



# Assessing the effect of a light rail transit system on road traffic travel time reliability

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## Abstract

A travel time reliability-based approach is proposed to assess the effect of the light rail transit (LRT) system on the road network within its vicinity. A 4-mile stretch of the Blue Line LRT extension, which connects the Old Concord Road and the University of North Carolina at Charlotte (UNC Charlotte) main campus in Charlotte, North Carolina (NC), was considered as the study corridor. The raw travel time data was 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 link, referred to as Traffic Message Channel (TMC) in this research, by day-of-the-week and time-of-the-day. Further, the travel time reliability of the links on the LRT extension corridor and adjacent corridors (both the parallel route and the cross-streets) were computed for different scenarios: network without LRT, testing phase of LRT, first month of LRT operation, third month of LRT operation, sixth month of LRT operation, and ninth month of LRT operation. The travel time reliability of the alternate route and cross-streets was affected by the LRT system operation. Increased green times and better coordination on the LRT corridor and the benefits associated with the alternate mode/route choice for commuters may be the reason behind the steadiness in travel time performance measures due to the LRT. The methodology and findings help transportation planners and engineers in comparing the performance or efficiency of large-scale public transportation projects like LRT and bus rapid transit (BRT) on travel time reliability within its vicinity.

**Keywords** Light rail transit · Travel time reliability · Planning time · Buffer time · Buffer time index

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## 1 Introduction

Mobility-oriented transportation infrastructure investments in recent decades, along with increasingly insufficient public transportation infrastructure, have compelled more and more people to choose private vehicles for commuting. The unintended consequences due to an increase in the number of private cars, such as congestion, have severely degraded the quality of urban commuting. The growing demand for road traffic has not been offset by a proportionate increase in the road infrastructure in most major cities around the globe, mainly due to space and resource constraints. To contain such trends, cities are looking into measures to increase public transit ridership with proper transit planning, investments in public transit infrastructure, and the introduction of smart technologies to improve accessibility, convenience, and comfort.

Transit systems such as light rail transit (LRT) and bus rapid transit (BRT) move large numbers of passengers while requiring lesser capital and operational costs compared to rapid rail transit systems (Knowles 1996). This research is mainly aimed at assessing the effect of an LRT system on the road traffic performance within its vicinity.

The popularity of the LRT system in the United States is mainly due to its capability in reducing congestion and delivering safer, more predictable commutes for users who need to reach their destination on time (Clark 1984). The benefits of lower transportation costs, changing land-use patterns, higher property values, and reduction in emissions due to the implementation of the LRT system was pointed out by Litman (2012). Exploring such benefits, Charlotte Area Transit System (CATS) opened the Blue Line LRT system, in November 2007, from I-485 at South Boulevard to Uptown Charlotte in Charlotte, North Carolina (NC). The LRT system was extended from Uptown Charlotte to the University of North Carolina at Charlotte (UNC Charlotte) main campus in March 2018.

The decision to implement such an LRT system and to design its operational attributes are made after a comprehensive transportation planning process or a feasibility study. Additionally, the effectiveness of an LRT system in mitigating congestion and improving travel time must be monitored and frequently evaluated after the 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 are adjusted to incorporate the frequency of operation of the LRT system. Assessing the effect of the LRT system on near-vicinity road traffic is difficult because of its complex interaction with moving traffic. In other words, the short-term and long-term impacts of such changes on the traffic operations are uncertain and warrant attention and research.

Typical travel demand models capture the effect of large-scale transportation projects like the LRT system from a socio-economic-spatial aspect. However, it is difficult to fully understand the effect of the LRT system on the region's traffic from typical travel demand models. In that context, providing short-term evidence of the LRT systems' effect on traffic based on travel time reliability indices can be considered as significant research development. Therefore, this study is carried out to

assess the effect of an LRT system in reducing travel time and improving travel time reliability on links (short segments of a corridor) along an at-grade LRT corridor, a parallel alternate corridor, and cross-streets within its vicinity, using travel time data. The effect of the LRT system on travel time reliability of the links adjacent to the LRT corridor was analyzed without LRT and considering different phases of the LRT system operation.

As summarized at the end of Sect. 2, a few studies focused on the effect of LRT on road traffic operational aspects. However, none of the past studies focused on the effect of LRT on travel time reliability of the near vicinity road traffic. The findings from this research indicate that there was an improvement in travel time reliability on most of the links while there was a deterioration in travel time reliability on some of the links on the LRT corridor, in many operating scenarios compared to the network without the LRT system operation. Contrarily, the findings indicate that there was a deterioration in travel time reliability on most of the parallel route and cross-street links with the LRT system operation. In particular, no notable improvement in travel time reliability was observed during the peak hours of traffic. The lack of expected improvement in travel time reliability on the parallel alternate route and cross-street links, with the LRT system operation, could be attributed to the increase in traffic volume, increase in movement of traffic in and out LRT parking facilities, and changes (for example, signal phasing and timing patterns) at at-grade intersections. The improvement in travel time reliability on most of the links on the LRT corridor could be attributed to the increase in green times and better coordination of signals on the LRT corridor.

The remainder of the paper comprises four sections. The relevant literature is summarized in Sect. 2. Section 3 presents the framework adopted for developing travel time distributions and reliability measures. Section 4 quantifies the effect of the LRT system in terms of improvement in travel time reliability on the LRT corridor, the parallel alternate route, and the near vicinity cross-streets, and statistically validating the trend in improvement. Section 5 summarizes the findings from this study.

