delay in seconds; P is % diff. compared to LRT is in operation with pedestrian activity scenario.

Table 26. Vehicle Delay along Eastbound and Westbound Approaches by Intersection due to Bicyclist Activity (Build and LRT is in Operation)

Cross-street	Eastbound		Westbound	
	D	**P**	**D**	**P**
University City Blvd	173.18	9.30	21.01	9.30
University Pointe Blvd	134.66	1.60	16.68	7.80
McCullough Dr	76.57	5.70	64.15	10.10
Ken Hoffman Dr	65.84	-2.10	102.81	-15.60
E WT Harris Blvd	41.47	6.20	2.60	-42.70
J M Keynes Dr	15.78	8.50	11.56	-8.60
JW Clay Blvd	19.45	-8.30	81.49	4.20
Institute Cir	29.46	20.00	65.15	4.50

D is vehicle delay in seconds; P is % diff. compared to LRT is in operation with pedestrian activity scenario.

In comparison to pedestrian volume, very few bicyclists were observed during the study period. Geometric changes between 2016 and 2018 include an additional on-street bicycle lane along the corridor. The travel patterns allow bicyclists to traverse the road in parallel to vehicle traffic before approaching the intersection and to travel along the pedestrian crosswalks at the intersection. There are some conflict points along the network where these areas merge, and right-of-way is provided to bicyclists at these locations.

There was no significant increase in vehicle delays between the "LRT is in operation with pedestrian activity" scenario and this scenario with bicyclist activity. The average vehicle delays for the northbound and southbound approaches at all the intersections increased, while there was a slight decrease in the average vehicle delay along the cross-street approaches in the eastbound and westbound directions.

Queue Length and Level of Service (LOS)

The queue length, maximum queue length, and LOS were captured and tabulated for each study intersection. They were captured by creating nodes around the intersections. The nodes are polygonal areas created around an area of interest to capture the operational characteristics. Tables 27, 28, and 29 summarize the queue length, maximum queue length, and LOS for each intersection, respectively. The intersection of E Mallard Creek Church Rd at N Tryon S is not considered in the analysis, as the LRT system does not extend to this intersection, but the vehicle inputs are provided starting from the E Mallard Creek Church Rd and N Tryon St intersection.

Table 27. Queue Length at Intersections on N Tryon St

Cross-street	Queue length (feet)		
	2016	2017	2018
University City Blvd	20.24	91.10	104.31
University Pointe Blvd	15.94	21.34	21.29
McCullough Dr	39.26	28.50	30.05
Ken Hoffman Dr	30.06	32.37	48.76
E WT Harris Blvd	33.99	30.40	67.66
J M Keynes Blvd	33.58	66.58	149.46
JW Clay Blvd	291.81	379.28	439.75
Institute Cir	266.56	208.71	259.54

Table 28. Maximum Queue Length at Intersections on N Tryon St

Cross-street	Maximum queue length (feet)		
	2016	2017	2018
University City Blvd	97.84	1032.27	1079.15
University Pointe Blvd	282.10	436.68	449.87
McCullough Dr	355.80	360.87	413.91
Ken Hoffman Dr	360.74	401.95	767.87
E WT Harris Blvd	430.72	302.91	715.62
J M Keynes Blvd	306.96	863.32	1268.30
JW Clay Blvd	1312.82	1344.81	1347.47
Institute Cir	1658.85	1538.92	1553.45

From 2016 to 2018, queue length increased at all intersections. One notable example is the intersection at University City Blvd. A comparison of queue lengths at selected intersections between 2017 and 2018 would summarize the influence of the LRT system on vehicular traffic.

Table 29. Level of Service at Intersections on N Tryon St

Cross-street	LOS		
	2016	2017	2018
University City Blvd	E	F	F
University Pointe Blvd	C	C	C
McCullough Dr	C	C	C
Ken Hoffman Dr	C	C	C
E WT Harris Blvd	D	D	D
J M Keynes Blvd	D	E	E
JW Clay Blvd	F	F	F
Institute Cir	F	F	F

An increase in queue length between the years for each intersection could be contextualized via an increase in the queue length by approach, all of which can be observed during the simulation. Increases in queue length at University City Blvd and E WT Harris Blvd on N Tryon St is due to the northbound and southbound traffic—mainly due to its accumulation at the intersections. The increase in queue length at JW Clay Blvd and Institute Cir occurs due to queuing along the eastbound and westbound approaches.

The maximum queue length at all intersections has increased from 2017 to 2018. This parameter is a better indicator in some ways compared to the queue length. There is not much of a difference in maximum queue length at the intersections of Institute Cir and JW Clay Blvd. The reason there is no change (or a decrease) in the maximum queue length is the geometric improvements and frequent green times for through movements on N Tryon St to accommodate the LRT system. The maximum queue length would extend until the length of the node in some cases. This indicates that the signal timings at these intersections were not sufficient to accommodate the entire volume of traffic coming off the cross-street even before the LRT was in operation. After the LRT system was in operation, signal timings were adjusted, and lane configurations were changed. That said, vehicle delays along cross-streets increased in some cases.