## 2 Literature review

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

Good quality of service attracts personal vehicle users to the LRT system, thus reducing traffic congestion (Knowles 1996). On the contrary, such a capability of the LRT in reducing the congestion was also questioned in some studies. Mackett

and Edwards (1998) stated that the positive effect of many rail-based transit systems throughout the world on traffic congestion was less than the earlier projections.

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

The analysis of the effect of the LRT on the road traffic within its vicinity requires a comprehensive understanding of traffic and LRT signalization. Venglar et al. (1994) explored the possibility of measuring the effect of the LRT system using various factors such as delay to automobile occupants, delay to LRT users, “person-delay” at intersections, the volume-to-capacity ratio at intersections, queue lengths, the number of stops, and the travel times on adjacent streets. Another measure recommended for LRT affect quantification is the length of the automobile queue accumulated during the passage of an LRT (Bates and Lee 1982). Islam et al. (2016) studied the applicability of transit signal priority strategies in improving the reliability of LRT operation with less effect on the general traffic. They computed various measures like total travel time, total delay, and the average speed to evaluate the corridor performance.

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

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

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

Travel time reliability measures include buffer measures, statistical measures, and delayed trip indicators. The United States Department of Transportation (USDOT) proposed four different measures of travel time reliability. 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% percent of the trips.

The average travel time (ATT) indicates the nominal level of congestion in a road segment. The PT and BT indicate the variability in travel times from a road user perspective. The BTI suggests the reliability of the transportation system over time. According to the report published by FHWA (2005), 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 in comparison to the light traffic condition. Wakabayashi et al. (2003) studied commuters' attitudes toward travel time reliability while considering alternate modes of transportation. They studied travelers' decision making in choosing their mode after a public transportation service closure and concluded the effect of travel time variations in the selection process. Pulugurtha et al. (2017) surveyed transportation system users' perception toward travel time reliability and monetized the value of reliability for evaluating transportation projects/alternatives.

In summary, the effect of LRT operation on road traffic, such as inducing delays at the intersections and reducing the capacity of the road, was studied by a few researchers in the past. The travel time and travel time reliability measures were also established in the past. However, the travel time and travel time reliability measures were not explored to evaluate the effect of an LRT system on the near vicinity road traffic. The spatial and temporal effects due to LRT operation was also not studied in the past. Therefore, the main focus of this research is to develop a systematic framework and evaluate the effect of the LRT system on the road traffic within its vicinity using travel time and travel time reliability measures, over space and time. The objectives of this research are:

1. to propose a methodology to quantify the effectiveness of the LRT system in influencing travel time reliability using the N Tryon St as the study corridor, and,
2. to assess the changes in travel time reliability with its vicinity, over time, after the implementation of the LRT system.

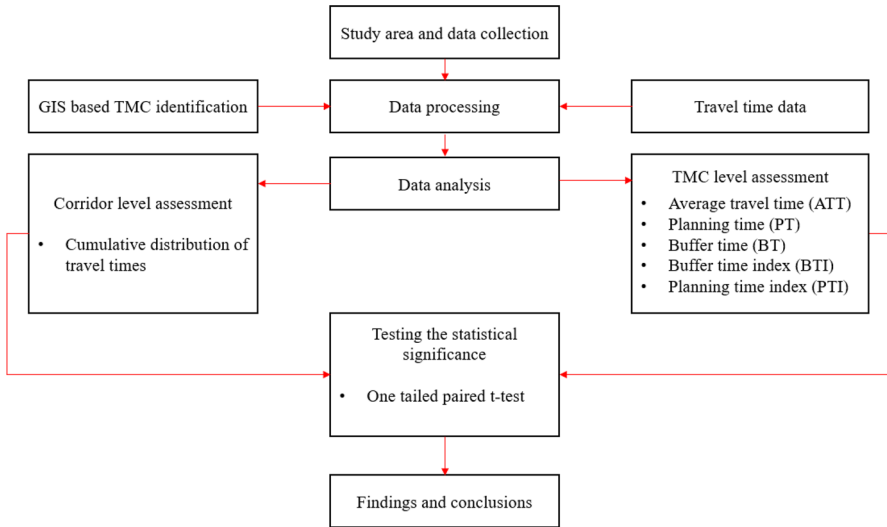
### 3 Methodology

Figure 1 represents the methodological framework adopted for the travel time reliability-based assessment of the LRT system.

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

#### 3.1 Study area and data collection

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 UNC Charlotte's main campus. The first section was opened in November 2007 from I-485 at South Boulevard to Uptown Charlotte. This section is 9.6-miles long with 15 stations and 7 park and ride facilities. The second section from uptown Charlotte to UNC Charlotte main campus was opened in March 2018. This extended section is 9.3 miles long with



**Fig. 1** Methodological framework to assess the effect of an LRT system on traffic

11 stations and 4 park-and-ride facilities. The weekday service operates from 5:26 AM to 1:26 AM. The service is available every 7.5 min during weekday rush hour and every 15 min during non-peak hours (Charlotte Area Transit System 2018). A 4-mile stretch of the new extension that connects Old Concord Rd and UNC Charlotte main campus, through the N Tryon St median, was considered for this study and analysis. Figure 2 shows the selected study area.

Six different scenarios; network without LRT, the testing phase of LRT, the first month of LRT operation, the third month of LRT operation, the sixth month of LRT operation, and the ninth month of LRT operation were considered in the travel time reliability analysis.

The raw minute-wise travel time data was 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, Traffic Message Channel (TMC) ID. The data contains nine-digit TMC IDs, unique segment identification numbers (for example, 125+08373). The data processing is carried at two levels: GIS-based link (TMC) identification and the computation of travel time reliability indices.

### 3.2 Data processing

Geo-referencing of the links was made 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 NC. A buffer of 1 mile was created along the N Tryon St, and all the links within the 1-mile-buffer were identified.





The travel time variability for different hours of the day and days of the week was first examined. These travel time variability patterns help in determining the peak and off-peak hours of the day and peak day of the week. In this research, four typical hours of a weekday, morning peak (7:00 AM–8:00 AM), afternoon peak (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 travel time reliability measures (FHWA 2005) were considered to assess the effect of the LRT system on the transportation system performance. All these measures were derived from the travel time distributions (for example, as shown in Fig. 3).

The ATT, the free flow travel time, and the 95th percentile travel time were computed for each link, by aggregating data by day-of-the-week and time-of-the-day using Microsoft SQL. The 95th percentile travel time indicates that 95% of the time, the performance of the study segment will not be worse than the values associated with the 95% percentile travel time. PT is directly computed from the travel time data. BT is the difference between the PT and the ATT (FHWA 2005), as shown in Eq. 1. It indicates the extra travel that travelers add to their ATT for the on-time arrival at their destination.

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

The PTI and BTI (FHWA 2005) 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 Eq. 2. It compares the near worst travel time with the ideal travel time.

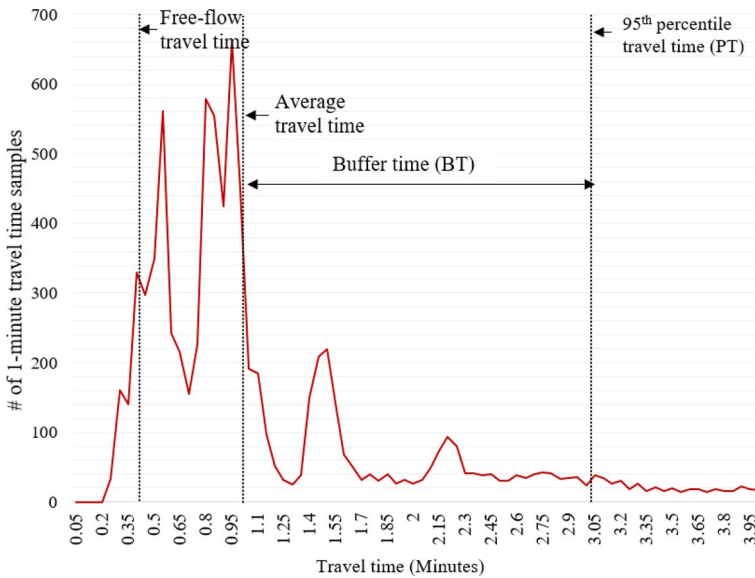


Fig. 3 Travel time distribution for the N Tryon study corridor



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

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

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

### 3.3 Data analysis

An LRT system with dedicated right-of-way and signal priority influence the arterial street traffic. Figure 4 shows the interaction of the LRT system with moving traffic and pedestrians. The initial assessment of travel time reliability was carried out at the link-level, as it can capture the effect of the LRT system on a specific segment of the road. Moreover, route-level aggregation may only provide the overall effect of travel time variability along the selected study corridor. As this study proposes a methodological framework for the assessment of the effect of an LRT system on the road traffic within its vicinity, the initial assessment was performed at the disaggregated level. The link-level analysis was followed by a corridor-level travel time distribution analysis. As the lengths of the link are not the same, data normalization was carried out by dividing the travel time with the length of each link. The measures of travel time reliability (ATT, PT, BT, BTI, and PTI) are basically derived from these distributions.

The statistical significance of the change in travel time performance measures (ATT, PT, BT, BTI, and PTI) over different phases of LRT operation was evaluated using the one-tail paired t-test. The analysis was performed at 99%, 95%, and 90% confidence levels (CLs). The null hypothesis assumes that the mean difference between the travel time performance measure between the network without LRT and



Fig. 4 Interaction of the LRT system with the moving traffic

the selected operational phase is equal to zero. The alternative hypothesis assumes that the mean difference between the selected performance measures is less than zero.

## 4 Analysis and findings

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

### 4.1 Travel time reliability at link-level

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

#### 4.1.1 Effect on the LRT corridor (N Tryon St)

The travel time reliability assessment was carried out on 12 different links along the N Tryon St for six different phases of LRT operation. The selected links are shown in Fig. 2. The travel time reliability assessment of 125+08371 (a sample link) is illustrated in Fig. 5. From Fig. 5, there is no specific trend in travel time reliability over different phases of LRT operation.

Further, for each selected link, the ratio between the respective travel time performance measure for the analysis phase compared to the network without the LRT phase was computed. A value of ratio greater than one indicates a deterioration in the travel time performance measure while a value of ratio less than one indicates an improvement in travel time reliability. The analysis performed for the N Tryon St on a typical weekday evening peak hour is summarized in Fig. 6.