The levels of service at University City Blvd and J M Keynes Dr on N Tryon St worsened from 2016 to 2017. At all the other intersections, the LOS was found to be the same between 2016 and 2018.

VI. Conclusions

Providing for and encouraging the use of alternative modes of transportation helps to alleviate the growing traffic demand and associated congestion problems. However, the provision of infrastructure elements for alternative modes of transportation results in heterogeneous traffic conditions. This research has examined the influence of the addition of a new mode of travel along a corridor on the performance of vehicular traffic. Travel time and TTR measures with heterogeneous conditions and without heterogeneous conditions were examined. A simulation-based approach was used to examine the influence of the LRT system, pedestrian activity, and bicyclist activity on vehicular traffic.

Travel time and TTR patterns before and after the operation of the LRT system began were examined on the study corridor (N Tryon St), the parallel route (along I-85), and near vicinity cross-streets. The average travel times during peak hours of travel in the study area increased after the LRT system came into operation. Other TTR measures like BT and BTI also increased after the LRT system is in operation. To reveal the statistical significance of the results, a paired t-test was conducted at a 95% confidence level. 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 the Blue Line LRT extension. The 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 the less significant changes observed in TTR measures. In the parallel route, as observed in the link-level and corridor-level analysis, there is a 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.

In the simulation-based analysis, all the network characteristics were captured for 2016, 2017, and 2018 to develop the models. Significant geometric changes were made in the network to encourage walking and bicycling along with the use of the LRT system. The traffic signal timings were also changed in 2018, allowing more green time for traffic on N Tryon St and to give priority to the LRT system in operation. Vehicle delay was captured by the direction of travel along the study corridor (N Tryon St) and the cross-streets at each selected intersection. Queue length and level of service were also captured to better understand the influence at the intersection level from a multimodal perspective.

At a corridor level, the results indicate that the cross-streets of N Tryon St incurred a relatively higher increase in vehicle delay after the LRT is in operation. A reduction in total green time for cross-streets at at-grade intersections is the primary reason for these trends. An increase in LRT-related activity also seems to increase the vehicle delay on cross-streets. Observations also indicate that vehicle delay between 2017 and 2018 has not increased by a large margin, while queue length and maximum queue length have increased. In order to accommodate these vehicles, improvements were made by allowing the vehicles to enter the study corridor from cross-streets using dedicated right-turn lanes.

Along N Tryon St, the vehicle delay during peak hours were found to be consistent in all analytical scenarios. There was an increase in vehicle delay on northbound and southbound approaches of N Tryon St in some cases even after the LRT was in operation. This could be attributed to higher vehicle delays for left-turn traffic at some intersections (having to wait longer to accommodate the LRT system, for example) from N Tryon St. However, a decrease in vehicle delays was observed on the eastbound approaches of JW Clay Blvd and Institute Cir after the LRT is in operation. This could be attributed to the existence of dedicated right-turn lanes for traffic exiting UNC Charlotte's main campus, proportionally higher green times for some key turning movements, and allowing right-turns on red.

Pedestrian and bicyclist counts do not account for even 0.5% of the vehicular traffic at the selected intersections. The scenarios with pedestrian and bicyclist activity indicate that they increase vehicle delay at some intersections. Their influence seems to depend on geometric conditions. No signal preemption or special provisions were observed for pedestrians and bicyclists on the study corridor. Therefore, pedestrian and bicyclist movement are only allowed when the vehicle volume would not conflict with the path of pedestrians and bicyclists.

Safety statistics along the study corridor during the years of analysis could not be explored as data were not readily available at the time of this research. Besides, no dedicated signals for pedestrians and bicyclists exist at present. Research that aims to evaluate these scenarios is recommended.

Endnotes

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About the Authors

Swapneel Rao Kodupuganti, MS

Mr. Swapneel Rao Kodupuganti is pursuing his PhD in Infrastructure and Environmental Systems (INES) program at the University of North Carolina at Charlotte. He earned his master's degree from the University of North Carolina at Charlotte. His areas of interest are transportation planning, traffic operations, simulation and modeling of transportation facilities, and traffic safety.

Sonu Mathew, PhD

Dr. Sonu Mathew, recently, graduated with his PhD in Infrastructure and Environmental Systems (INES) program at the University of North Carolina at Charlotte. He earned his master's degree from Sardar Vallabhai National Institute of Technology, Surat, India. His areas of interest are transportation planning, traffic flow modeling and simulation, Geographic Information Systems (GIS) applications, and traffic safety.

Srinivas S. Pulugurtha, PhD

Dr. Srinivas S. Pulugurtha, PE, F. ASCE is currently working as Professor & Research Director of the Department of Civil & Environmental Engineering at The University of North Carolina at Charlotte. He is also currently directing the Infrastructure, Design, Environment, and Sustainability (IDEAS) Center at the University of North Carolina at Charlotte.