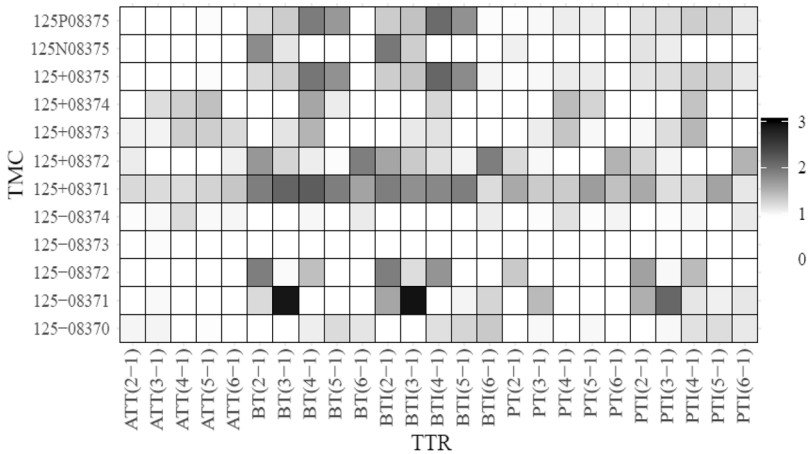
The grey-shaded cells have a ratio greater than one, which indicates a deterioration in performance measure after the operation of the Blue Line LRT. The white color cells indicate an improvement in the travel time reliability measure compared to the system without LRT. For example, the ratio of ATT during the testing phase of the LRT divided by the ATT for the network without the LRT, ATT (1–2) in Fig. 6, is reported as 1.22 for link ID –125+08371. This implies a 22% increase in the ATT during the testing phase of the LRT when compared to the network without the LRT condition.

The variation in the ATT is minimal during the testing phase. However, many links showed an apparent deterioration in buffer measures over different phases of LRT operation. A significant deterioration in other travel time performance measures on some of the links during the evening peak hour was observed. The delay associated with the at-grade LRT system crossings can be considered as one primary reason behind the increase in travel time. Moreover, one can also



**Fig. 5** Travel time reliability for 125+08371 over different phases of LRT operation

see a very consistent deterioration in travel time performance measures, on link IDs 125+08371 and 125+08372, during different phases of the LRT operation. The delay associated with the left-turn turning movements to parking decks and significant trip attractions to the university area and other public offices in the vicinity may have influenced the travel time performance on 125+08371 and 125+08372. Moreover, these links are the starting point of the 4-mile extension stretch of the Blue Line LRT corridor.



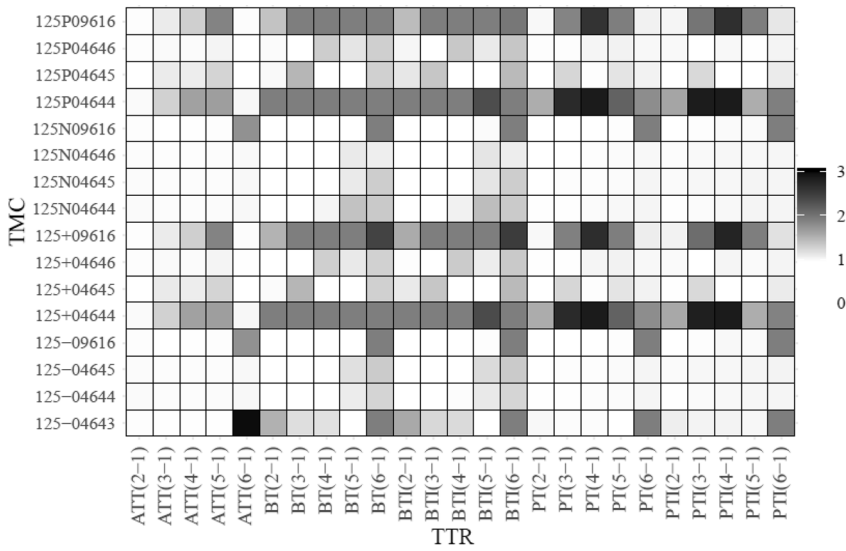
Note: 2-1: Testing phase of LRT - Network without LRT; 3-1: First month of LRT operation - Network without LRT; 4-1; Third month of LRT operation - Network without LRT; 5-1: Sixth month of LRT operation - Network without LRT, 6-1: Ninth month of LRT operation - Network without LRT

Fig. 6 Travel time reliability (TTR) measures—LRT corridor

Another major link with a significant effect is 125–08373, which connects the LRT corridor to the university area. The travel time reliability of this segment showed a clear trend of improvement in the evening peak hour. However, a trend reversal was also observed in the morning peak hour. The links connecting the N Tryon St to the I-485, 125+08375 and 125P08375, showed a trend of deterioration in buffer measures during each phase of the LRT operation. Similar plots were generated for all the selected time periods.

#### 4.1.2 Effect on the parallel alternate route (I-85)

The travel time reliability assessment was carried out on 18 different links along the parallel alternate route for six different phases of LRT operation. The heatcharts developed for the I-85 parallel alternate route for a typical evening peak hour is shown in Fig. 7. From the link-level travel time reliability assessment of the parallel alternate route, a substantial adverse effect on travel time reliability was observed during the evening peak, especially during the sixth and ninth month of the LRT operation. However, in the case of the afternoon peak (12:00 PM–1:00 PM), there exists a clear trend of improvement in travel time reliability.



Note: 2-1: Testing phase of LRT - Network without LRT; 3-1: First month of LRT operation - Network without LRT; 4-1; Third month of LRT operation - Network without LRT; 5-1: Sixth month of LRT operation - Network without LRT, 6-1: Ninth month of LRT operation - Network without LRT

Fig. 7 Travel time reliability (TTR) measures—I-85 parallel alternate route

### 4.1.3 Effect on the near vicinity cross-streets

A similar analysis was performed on 42 links along the selected near vicinity cross-streets. There is a trend of deterioration in travel time performance measures on some of the cross-street links. During the morning peak hour, the majority of the links showed an adverse change in travel time reliability. The travel time reliability of the near vicinity cross-streets during the testing phase of LRT gives a clear picture of the effect of signal cycle adjustments. The study results showed a clear trend of deterioration in travel time performance measures during morning peak hour, and a mixed trend during the evening peak of the testing phase of the LRT system.

Overall, the link-level analysis indicates that many links on the LRT corridor clearly showed an improvement, while the travel time reliability worsened in some of them during many operating scenarios, compared to the network without the LRT system operation. To avoid delays at signalized intersections due to the LRT system operation, there exists a clear exhibit of alternate route choice during the morning, evening, and nighttime hours. The worsening in travel time reliability on the parallel alternate route links indicates the same. Overall, link-level travel time reliability analysis is useful in identifying locations or links where system control, regulation, advisory, and other strategies are needed to enhance route reliability.

### 4.2 Corridor-level analysis

To compare the overall effect of the LRT system on travel time reliability measures, cumulative frequency diagrams were plotted at an aggregate level. Data normalization was carried out by dividing the travel time with the length of each link.

#### 4.2.1 Effect on the LRT corridor (N Tryon St)

The cumulative distribution of travel times per mile for the N Tryon St during the analysis period is shown as Fig. 8. The cumulative distribution of travel times along the N Tryon St showed a similar pattern, but the central tendency shifted during different hours of the day. For example, in the morning peak hour, lower travel time can be seen for the network without the LRT phase, whereas, in the evening peak hour, lower travel time was observed during the third month of the LRT system operation.

Similar to link-level analysis, the travel time distribution diagram shows a negative trend in travel time distributions during the morning peak hour. The higher shift was observed during the first month of LRT operation. The ATT is 2 to 2.5 min/mile in all the selected scenarios. Over time, the shift is diverse for different time periods. The standard deviation and dispersion of the distribution are found to be very high

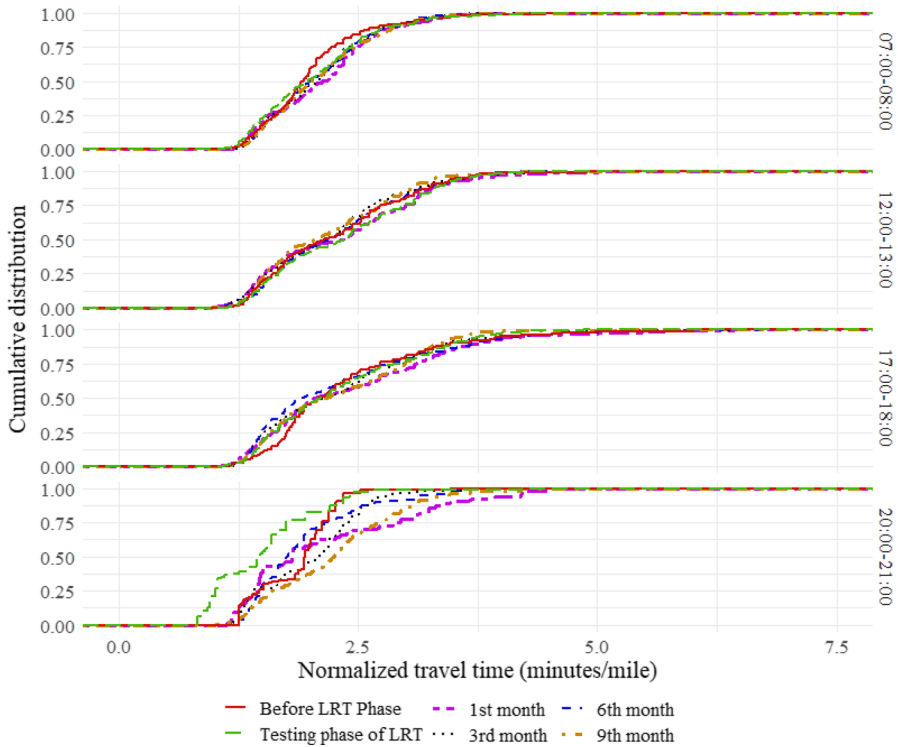


Fig. 8 Cumulative distribution of travel times—N Tryon St

in the LRT corridor in all the selected scenarios of LRT operation. On the other hand, this indicates the lack of travel time reliability on the LRT corridor.

### 4.2.2 Effect on the parallel alternate route (I-85)

A corridor-level analysis was also performed for the I-85 parallel alternate route (Fig. 9).

The travel time distributions for morning peak hours substantiate the results obtained from the link-level analysis. Mean or 50th percentile travel time is found to be approximately 1 min/mile in all the selected scenarios. However, an overall shift in distribution was also observed beyond the 50th percentile normalized travel time for morning and evening peak periods. The deterioration in the PT or the 95th percentile travel time, and buffer measures (the difference between ATT and PT) can be observed from Fig. 9, similar to observations in the link-level analysis. A similar trend of travel time distribution was observed for the before LRT phase and the testing phase where there was no ridership on the LRT system. However, during the morning and evening peak hours, a shift in travel time distribution was observed beyond the 50th percentile. Overall, the results obtained indicate that the parallel alternate route (I-85), a freeway, is more reliable for daily commutes, is still the first-choice preference for daily commutes in the study region.

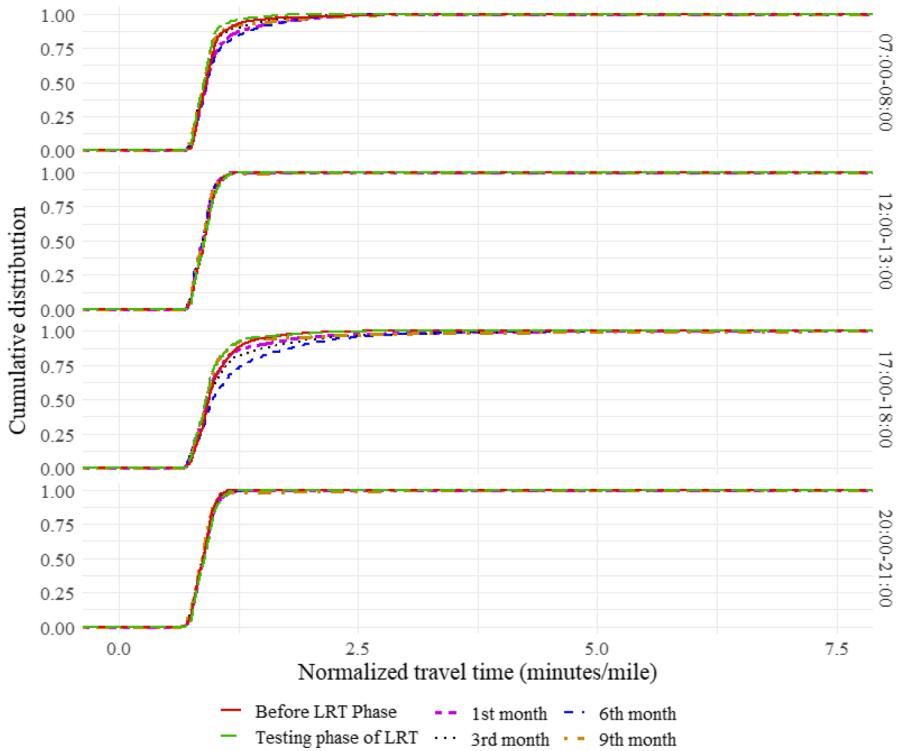


Fig. 9 Cumulative frequency diagrams of travel times—I-85 parallel alternate route



### 4.2.3 Effect on the near vicinity cross-streets

The results obtained for the cross-street analysis is shown in Fig. 10. The travel time distribution for cross-streets follows a similar pattern during the morning peak and afternoon peak hours, whereas, a shift in distribution can be seen during the nighttime hour. The median travel time ranges from 1.5 to 2 min/mile in the morning, afternoon, and evening peak periods, whereas, the median travel time during nighttime is ~ 1 min/mile. The higher dispersion in the distribution can be observed in all the selected scenarios.

One point that arises from the corridor-level analysis is the difference in morning and evening peak commutes in the study region. In general, there is a significant difference in travel time patterns between the morning peak and evening peak. In Charlotte, NC, the majority of people seeking to travel during rush hours use personal cars. From a general perspective, the peak evening commute is defined between 3:00 PM and 7:00 PM. A chance of uneven distribution of trips is possible during this entire peak period, rather than a single peak hour (based on working hours). Besides, the variations in normalized travel times were observed

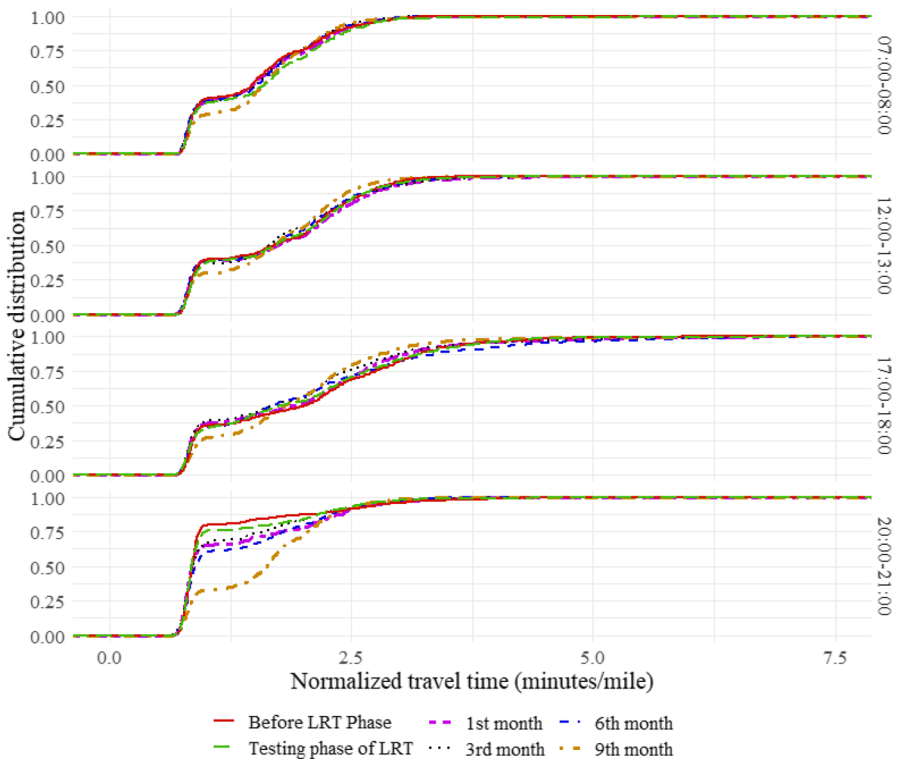


Fig. 10 Cumulative frequency diagrams of travel times—near vicinity cross-streets

to be minimal during 12:00 PM–1:00 PM time period for the selected categories of roads in the travel time reliability assessment.

### 4.3 Testing the statistical significance

To understand the statistical significance of changes in travel time reliability measures (ATT, PT, BT, and BTI), a paired *t*-test analysis was conducted at 99%, 95%, and 90% CLs. Generally, the one-tail paired *t*-test is used for before-after comparisons of the same subject matter. The null hypothesis is ‘H<sub>0</sub>: Travel time reliability measure remained the same during a phase of the LRT operation compared to the network without the LRT (for example, BT for a network without LRT minus BT for the testing phase of LRT is equal to 0)’. The alternate hypothesis is ‘H<sub>1</sub>: Travel time reliability measure reduced during a phase of the LRT operation (for example, BT for a network without LRT minus BT for the testing phase of LRT is less than 0)’. The mathematical representations of the null and alternative hypotheses are shown as Eqs. 4 and 5.

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

$$H_0 : TTR_d < 0 \quad (5)$$

In Eqs. 4 and 5,  $TTR_d$  is the difference in the selected travel time reliability 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 1. The statistical significance of the variations in travel time performance measures was found to be particularly less in the case of the N Tryon St (LRT extension corridor). The results obtained are insignificant in a clear majority of cases. A balance between the travel time loss due to frequent lane closures and the benefits associated with the alternate route choice for commuters may be considered as the reason behind such a result.

Buffer measures give an idea about the extra time that a traveler needs to add to their ATT to ensure timely completion of the trip, 95% of the time. Here, no significant increase in buffer measure along the N Tryon St for the majority of the scenarios can be considered as a good indication in a short-term perspective.

The paired *t*-test results for the I-85 parallel alternate route revealed that there exists a significant deterioration in all the travel time performance measures during the morning and evening peak hours. However, the paired *t*-test results showed a clear trend of improvement in travel time reliability during 12:00 PM–1:00 PM time period.

In the case of cross-street links, the change in reliability is found to be marginal compared to the parallel alternate route. While considering the morning peak hour, PTI showed statistically significant deterioration in all the LRT operation scenarios. In the evening peak hour, the change in travel time reliability is limited to a few analysis scenarios. One can also notice a clear trend of deterioration in travel time reliability in the afternoon peak hour.

Table 1 Paired *t*-test results

| Travel Time Reliability (TTR) Measure | Scenario | LRT Corridor |    |    |     | Parallel Alternate Route |     |    |     | Near Vicinity Cross-streets |     |     |     |
|---------------------------------------|----------|--------------|----|----|-----|--------------------------|-----|----|-----|-----------------------------|-----|-----|-----|
|                                       |          | M            | L  | E  | N   | M                        | L   | E  | N   | M                           | L   | E   | N   |
| Average Travel Time (ATT)             | 1-2      | -            | ** | -  |     | ***                      |     | ** | **  | **                          | **  | -   | -   |
|                                       | 1-3      | -            | *  | -  | *   | ***                      | *** | *  | **  | -                           | **  | -   | -   |
|                                       | 1-4      | -            | -  | -  | **  |                          | *** | *  | **  | *                           |     | *   | *   |
|                                       | 1-5      | -            | -  | -  | *   | ***                      | *** | ** | **  | -                           | *   | -   | -   |
|                                       | 1-6      | -            | *  | -  | **  | **                       | *** | *  | **  | -                           | **  | *** | *** |
| Planning Time (PT)                    | 1-2      | -            | *  | -  | **  | **                       | *** |    | *** | **                          | *   |     |     |
|                                       | 1-3      | -            |    | -  | **  | **                       | *** | ** | *** |                             | *   | *   | *   |
|                                       | 1-4      | -            |    | -  | **  | -                        | *** | *  | *** | **                          | **  | **  | **  |
|                                       | 1-5      | -            | *  | -  | **  | -                        | *** | ** | *** | -                           | **  | *   | *   |
|                                       | 1-6      | -            | -  | *  | **  | *                        | *** | ** | -   | -                           | -   | **  | **  |
| Buffer Time (BT)                      | 1-2      | -            | -  | -  | -   | **                       | *** | -  | *** | -                           | -   | -   | -   |
|                                       | 1-3      | -            | -  | -  | **  | *                        | *** | ** | *** | -                           | *   | *   | *   |
|                                       | 1-4      | -            | *  | *  | **  | -                        | *** | ** | *** | -                           | *** | *   | *   |
|                                       | 1-5      | -            | -  | -  | **  | -                        | *** | ** | *** | -                           | **  | *   | *   |
|                                       | 1-6      | -            | -  | *  | *** | *                        | *** | ** | *   | **                          |     | -   | -   |
| Buffer Time Index (BTI)               | 1-2      | -            | -  | -  | -   | ***                      | *** | *  | *** | **                          | *** | -   | -   |
|                                       | 1-3      | -            | -  | -  | *   | **                       | *** | ** | *** | *                           | **  | *   | *   |
|                                       | 1-4      | -            | ** | ** | **  | -                        | *** | ** | *** | -                           | *** | *   | *   |
|                                       | 1-5      | -            | *  | -  | **  | -                        | *** | *  | *** | -                           | *** | -   | -   |
|                                       | 1-6      | -            | *  | -  | *** | **                       | *** | ** | **  | **                          | **  | -   | -   |
| Planning Time Index (PTI)             | 1-2      | -            | -  | -  | -   | **                       | *** | -  | *** | **                          | *** | -   | -   |
|                                       | 1-3      | -            | -  | -  | **  | **                       | *** | ** | *** | *                           | **  | -   | -   |
|                                       | 1-4      | -            | *  | ** | **  | -                        | *** | ** | *** |                             | *** | -   | -   |
|                                       | 1-5      | -            | -  | -  | **  | **                       | *** | *  | *** | **                          | **  | -   | -   |
|                                       | 1-6      | -            | -  | -  | *** | **                       | *** | ** | **  | **                          | *** | *   | *   |

1-2: Network without LRT—testing phase of LRT; 1-3: network without LRT—first month of LRT operation; 1-4: network without LRT—third month of LRT operation; 1-5: network without LRT—fifth month of LRT operation, 1-6: network without LRT—sixth month of LRT operation

\*\*\*Improvement in 99% CL, \*\*improvement in 95% CL, \*improvement in 90% CL, Blank – no change, \*\*\* : deterioration in 99% CL, \*\* : deterioration in 95% CL, and \* : deterioration in 90% CL  
 M: morning peak (7:00 AM–8:00 AM), L: afternoon peak (12:00 PM–1:00 PM), E: evening peak (5:00 PM–6:00 PM), N: nighttime (8:00 PM–9:00 PM)

### 5 Conclusion

This study proposes a travel time reliability-based assessment procedure to quantify the effect of an LRT system on the near vicinity arterial traffic. The effect of the LRT system on travel time reliability of the LRT corridor, the parallel alternate route, and

the near vicinity cross-streets was analyzed for six different scenarios: network without LRT, the testing phase of LRT, the first month of LRT operation, the third month of LRT operation, the sixth month of LRT operation, and the ninth month of LRT operation. ATT, 95th percentile travel time (or PT), BT, BTI, and PTI were computed for each link, by day-of-the-week and time-of-the-day. Specifically, data corresponding to typical peak hours and a nighttime hour of a weekday was identified for the analysis.

Most of the links on the LRT corridor clearly showed an improvement, while some of them showed a lack of reliability during many operating scenarios, compared to the network without the LRT system operation. To avoid delays at signalized intersections due to the LRT system operation, there exists a clear exhibit of alternate route choice during the morning, evening, and nighttime hours. Overall, link-level travel time reliability analysis is useful in finding locations or links where system control, regulation, advisory, and other strategies are needed to enhance route reliability.

A corridor-level assessment quantified the overall effect of the LRT system on the road traffic within its vicinity. The travel time distribution plots generated for different scenarios provide much better clarity about how travel time has changed over different phases of the LRT system operation. The statistical significance of the variations in travel time performance measures was found to be nominal in the case of the LRT corridor. The changes in signal timings at intersections seem to influence traffic to take the alternate route. This may have resulted in the inconsistency of performance measures during the morning and evening peak hours.

The travel time reliability of the parallel alternate route was significantly affected by the LRT system operation. A positive effect was observed during the afternoon hours, and a negative trend was observed during the morning, evening and nighttime hours. The effect of large-scale transportation projects varies spatially and temporally. In the case of cross-streets, the change in travel time measures is mainly significant during the afternoon hours.

The Blue Line LRT extension project's purpose was to mitigate congestion, increase access and enhance mobility in the region. However, such a notable improvement in route reliability (statistically significant improvement in travel time reliability measures) was only observed during the afternoon hours. Also, statistical test results indicated a consistent trend in travel time reliability on the LRT corridor (no significant change) during the morning and evening peak for many operating scenarios. In its first year, the ridership on Blue Line LRT extension has been consistently below the original projections (Harrison 2019). While the projection was around 33,500 average weekday riders, the reported ridership in January 2019 (the ninth month of LRT operation) was 25,200 average weekday riders. According to a report published by Portillo (2019) in 'the Charlotte Observer', private vehicle ownership and relatively low gasoline price still motivate people to more often travel by car. Also, there are no high-density developments along the new extension corridor. These can be attributed as significant factors influencing the ridership.

The analysis presented in this paper portrays the short-term effect of the LRT system on the arterial road network within its vicinity. Traffic changes due to other events beyond the scope of the study seem to be insignificant (short-term evaluation considering data over a 9-month period). However, conducting the same research over time and incorporating data related to the LRT ridership, traffic volume, and

delay at the intersections may provide more insights about the network-level benefits of the LRT system.

The goal of any large-scale transportation project such as LRT is to provide travel mode choices, improve mobility, and reduce congestion on roads. However, a significant improvement in travel time reliability was not observed on some links in several analytical scenarios, particularly during the peak hours of traffic. The findings are similar to those observed by Mackett and Edwards (1998) and Lane (2008). The difference between what was forecasted and what is observed could be due to the performance measures, study area (regional vs. near vicinity), data, and methodological approaches used to conduct analysis in the past. The findings from this research reiterate the fact that a more systematic and comprehensive analysis is needed along with considering suitable performance measures prior to making decisions for implementation of LRT or similar large-scale transportation projects. Adopting the proposed methodology adds novelty to the current practice and helps transportation planners and engineers in effectively evaluating the performance of large-scale transportation projects.

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